Deliverable 10.19: UMAN – Possible management options and preferences of different actors for near-field related uncertainties

Work Package 10

Uncertainty Management multi-Actor Network (UMAN)

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This report is a supplement to WP UMAN Deliverables D10.11 (Kaempfer et al., 2023) and D10.12 (Haverkate et al., 2024). In order to produce a complete and readable document, while, at the same time, remaining consistent with the above-mentioned reports, some parts of the text have been verbally (or nearly verbally) copied, with the kind permission of the authors.

Executive Summary[1]

This report presents the aspects of management of near-field uncertainties as investigated in Subtask 4.2 as well as in the 5th Workshop of Subtask 4.3 in the extension 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 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 Support 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. Subtask 4.3 aims at synthesising the preferences of the different actors regarding uncertainties associated with specific topics and identifying needs for future research, development and demonstration.

The initial focus of the WP UMAN lies on four types of uncertainties related to site and geosphere, human aspects, spent nuclear fuel and waste inventory, discussed for disposal of different waste types in different host rocks. In the framework of the EURAD second wave, the UMAN scope was extended by the near-field uncertainties, put in the context of geological disposal of high level waste/spent nuclear fuel in clay and crystalline rocks. This report deals with the management of the near-field uncertainties, which covers the identification of possible management strategies and options as well as the different actors' preferences. It can be seen as a supplement to reports by Kaempfer et al. (2023) and Haverkate et al. (2024), summarising the outcome of Subtasks 4.2 and 4.3 of the first phase of the WP UMAN, respectively.

For the purpose of this study, three examples of the near-field-related uncertainties, called topical uncertainties, were selected from the comprehensive list of near-field uncertainties developed in UMAN Subtask 3.6 (Pfingsten et al., 2024).

The overview about different approaches and uncertainty management options was developed by using information on generic strategies in uncertainty management (from Subtask 2.1) 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. Furthermore, the experience of organisations participating in UMAN were gathered from the responses to UMAN questionnaires and from additional input collected by Subtask 4.2 through 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 5th UMAN Workshop organised by Subtask 4.3, which was dedicated to near-field uncertainties.

The second part of this report provides an overview of the outcome of the 5th UMAN Workshop, which was dedicated to analysing the different actors' views and preferences on managing options for the selected topical near-field uncertainties. There is some inhomogeneity regarding the assessment of uncertainty significance between the actors representing differently advanced disposal programmes. This is obviously due to the confidence in the developed concepts and their effectiveness to reduce, avoid or mitigate uncertainties. Many workshop participants generally assessed the near-field uncertainties less relevant than far-field uncertainties, which is predominantly valid for concepts that rely on the geological barrier. The workshop participants identified a variety of research needs that are also presented in this report.

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[1] This section contains passages taken from (Kaempfer et al., 2023) and (Haverkate et al., 2024)

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Abbreviation List

ACED	EURAD Work Package "Assessment of Chemical Evolution of ILW and HLW Disposal Cells"
BEACON	European research project "Bentonite Mechanical Evolution"
BIGBEN	Research project "Constitutive Equations for Sodium and Calcium Bentonites"
CONCORD	EURAD Work Package "CONtainer CORrosion under Disposal conditions"
CS	Civil Society
DECOVALEX	International research and model comparison collaboration "DEvelopment of COupled models and their VALidation against Experiments"
DGR	Deep geological repository
EBS	Engineering barrier system
EDZ	Excavation damaged zone
ELBRock	Research project "Entwicklung von Endlagerbehälterkonzepten für die geologische Tiefenlagerung von hochradioaktiven Abfällen in kristallinem Wirtsgestein"
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"
HITEC	EURAD Work Package "Influence of temperature on clay-based material behaviour"
HLW	High level waste
IAEA	International Atomic Energy Agency
IGD-TP	Implementing Geological Disposal of radioactive waste Technology Platform
KM	Knowledge Management
L/ILW	Low/intermediate level waste
LOMIR	IGD-TP research project "Long-Term Monitoring of C-14 Compounds Released During Corrosion of Irradiated Metal"
MICA	Research project "Michigan International Copper Analogue"
MICADO	European research project "Model Uncertainty for the Mechanism of Dissolution of Spent Fuel in a Nuclear Waste Repository"
NEA	Nuclear Energy Agency/
NS	Not specified
PA	Performance assessment
QA	Quality Assurance
QC	Quality Control
OECD	Organisation for Economic Co-operation and Development
QUADER	Research project "Qualifizierung der Rechenprogramme d³f und r³t"
QVV	Qualification, Verification, Validation

R&D	Research and Development
RD&D	Research, Development and Demonstration
RE	Research Entity
RWM	Radioactive Waste Management
SA	Safety assessment
SCC	Stress corrosion cracking
SFC	EURAD Work Package "Spent fuel characterisation and evolution until disposal"
SIRUB	Research project "Sicherheitsrelevante Untersuchungen zur Bentonitaufsättigung"
SNF	Spent nuclear fuel
StSt	Strategic Study
THMC	Thermal, hydraulic, mechanical and chemical processes
THMCBR	Thermal, hydraulic, mechanical, chemical, biological and radiation processes
TSO	Technical Support Organisation
UMAN	EURAD Work Package "Uncertainty Management multi-Actor Network"
WMO	Waste Management Organisation
WP	Work Package

1. Introduction

1.1 Background[2]

The Work Package (WP) “Uncertainty Management multi-Actor Network” (UMAN), representing one of the strategic studies (StSt) initiated in the framework 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 (RWM) stages and programmes. The focus of the WP UMAN lies on four types of uncertainties related to site and geosphere, human aspects, spent nuclear fuel and waste inventory, discussed for disposal of different waste types in different host rocks. In the framework of the EURAD second wave, the UMAN scope was extended by the near-field uncertainties, put in the context of geological disposal of high level waste/spent nuclear fuel in clay and crystalline rocks. The WP includes various activities such as exchanges on views, practices and preferences regarding uncertainty management options as well as review of existing strategies, approaches, and tools. Interactions between different types of actors involved in RWM, including Waste Management Organisations (WMOs), Technical Support Organisations (TSOs), Research Entities (REs) and Civil Society (CS), are however central to this WP. These interactions aim at meeting the shared objectives of:

- fostering a mutual understanding of uncertainty management and how it relates to risk and safety,
- sharing knowledge and know-how as well as discussing common methodological and strategical challenging issues related to uncertainty management,
- identification of past and ongoing research and development (R&D) projects to the overall management of uncertainties,
- identification of remaining and emerging issues and needs associated with uncertainty management.

In cases, where the common understanding was beyond the reach, an effort was made to understand the similarities and differences in the actors´ views and preferences as well as the reasons behind them. With respect to the latter, it was expected that the views on uncertainty management may vary among these actors due to:

- their different roles in RWM programme, interest and concerns, which in turn would drive their preferences with respect to management strategies and options,
- the specificities of the national programmes these actors represent (including regulations, considered waste types and host rock(s), repository type and design as well as safety concept),
- the current implementation phase of the national programme,
- lessons learned,
- and even cultural aspects.

The present report was prepared in the framework of Task 4, Subtasks 4.2 and 4.3 of the extension of the WP UMAN. The views and preferences of three actors´ groups (namely WMOs, TSOs and REs) on uncertainty management were explored in the framework of WP UMAN in Task 4 “Uncertainty management options and preferences of different actors across the various phases” (see Figure 1 for the structure of the WP UMAN). The overall objectives of this task were to identify, for the different phases of a disposal programme (shown in Figure 2) and the associated decision-making, a bundle of possible options for:

- treating uncertainties associated with specific topics in the safety assessment (SA) (e.g. uncertainty propagation methods, scenario development, stylisation approaches, …),
- avoiding, reducing or mitigating these uncertainties,

[2] This section contains passages taken from (Kaempfer et al., 2023) and (Haverkate et al., 2024)

- making a safety case robust vis-à-vis these 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.

Within UMAN Task 4, the identification of the actors´ preferences on uncertainty management options was performed by Subtask 4.3 "Preferences of the different actors on uncertainty management options", which overall objectives were to:

- synthetise the preferences of the different actors for uncertainties associated with specific topics based on the outcomes of Subtasks 4.1, 4.2 and 5.1,
- preparation of material needed by Task 5 to interact with a broader audience on the views of different actors considering the whole process of RWM,
- identification of needs for future research, development and demonstration (RD&D), knowledge management (KM) or strategic study (StSt) activities.

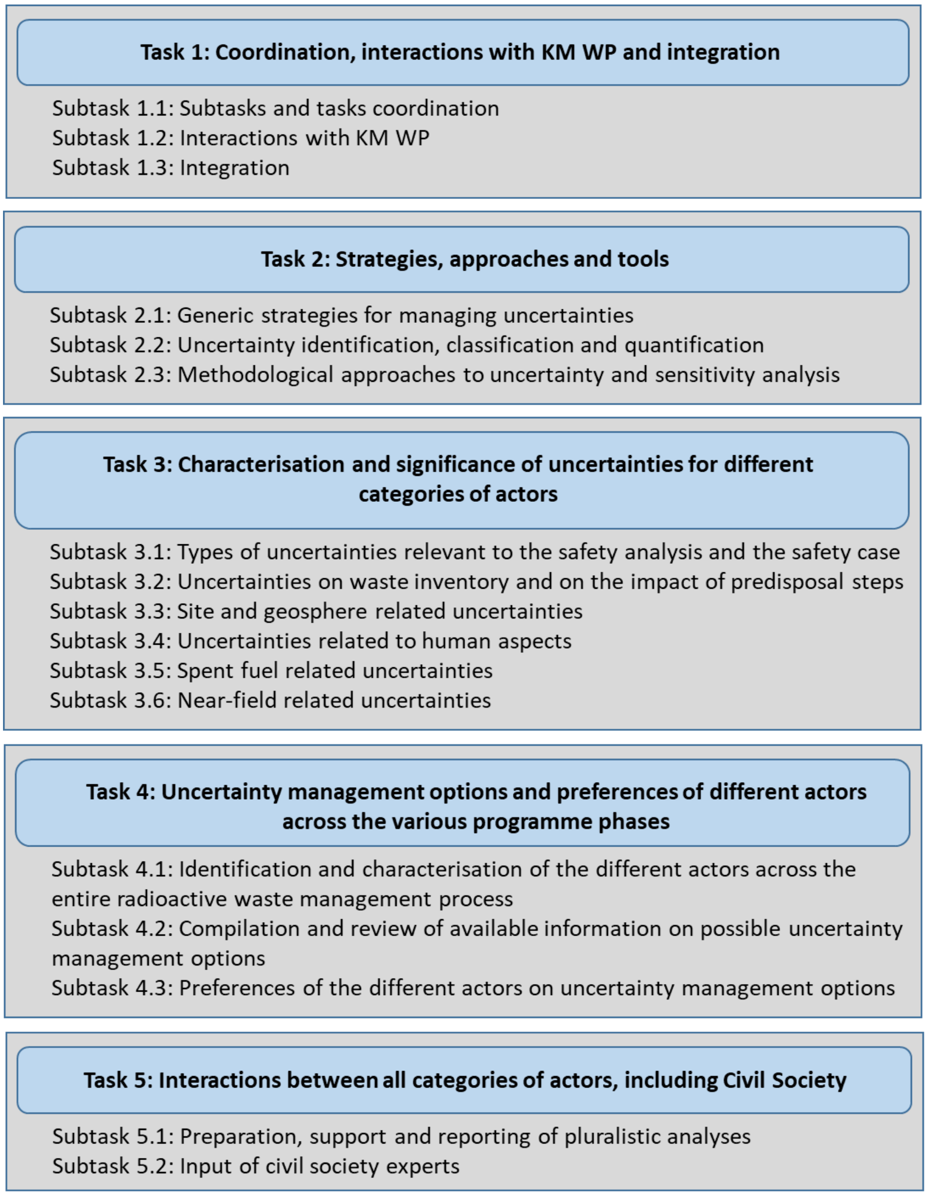

Figure 1 – Structure of WP UMAN

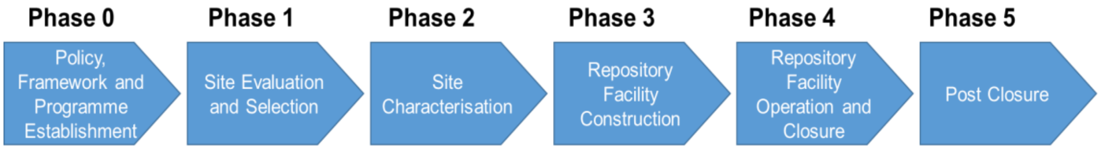

Figure 2 – Phases of a Radioactive Waste Management programme (RWM) referring to the EURAD Roadmap

For the purposes of meeting the above-mentioned objectives, workshops bringing the three different actors' groups (i.e., WMOs, TSOs and REs) together and providing a platform for discussions, exchange and networking on their views and preferences with respect to uncertainty management were developed and organised by Subtask 4.3.

1.2 Objectives[3]

One objective of this report is to provide an overview about different approaches and uncertainty management options, identified by Subtask 4.2 in the framework of the extension of the WP UMAN for selected examples of near-field uncertainties. 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 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. The overview of the possible management strategies and options for the uncertainties considered in the first phase of the WP UMAN (i.e., uncertainties associated with site and geosphere, human aspects, spent nuclear fuels and waste inventory) is not in the scope of this report and is provided in Kaempfer et al. (2023).

The other main objective is to present a summary of the outcome of the 5th UMAN Workshop, organised by Subtask 4.3 in the second stage of the WP UMAN, in particular the identified preferences of the participating actors´ groups (i.e., WMOs, TSOs and REs) with respect to the uncertainty management strategies and options as well as the resulting similarities, differences and the rationale behind them. In addition, the views of the different actors´ groups on the relevance of considered uncertainties for safety as well as the evolution of their safety significance over the programme phases are described. Moreover, future joint activities and initiatives identified by the three actors' groups are part of this report. Issues related to correctness and completeness of the workshop input materials prepared by Subtask 4.2, summarising available uncertainty management strategies and options, are not addressed in this report. Is should be noted that the afore-mentioned issues were presented by the participating organisations from the perspective of the knowledge and experience available at the time of the workshops' organisation, reflecting the implementation phase of the national programmes at that time. The description of the results of the UMAN workshops organised in the first phase of the WP UMAN is not scope of this report and is provided in Haverkate et al. (2024).

It should be recalled that the discussion of the management issues for the near-field uncertainties was focused on geological disposal of high-level waste (HLW) and spent nuclear fuel (SNF) in clay and crystalline rocks. Nevertheless, some remarks in this report refer to L/ILW disposal, mainly to provide additional examples or to point out specific differences in uncertainty management, depending on waste type.

[3] This section contains passages taken from (Kaempfer et al., 2023) and (Haverkate et al., 2024)

1.3 Methodology[4]

The methodology for near-field uncertainties was adopted from that already applied for the first four types of uncertainties considered in WP UMAN. In order to focus the work in Subtasks 4.2 and 4.3, three specific topical uncertainties were selected from the comprehensive list of near-field uncertainties potentially relevant for disposal safety developed by UMAN Subtask 3.6 (Pfingsten et al., 2024). The selection was done on the basis of responses to 3rd UMAN Questionnaire designed by Subtask 3.6 (Pfingsten et al., 2024), following the goal to consider those uncertainties that were given a high significance by the respondents and to cover all groups of uncertainties. The selection process of these topical uncertainties is described in more detail in Section 2.2.

For each of the topical uncertainties, management strategies and options were identified and assessed, based on experience of organisations participating in the WP UMAN as well as the review of the existing documentation. For this purpose, the overview on generic uncertainty management strategies from UMAN Subtask 2.1 (Hicks et al., 2023) was used as a basis. The experiences of organisations participating in UMAN were mainly gathered from input collected with a specifically designed template (**Erreur ! Source du renvoi introuvable.**), supplemented by available information and the discussions of the 5th UMAN Workshop.

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. Temporal aspects were addressed via the programme phases according to the EURAD roadmap (see *Figure 2*).

Moreover, this report summarises the results of the 5th UMAN Workshop organised by Subtask 4.3 in the second stage of the WP UMAN, which was dedicated to near-field uncertainties and focused on the same topical uncertainties that were considered in Subtask 4.2. As a basis for this part serve the available summaries of the discussions within each actors' group (i.e., for WMOs, TSOs and REs, separately) as well as the summaries of the workshops' outcome, indicating the similarities and differences among these actors' groups. Both summaries are drafted from the written statements (termed homework) submitted by the participating organisations as well as oral statements made in the direct discussions within the actors' groups.

This report is a supplement to WP UMAN Deliverables D10.11 (Kaempfer et al., 2023) and D10.12 (Haverkate et al., 2024).

1.4 Report structure

In Chapter 1 of this report, a general description of the WP UMAN and the Subtasks 4.2 and 4.3 as well as description of report objectives and the adopted methodology is provided. Chapter 2 presents a general overview of uncertainty classification and explains the selection of the topical uncertainties that are considered. In Chapter 3, a short overview of generic uncertainty management schemes and strategies is given. Chapters 4 and 5 are the central part of this report. Chapter 4 presents characteristics of the selected topical near-field uncertainties together with the possible management options and other relevant related information. Chapter 5 is dedicated to the outcome of the 5th UMAN Workshop, including the assessment of safety significance and its evolution over programme phases for each of the selected topical uncertainties, the preferred management options of the different actors as well as the identified

[4] This section contains passages taken from (Kaempfer et al., 2023) and (Haverkate et al., 2024)

future joint activities and initiatives. Finally, in Chapter 6 a summary of the report and the conclusions from Chapters 4 and 5 are given.

2. Overview of the addressed uncertainties and their classification

2.1 Uncertainty classification[5]

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 was synthetised and adopted in this study (Grambow, 2023). At the highest level, the following five types of uncertainties were identified (Figure 3):

- **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 4. The different uncertainties types considered in WP UMAN (i.e. uncertainties related to site and geosphere, human aspects, spent nuclear fuel, waste inventory and near-field) represent indirectly the second classification level of this scheme. The last level of this classification scheme is represented by uncertainties identified by Subtask 3.6 as potentially significant for disposal safety, based on analysis of responses to the 3rd UMAN Questionnaire (Pfingsten et al., 2024). They include the topical uncertainties selected for the purposes of the 5th UMAN Workshop, which are presented in Section 2.2.

It is also possible to categorise uncertainties with respect to availability and use of knowledge as illustrated in Figure 5. Since the distinction between *unknown/ignored knowns*[6] 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 6).

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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5 This section contains passages taken from (Kaempfer et al., 2023).

6 The term "ignored knowns" is understood as knowledge that is voluntarily discarded without proper justification.

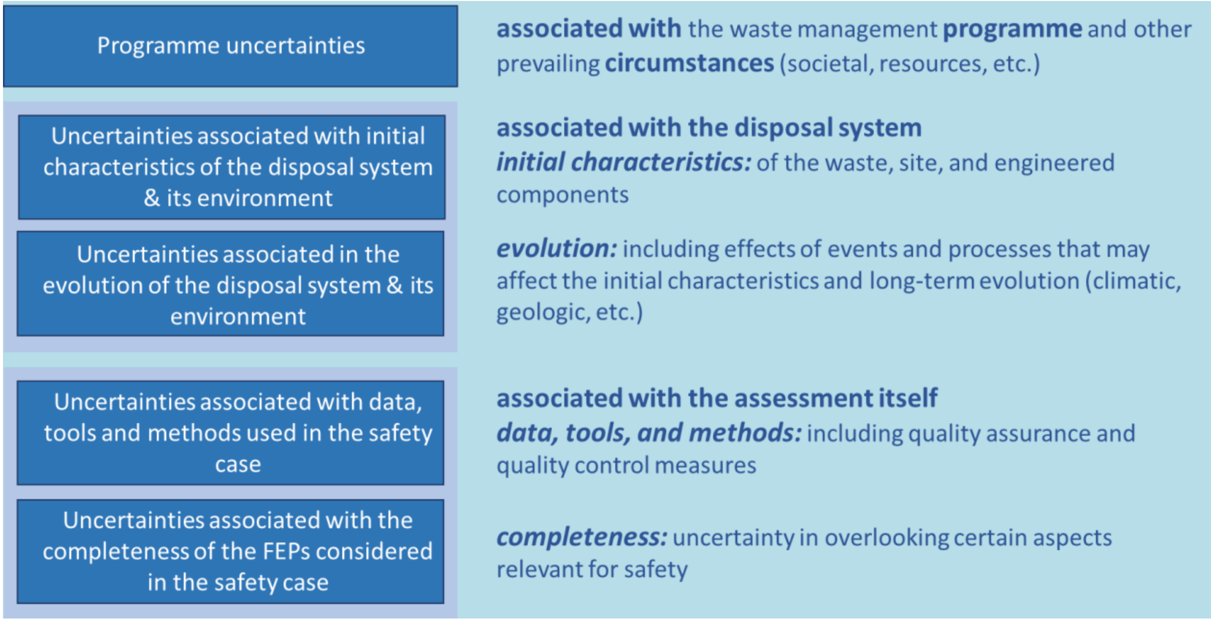

Figure 3 – Generic uncertainties identified in WP UMAN, representing also the first level of the multi-level uncertainty classification scheme depicted in Figure 4

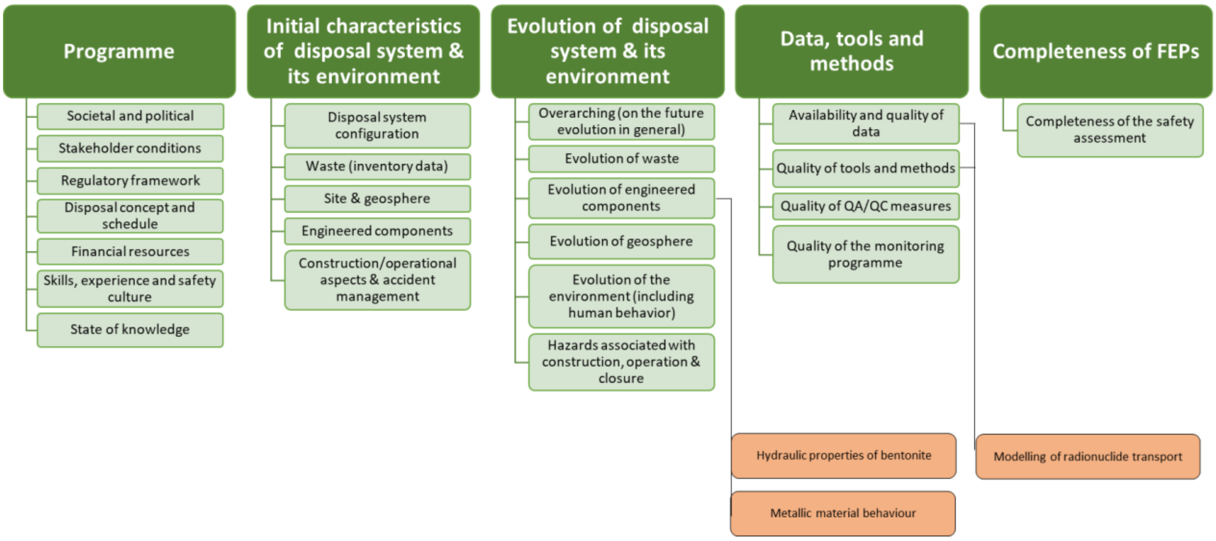

Figure 4 – Three-level uncertainty classification scheme

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 5 – 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 6 – Uncertainty classification matrix developed in WP UMAN

2.2 Selection of topical uncertainties

The second phase of WP UMAN was dedicated to management of uncertainties related to the near-field. According to IAEA, the near-field is *the excavated area of a disposal facility near or in contact with the waste packages, including filling or sealing materials, and those parts of the host medium/rock whose characteristics have been or could be altered by the disposal facility or its contents* (IAEA 2019). In UMAN Subtask 3.6 a list of near-field uncertainties potentially significant for disposal safety was developed, based on the 3rd UMAN Questionnaire (Pfingsten et al., 2024).

Three major categories of near-field uncertainties were identified in Pfingsten et al. (2024):

- uncertainties related to the processes governing or altering radionuclide migration and the performance of disposal system components in the near-field,
- uncertainties to be taken into consideration when conceptualising waste packages, technical barriers and adjacent excavation damaged zone (EDZ) of natural barriers,

- uncertainties associated with thermal, hydraulic, mechanical, chemical, biological and radiation (THMCBR) processes, dominating at different time scales (except those already taken into account in Subtask 3.2 on the waste inventory and Subtask 3.3 on geosphere and sites related uncertainties) as well as with gas migration in near-field systems.

From the list of uncertainties potentially relevant for disposal safety (Pfingsten et al., 2024), three specific uncertainties ("topical uncertainties") were selected for discussion of management strategies and options as well as actors' preferences, foreseen in UMAN Subtasks 4.2 and 4.3. The selection was driven by the goal to investigate one uncertainty of each of the above mentioned category, preferring those that were ranked important by the respondents of the 3rd UMAN Questionnaire (Pfingsten et al., 2024).

In the first category, the uncertainty of partition coefficients (Kd) in the near-field was ranked highest by all types of actors. However, as this uncertainty had already been addressed in the context of site and geosphere (Kaempfer et al., 2023), it was not selected as a topical uncertainty for the near-field. Instead, the

- uncertainty related to **hydraulic properties of the bentonite**, related to the effects of re-saturation and swelling pressure evolution) as example of uncertainty related to the evolution of the disposal system and its environment

was selected, which was ranked similarly high by REs and WMOs, but only half as high by TSOs (see Pfingsten et al., 2024).

In the second category, all types of actors gave the highest ranking (see Pfingsten et al., 2024) to the

- uncertainty of **metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different barriers (waste package, liners…)**, as an example of uncertainty related to the evolution of the disposal system and its environment

which was therefore selected as a topical uncertainty.

In the third category, the rankings by the different types of actors were rather uneven, and there was no unique preference. However, it was conspicuous that one uncertainty of this category was ranked very differently, namely highest by WMOs and lowest by TSOs and REs (see Pfingsten et al., 2024). This was the

- uncertainty related to **modelling of radionuclide transport (full 4D description or 1D or mixed compartments, …)**, as an example of uncertainty associated with data, tools and methods used in safety case.

Therefore, this uncertainty was selected as the third topical uncertainty. For this purpose, it is not restricted, however, to the specific aspect of modelling dimensionality but is understood to cover the total field of modelling uncertainty with respect to fluid and radionuclide transport, including permissibility of simplifications, reliability of concepts and mathematical approaches – maybe also in extreme situations – coupling of models, numerical realisation, exactness of numerical results, possibility of programme errors, etc.

The aforementioned assignment of the topical uncertainties to the different types of the generic uncertainties identified in UMAN is illustrated in Figure 4 and summarised in Table 2. Further, this assignment was transferred to the uncertainties matrix, in which concrete examples of uncertainties reflecting the availability and use of knowledge (i.e. known unknowns, unknown/ignored knowns, unknown unknowns) are provided (see Table 3). Detailed description of the uncertainties matrix can be found in Section 2.1.

Table 1 - Assignment of the topical uncertainties associated with near-field to the first level of the multi-level uncertainty classification scheme (grey cross means "up to some extent")

Selected topical uncertainties	**Programme uncertainties**	**Uncertainties associated with the initial characteristics of the disposal system and its environment**	**Uncertainties associated with the evolution of the disposal system and its environment**	**Uncertainties related to data, tools and methods**	**Uncertainties associated with the completeness of FEPs**
Uncertainties related to near-field					
Hydraulic properties of bentonite		×	×		
Metallic material behaviour			×		
Modelling of radionuclide transport				×	

Table 2 - Uncertainties matrix developed for topical uncertainties related to near-field

Generic types of uncertainties	**Selected topical uncertainties**	**Known Unknowns**	**Unknown/Ignored Knowns**	**Unknown Unknowns**
1. Programme uncertainties				
2. Uncertainties associated with initial characteristics of the disposal system & its environment	Hydraulic properties of bentonite	Porosity, permeability, swelling pressure, saturation degree	Homogeneity	
3. Uncertainties in the evolution of the disposal system & its environment	Hydraulic properties of bentonite	Swelling pressure evolution; re-saturation		Processes delaying re-saturation
	Metallic material behaviour	Chemical microbiological processes, gas generation rate	Microbiological processes	Processes/interactions with other components accelerating corrosion
4. Uncertainties associated with data, tools & methods used in the safety case	Modelling of radionuclide transport	Coupling the THMCBR processes	4D modelling	
5. Uncertainties associated with completeness of FEPs considered in the safety case				

For the sake of consistency, the same three selected uncertainties were considered in Subtasks 4.2 and 4.3.

3. Generic uncertainty management strategies and uncertainty management scheme[7]

Uncertainty management in the context of final disposal means all actions and measures that can be taken to reduce the overall uncertainty of the statement made about the long-term safety of the repository system as a whole. Due to the nature of radioactive substances, safety is an issue for up to 100 000 years or even more. Various uncertainties occur in all parts of the repository system, including the methods of assessment of the safety, and they altogether result in an uncertainty of the safety statement, which should be kept as low as possible. Depending on the specific disposal concept, the primary uncertainties are differently relevant for the resulting uncertainty of long-term safety. Uncertainties that play a major role in one concept may be less important or even negligible in another concept.

Therefore, a holistic approach to managing uncertainties is necessary. In a first step all uncertainties should be identified and assessed in view of their relevance for the disposal concept under investigation. The disposal concept includes all system components and features like waste type, container concept, buffer materials, host rock type and properties, far-field and biosphere, as well as their expected future development. The relevance of specific near-field related uncertainties can depend on far-field properties and considerably differ between different disposal concepts, which is one reason for differing views of organisations representing different programmes.

One should distinguish between uncertainties that are principally *irrelevant* and those that can be *tolerated*. While the former obviously do not affect safety (to a relevant extent) and can be disregarded, the latter should be named and ruled out by proper argumentation, making clear why their toleration seems reasonable in the concept under investigation. For uncertainties that are not tolerated, one should consider measures to reduce, mitigate or avoid them, see Section 4.1. This report focuses on management strategies for uncertainties that are not considered tolerable.

Within Subtask 2.1 of WP UMAN, generic uncertainty management strategies were identified (Hicks et al., 2023). Based on this work, uncertainty management elements have been structured as follows (Figure 7).

General principles and strategies (left in Figure 7) 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 7):

- 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,

[7] This section contains passages taken from (Kaempfer et al., 2023) and (Haverkate et al., 2024).

- representation of (remaining) safety-relevant uncertainties in safety assessment.

Examples of the above mentioned specific actions aiming at uncertainties reduction, mitigation and/or avoidance are provided in *Figure 8*.

This schematic representation of options, strategies, and tools served as guideline when analysing the management options for the specific topical uncertainties in Chapter 4.

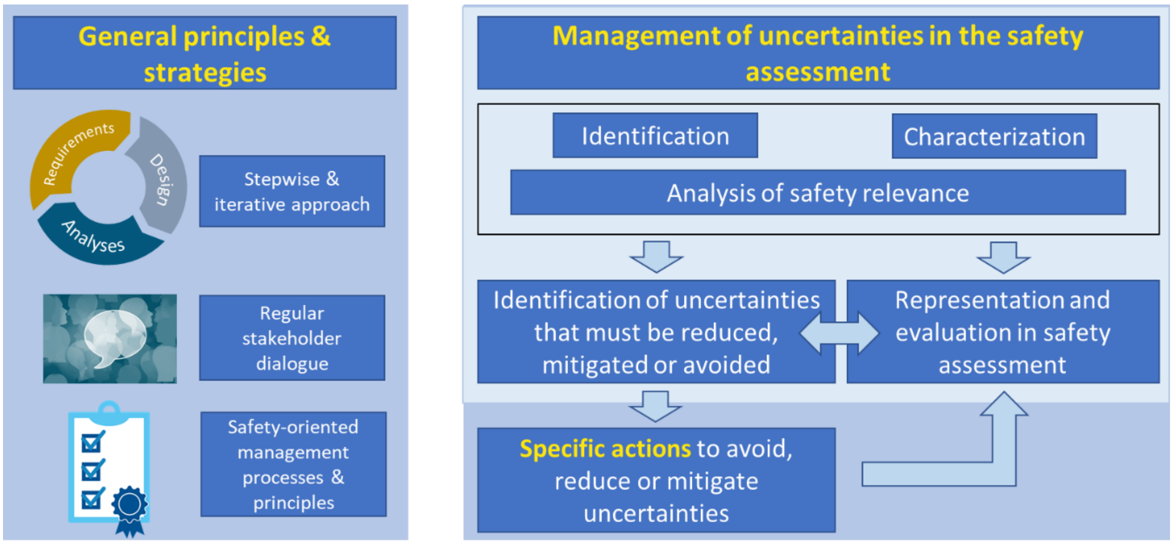

Figure 7 – General principles and strategies (left) and uncertainty management scheme for safety assessments (right)

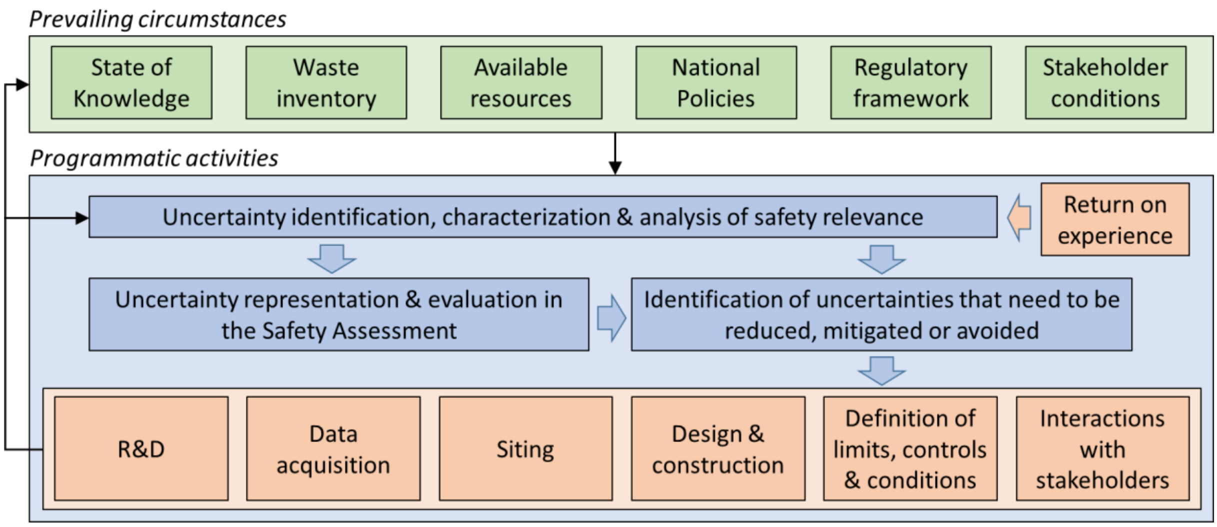

Figure 8 – Uncertainty management scheme with examples of specific options for uncertainty reduction, mitigation and avoidance, set up in the context of prevailing circumstances as well as return of experience

4. Management options for near-field-related uncertainties

4.1 Specific actions to avoid, reduce or mitigate uncertainties

The general goal of uncertainty management in the safety case is to generate trust by identifying the uncertainties and showing that they do not jeopardise the safety of the system. Since, however, all uncertain influences have the principal potential to affect the final safety statements; measures should be taken to minimise this influence, as long as it is not considered tolerable. Different approaches are possible to manage uncertainties in the safety case (see also Figures 7 and 8):

- Reducing an uncertainty means any measures that act on the uncertainty itself. For epistemic uncertainties, reduction can be achieved by increasing the knowledge about the parameter or process in question, which normally means research activities. Aleatory uncertainties resulting from variations in material parameters or fabrication quality can be reduced by measures like quality control or acceptance criteria.
- Mitigating an uncertainty means to leave the actual uncertainty as it is but to minimise its relevance for safety. That can often be achieved by conceptual measures or making use of geological features. If, for example, the host rock provides effective containment, one has to care less about the uncertainty of canister lifetime.
- Avoiding an uncertainty means that the source of the uncertainty is, as far as possible, excluded from the system. That does neither affect the uncertainty itself nor its safety relevance but simply its "degree of presence". Uncertainties can sometimes be avoided – at least to some extent – by appropriate conceptual measures.

4.2 Programme uncertainties

Programme uncertainties are not addressed in the context of near-field-related uncertainties.

4.3 Uncertainties associated with initial characteristics of the disposal system and its environment

Uncertainties associated with initial characteristics are not addressed in the context of near-field-related uncertainties.

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

4.4.1 Uncertainty related to hydraulic properties of the bentonite

This uncertainty covers all uncertain aspects related to effects of re-saturation and swelling pressure evolution of bentonite. Bentonite re-saturation is assumed to be homogenous to achieve the expected swelling pressure. However, preferential flow paths might develop due to inhomogeneous initial conditions, or material properties. According to the conclusions of the BEACON project, for example, bentonite-based plugs are not homogeneous due to their placement (pellets or blocks) and the saturation process is not uniform.

Bentonite is supposed to provide a (nearly) watertight barrier after swelling. If this is not or not completely the case, or occurs slower than expected, there can be considerable water flow towards the waste package and with that increased risk of metal and matrix corrosion, contaminant release and gas production. This can lead to higher radionuclide release from the repository and is therefore safety relevant.

The role of bentonite differs substantially between disposal concepts. For concepts where safety is mostly provided by the tightness of canisters, bentonite is used to limit water flow into disposal cells, thus extending the canisters' watertightness and mitigating the leakage process. This is the case, for example, in the Finish concept, where bentonite components are used for canister sealing and are subject to strict compliance limits. For clay-rock based concepts where safety is mostly provided by the confining properties of the host rock, swelling and watertight properties of bentonite are used in sealing devices to limit water flow between waste and geosphere. Bentonite components will also contribute to enhancement of self-sealing of the excavation damaged zone (EDZ), thereby reducing the water permeability around the seals after the water saturation of the repository.

In Cigéo (France), for the clay core of the sealing devices of underground and surface-bottom tunnels and wells, bentonite is used with additives such as sand to adapt the properties to the requirements These sealing devices are designed so that post-closure transport of radionuclides and toxic species remains much lower than that across the Callovo-Oxfordian formation.

In Nagra's current repository concept (Switzerland), pure bentonite is used as backfill material in the emplacement room and seal element for the high level waste (HLW) repository part. A bentonite/sand mixture is planned to be used as seal element for the sealing system in the low/intermediate level waste (L/ILW) repository part.

In the German site selection process, in which three different types of host rocks are considered in the current phase, this uncertainty is relevant for claystone and crystalline rock, where bentonite is considered as sealing material.

In Posiva's HLW Finnish ONKALO repository, bentonite components are used for canister isolation and tunnel sealing and are subject to strict compliance limits. Bentonite components are measured through a variety of quality control tests, with numeric qualifications and statistical evaluation of the risk.

(1) Identification and assessment of safety relevance

Bentonite behaviour is subject to a lot of uncertainties, but not all of them matter in all concepts. Bentonite re-saturation and swelling are important for barrier integrity and sealing. Bentonite-related uncertainties have been identified and investigated in a variety of research projects, such as exemplarily:

- Full scale Demonstration of Plugs and Seals (DOPAS).
- Bentonite Mechanical Evolution (BEACON) (Mokni et al., 2022; Charlier et al., 2021):
  - Bentonite re-saturation experiments and related modelling.
- Resaturation of bentonite in case of limited water supply (Kröhn, 2019a, 2019b).
- Bentonite degradation by alkaline solutions (Reijonen and Alexander, 2015).
- EURAD WP "Influence of temperature on clay-based material behaviour" (HITEC) (Villar et al., 2020):
  - Influence of modelling relationships.
- Project Opalinus Clay:
  - Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis) (Nagra 2002a, 2002b).
- Modelling the re-saturation of bentonite in final repositories in crystalline rock (SIRUB) (GRS):
  - Re-saturation at bentonite-water-interface, free swelling, re-saturation with vapour.
- "Constitutive Equations for Sodium and Calcium Bentonites" (BIGBEN) (Kröhn and Kröhn, 2020):
  - Dependency on bentonite composition.
- QUADER (Schneider et al. 2017):
  - Dynamics of water intrusion from fractures.

Such investigations help getting an understanding of the safety relevance of bentonite-related uncertainties under various circumstances and allow better assessment of whether a specific uncertainty actually matters in a specific concept. In principle, the above-mentioned research projects concern the material itself, the behaviour during the re-saturation and the conditions at steady-state. Even after reaching steady-state, there are processes introducing uncertainties such as bentonite erosion. Note that bentonite may be utilised in a repository in the form of powder, pre-compacted blocks, or pellets, causing in some cases different uncertainties.

As bentonite is a natural material, its composition, particularly the montmorillonite content, may change from one batch of bentonite to the next one, thereby changing the properties of interest.

During the transient phase of temperature evolution (backfill material in HLW repository) and re-saturation, swelling, water uptake, and the evolution of swelling pressure are of interest including related uncertainties. There is furthermore experimental evidence that the present understanding of the water uptake dynamics is incomplete.

Conditions at steady-state are particularly difficult for at least two reasons: (i) it is not entirely clear upon which criteria steady-state can be determined so that the time for reaching full saturation is somewhat uncertain; (ii) at repository scale, the re-saturation process takes time in the order of decades (Fernández et al., 2016; SKB, 2022) excluding the possibility of direct investigations and introducing further uncertainties from extrapolating the results of short-term laboratory experiments.

Experiments on different scales for different bentonite forms (blocks, pellets, powder, ...) have been performed. The BEACON project showed that in modelling of different bentonite re-saturation experiments (hydro-mechanical modelling) the final saturated state can be reproduced in terms of water content and dry densities, however the dynamics of the hydration process remains difficult to predict. Understanding the dynamics of the hydration process is especially important when predicting bentonite hydro-mechanical evolution of bentonite barriers within real repositories.

The total pressures and displacements remain difficult to reproduce. Adequate prediction of stresses is considered important since in some concepts swelling capacity and pressure are parameters supporting safety functions.

Some analyses have shown the sensitivity of the results to some parameters such as retention curve or the relationship of swelling pressure and dry density. A conclusion of BEACON is the need to determine more precisely a set of basic but essential data for a better representation of the physical processes that develop within bentonites during hydro-mechanical solicitations.

In the HITEC WP of EURAD (Villar et al., 2020), the different relationships between relative permeability and water saturation, or the retention curves, implemented in different THM codes, led to a wide range of calculated buffer re-saturation times.

The observed non-sensitivity of the models to the initial dry density distribution is contradictory to experimental observations. The sensitivity of the models to the micro-macro interaction functions, the retention curve as well as the relationship between the swelling pressure and dry density is quite relevant for further investigations.

(2) Characterisation

Conceptual uncertainty concerns the water uptake at the very beginning of re-saturation. A persistent highly saturated zone develops first at the water-bentonite contact (Kröhn, 2004; Harjupatana et al., 2015). In the same category falls a competing selection of water migration processes for different numerical models that eventually lead nevertheless to more or less equivalent mathematical descriptions of the re-saturation process (Kröhn, 2016). Core of all but the most basic numerical models is the retention curve or the equivalent isotherm. These curves are hysteretic, meaning that they follow different paths for wetting and drying (Mooney et al., 1952). This is only considered by few numerical codes. Recent experimental investigations have shown that a change from wetting to drying or vice versa does not result in following a scanline connecting adsorption and desorption isotherm. Instead, a unique isotherm is followed in such an event that connects adsorption and desorption isotherms only at their extreme ends (Kröhn and Kröhn, 2020). Up to now this effect is not acknowledged at all. A rather unheeded conceptual uncertainty concerns the interaction of groundwater flow in fractured rock and water uptake by the bentonite as flow in the rock cannot be observed directly. Some speculations are provided in Kröhn (2017). The hydraulic properties of bentonite mixed with additives such as sand, used as clay core for tunnels' sealing devices, can be characterised on both small and large scales. This characterization is all the more necessary as the large-scale behaviour of partially saturated material (between a dry and a water-saturated zone) depends on heterogeneities and internal deformations (internal swelling process). Consequently, characterisation must be complemented by long-term full-scale demonstrators (see DOPAS project).

Phenomenological uncertainty refers to a number of processes and conditions. One such process is the swelling into a limited space, where compacted bentonite in form of pellets or blocks initially experience basically no resistance against swelling until contact with a rigid wall or another bentonite body is established. Another example is the water uptake characteristics of pellet filling depending on the inflow rate. Particularly in the case of pellet fillings, where the dry density is low, microbial activity is to be expected that may influence hydraulic conditions for instance by gas production (Bernachy-Barbe et al., 2022) or even attack the waste canisters. Uncertain conditions such as the porosity at steady-state can also be found. This particular aspect also falls also into the category of conceptual uncertainty as it is unclear whether the final porosity is dependent on the state of the water wetting the bentonite, namely liquid water or water vapour (Kröhn, 2019a, 2019b).

Almost naturally, there is finally data uncertainty as all parameters, constitutive equations, and even the equations of state are essentially based on measurements. Among the sensitive inputs into numerical models is the isotherm/retention curve which is rather difficult to measure and at the same time dependent on the mineralogical composition (see above).

The uncertainty is influenced by:

- water/vapour availability,
- temperature,
- pressure,
- bentonite composition,
- bentonite homogeneity, grain size distribution (Posiva, 2016),
- degree of homogenisation,
- dry density at installation,
- swelling pressure/dry density relation,
- retention curves,
- bentonite composition (pure bentonite or mixture with other materials),
- form of bentonite elements (blocks, pellets, powder, etc.),
- erosion.

Safety-relevant effects are:

- duration of re-saturation phase,
- final permeability,
- transport times of relevant radionuclides,
- retention capability,
- influence on waste package lifetime.

Quantification of the uncertainty is possible by:

- measurements of bentonite properties and host rock environment (Posiva, 2012b),
- experimental studies and modelling,
- numerical qualification and statistical evaluation,
- sensitivity analysis.

(3) Classification and associated management actions

In those repository concepts that consider bentonite best appropriate for providing long-term water tightness, the uncertainty cannot be generally avoided.

Possible options for reducing the uncertainty are:

- Site exploration. In this context, iterative and stepwise approach of uncertainty management is very important.
- Research for improving understanding of the swelling process and the impact of heterogeneity through laboratory and in-situ experiments. Various research projects are in progress (see above) or planned, for instance, in EURAD-2 (WP ANCHORS).
- Evaluation of natural analogues.
- Optimisation of sealing concepts regarding thermal-hydraulic-mechanical-chemical coupled processes at the interfaces between sealing materials (e.g., backfill, plugs) and host rock.
- Comprehensive modelling and performance assessment is done to understand the behaviour and properties of the materials, for instance investigation of the cyclic effect of temperature and humidity on discontinuity surfaces of a prefabricated bentonite barrier. Codes should be quality-assured, and several models should be benchmarked against each other to create confidence, as done in Task D of "DEvelopment of COupled models and their VALidation against Experiments" (DECOVALEX).
- Use of well characterised and prepared-to-purpose bentonite, ensured by consequent quality assurance. Quality control tests comprise grain size, density, water content, detection of defects, etc. Materials that do not fulfil the requirements should be rejected.
- Defining acceptable bandwidths and performance targets for the process-relevant parameters like temperature, dry density, etc.

Options for mitigating the influence of the uncertainty are:

- Reducing the safety relevance of the bentonite barrier by conceptual measures like putting more emphasis on alternative barriers such as the canister or the host rock, where applicable.
- Siting (low head gradients) and design (one-way storage areas).
- Reducing external factors (place bentonite plugs far from sources of chemical and thermal perturbations).
- Use of alternative implementation methods (grained bentonite instead of bentonite blocks).

(4) Representation in safety assessments

Relevant FEPs (e. g. buffer re-saturation, swelling, and long-term alteration) are considered in the design of the engineering barrier system (EBS) components as reported by some surveyed countries in OECD (2003), Section 3.3, Table 3.6.

Where possible and sensible, conservative values can be used, but one has to keep in mind that conservatism is often problematic and not the optimal way of handling uncertainties. Principally, it is more significant to represent the uncertainty by scenario analysis via different parameter values in deterministic approaches or use of parameter distributions in probabilistic approaches (Posiva, 2012a). The quantification of uncertainties should be as unbiased as possible.

Parameters like porosity, permeability and swelling pressure are varied in safety assessments. Uncertainties that cannot be assigned to parameters are investigated by consideration of alternative scenarios and what-if-scenarios (no bentonite barrier, defective shaft seal).

The performance of the repository facility in the case of failure of the safety function of the backfill and the seal material is assessed by means of what-if-scenarios.

In line with international NEA practices for safety assessment, Andra represents seals with conservative properties, including an easy-to-achieve permeability based on available experimental data. The aim is to show that, for the Normal Evolution Scenario (NES), the flux of radionuclides (and toxic species) migrating through the backfilled tunnels is much lower than that passing through the clay-rock host formation. In addition, Altered Evolution Scenarios (AES), which assume that the seals do not meet their requirements, are evaluated to demonstrate that the impact remains acceptable.

(5) Additional comments

The near-field is the area with the largest material heterogeneity. There are the largest hydraulic gradients compared to other components. The complex evolution of the near-field together with the associated uncertainties must be considered for very long-term evolution of the deep geological repository (DGR).

The water for saturating the bentonite and bentonite/sand mixture comes mainly from the host rock; the radionuclide migration in liquid phase along the tunnel system does not play a big role (Nagra, 2024a).

4.4.2 Uncertainty related to metallic material behaviour in different barriers

This uncertainty covers all uncertain aspects related to metal corrosion (steel, copper, copper coated steel, composite, super container, etc.) and canister lifetime. Metal parts are present in waste packages, liners, etc. The field of processes comprises geochemistry (pH-, Eh-evolution), corrosion/degradation (including pitting corrosion), colloid formation, gas generation and pressure build-up. Uncertainties can come from metal mass, metal composition, surface structure, geochemical conditions, brine composition, flow conditions, temperature, etc.

Metal corrosion is the most relevant source of gas (hydrogen) in a repository. Gas spreads over parts of the system, influences the pressure and can displace brine, moreover it is a transport medium for volatile radionuclides. This can have significant effects to the radionuclide release from the waste form and from the near-field.

The subjects of metal corrosion, canister lifetime and gas generation are addressed in a number of national and international publications that provide information or regulation. An international survey was given by OECD (2003), requirements were formulated by IAEA (2011). Recommendations were given, for instance, by the German Repository Safety Commission (ESK, 2016a; ESK, 2021).

(1) Identification and assessment of safety relevance

Metallic materials – mainly carbon steel, stainless steel or copper – are being employed in all repository concepts, primarily as components of the waste canisters. Depending on the concept specifics, metal corrosion can trigger or influence various effects, and is itself affected by a range of factors. Therefore, its uncertainty is rather complex and differently relevant for safety in the different national programmes.

Metal corrosion has been investigated in different countries. Copper-related vast investigations were performed mainly by SKB (SKB, 2019). In different national programmes, corrosion calculations have been performed (SKB, 2010; Hedin et al., 2017; King and Kolář, 2019). The process of corrosion is influenced by various processes and conditions (SKB, 2019). The German Nuclear Waste Management Commission outlines sulphate and sulphide concentrations in the groundwater, microbiological conditions, fracture characteristics and possible effects of buffer erosion (ESK, 2021).

In a number of recent projects uncertainties associated with metal behaviour have been investigated:

- EURAD WP CONtainer CORrosion under Disposal conditions (CONCORD) (Abdelouas et al., 2022)
  - Container corrosion and understanding of coupled interfacial processes under disposal conditions.
- IGD-TP project Long-Term Monitoring of C-14 Compounds Released During Corrosion of Irradiated Metal (LOMIR) (Guillemot et al., 2021):
  - Corrosion experiment on irradiated steel in alkaline anoxic conditions.
- Full-scale prototype repository Äspö (SKB 2022):
  - Long-term observance of various effects.
- Entwicklung von Endlagerbehälterkonzepten für die geologische Tiefenlagerung von hochradioaktiven Abfällen in kristallinem Wirtsgestein (ELBRock):
  - Canister conceptualisation in crystalline rock.

- Entwicklung von Endlagerbehälterkonzepten für die geologische Tiefenlagerung von hochradioaktiven Abfällen in Tongestein (ELBTon):
  - Canister conceptualisation in claystone.
- "Michigan International Copper Analogue" (MICA) (Aaltonen et al., 2023):
  - Stability and corrosion of copper investigated by natural analogues.

The safety relevance of this uncertainty is generally assessed via sensitivity analysis.

(2) Characterisation

This uncertainty mainly concerns the corrosion of spent nuclear fuel (SNF)/HLW disposal canisters, metallic waste and the reinforcement of concrete tunnel liner or concrete waste containers. It involves various metallic materials, in different environments, which are affected by different corrosion mechanisms and rates.

The behaviour of metallic materials is subject to a lot of uncertain influences, which make altogether the uncertainty considered here. It comprises all kinds of uncertainty, including conceptual, phenomenological and epistemic data uncertainties, but also aleatory uncertainties resulting from microscopic inhomogeneity, like the locations and progress of pitting.

A number of uncertain factors that have influence on metal corrosion were identified. A global review of the metal corrosion related uncertainties is presented in Padovani et al. (2017). Some examples are:

- metal types and availability (carbon steel, stainless steel, copper, other),
- stress corrosion cracking (SCC) phenomena (Posiva, 2021),
- temperature,
- radiolysis,
- sulphate and sulphide concentrations in groundwater,
- hydraulic regime,
- geochemical conditions in the near-field and temporal evolution of these,
- buffer permeability,
- geochemical environment,
- fracture characteristics,
- homogeneity of canister materials,
- initial defects,
- reactive surface area of canisters,
- microbiological conditions,
- representativeness of data and models.

On the other hand, metal corrosion affects many safety-relevant features and processes in the repository, for instance:

- containment safety function:
  - local corrosion (pitting),
  - canister lifetime, durability of barrier function,
  - instant release of radionuclides,
  - source term,
  - dependence on waste package type (HLW, SNF, …),
- flow of radionuclides in the near-field,
- sorption on corrosion products,
- migration of corrosion products,
- influence of corrosion products to bentonite,
- gas generation and migration,
- pressure build-up:
  - mechanical integrity of the host rock,

- hindrance of closing or self-sealing effects,
- delay of water flow and contaminant transport by gas pressure.

Again, it should be mentioned that this does not mean that all of these uncertainties actually play a role in any disposal concept. A proper analysis of their safety relevance under the given conditions is important. As different uncertainties become relevant on different timescales, it may be useful to compare such timescales, such as container lifetime, waste form dissolution or geosphere travel time, for a specific concept to get an impression of which uncertainties are the most important ones.

(3) Classification and associated management actions

In principle, uncertainty management actions of all classes can be applied. Uncertainty reduction by targeted research and development under intended or expected conditions is an important option to deepen understanding of the processes and determine representative data sets (CONCORD, LOMIR, Äspö, ELBRock, ELBTon, …). Specific repository design can be used to reduce, mitigate or even avoid parts of the uncertainty. In advanced programmes and in the operating phase, technical quality assurance is an important means for reducing the uncertainty. This refers to all metallic components, but mainly to the canisters (for instance, avoiding defects like scratches on the surface of the copper). Padovani et al. (2017) provide a review of uncertainty management actions.

Some possible actions to reduce the uncertainty are:

- site exploration:
  - choose an anoxic geochemical environment,
  - design features to influence the water chemistry of the porewater stemming from the host formation (e. g., injecting alkaline matter at the interface between the rock and the steel components).
- optimisation of canister design and materials (thickness to avoid radiolysis, stress corrosion, weld stress relieving),
- analysis of natural analogues (e.g., MICA),
- experiments in laboratory and in-situ, for instance:
  - measurement of corrosion rates under relevant chemical conditions and temperatures,
  - strength resistance measurement,
  - effects of Gamma radiation (radiolysis), radioactivity concentration in aqueous solution,
  - interaction of corrosion products, radiolysis products and metal,
  - influence of microbial effects,
- modelling:
  - metal corrosion (CONCORD, Kursten 2019),
  - canister lifetime calculations,
  - reactive transport modelling,
- canister quality assurance:
  - metal purity and homogeneity,
  - quality control of canister components and overall canister integrity:
    - before loading,
    - at the time of emplacement,
  - avoiding/detection of manufacturing defects,
  - acceptance protocols.

Options for mitigating the influence of the uncertainty are:

- optimising local geochemical and hydrological conditions,
  - low sulphate/sulphide concentrations in the groundwater,
- optimising repository design,
- maximum temperature requirement,

- conceptual measures, e.g.:
  - organic content of bentonite,
  - use of matched geotechnical material to create a chemically favourable environment around the canisters (high pH conditions),
  - limiting the ingress of aggressive species during the thermal phase,
- optimising canister concept:
  - kind of metal (carbon steel, stainless steel, copper),
  - thickness of canister walls or protection layers,
- use of conservative values in the assessment of canister performance.

As metal components are included in every repository concept, the uncertainty can hardly be completely avoided (or minimised to a neglectable level), but nevertheless, specific actions are possible to minimise its occurrence:

- avoiding/removing non-necessary metal parts,
- choosing a site with low sulphate and sulphide concentration in groundwater.

(4) Representation in safety assessments

Comprehensive performance assessment and safety assessment is done to understand the impact of the uncertainty on the performance of the repository system. These assessments are based on values from extensive literature reviews aimed at covering the full extent of the uncertainties involved (Nagra, 2024b; Nagra, 2024c).

Generally, the uncertainty is relevant in concepts that rely on the barrier function of canisters, where it impacts the source term. But wherever metal is present in a repository, gas generation can become relevant in safety assessments.

An uncertainty that must be controlled is the rate of hydrogen production that determines the duration of the de-saturated phase. Evaluating a "best-estimate" scenario that accounts for the de-saturated phase would highlight the margin provided by the initially saturated facility assumption. However, such a scenario cannot be seen as a safety case given the postulated de-saturated phase.

Generally, gas generation is less relevant in crystalline concepts because of the release pathways via the rock micro-fissures.

To consider the uncertainty in safety assessments, conservative values or unfavourable assumptions can be applied, for instance, a limited canister lifetime.

To quantify the uncertainty as a whole, the available data from laboratory or in-situ measurements should be assessed as well as possible regarding their uncertainty margins and used for a comprehensive probabilistic uncertainty and sensitivity analysis. In statistical investigations, it makes sense to consider stylised parameters, like canister lifetime, that themselves depend on a variety of uncertain influences as aleatory uncertainties.

(5) Additional comments

This uncertainty is actually a complex field of uncertainties, related to different aspects and components of the repository. The relevance of the uncertainty is considered differently, depending on the characteristics and the current focuses of the national programmes.

The French Cigéo concept as well as the Swiss HLW repository concept are mostly based on the favourable properties of the clay rock formation and do not rely on the tightness of the canister, at least beyond the thermal phase. Thus, canister corrosion is of lower relevance.

In the representative preliminary safety analysis required by German Disposal Safety Analysis Ordinance, “it shall be assumed that technical and geotechnical barriers will in principle fulfil their function within the foreseen period of time in each case, provided that this does not appear impossible according to the current state of the art in science and technology” (§ 7 (6) 2, EndlSiUntV, 2020).

Therefore, no detailed uncertainty analysis has to be carried out in the current phase, but in general, aspects regarding uncertainties will be considered.

In the advanced Finnish programme, the uncertainty is mainly addressed by quality control with respect to the rock (deposition hole location) and bentonite properties.

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

4.5.1 Uncertainty related to modelling of radionuclide transport

Wherever models are used to represent physical processes, model uncertainties arise based on the data and tools utilised. This uncertainty covers all uncertain aspects related to reliability of concepts and mathematical models – maybe also in extreme situations – coupling of models, numerical realisation, exactness of numerical results, possibility of programme errors, etc. Model uncertainties might occur in modelling of complex processes that cannot be directly implemented in calculation tools: influence of thermal, chemical and mechanical near-field perturbations, competing effects, coupled transfers, etc.

One aspect of uncertainty that has been identified in Subtask 3.6 concerns the model dimensionality. The often-used 1D radionuclide transport modelling includes a lot of assumptions and associated uncertainties. Would there be a reduction of uncertainties by full 4D (3D plus time) modelling?

This kind of uncertainty is a bit different from others, as it does not describe a “real”, system-immanent uncertainty but reflects the differences between the reality and the simplified model applied for predicting the consequences. The uncertainty is due to the fact that one does not know how well the model represents the reality.

Models are used to assess the release of contaminants and (potential) hazard. Errors can lead to faulty assessment, which can be safety-relevant in case of significant underestimation.

(1) Identification and assessment of safety relevance

Uncertainty related to modelling transport of radionuclides can be split into further sub-categories (data, scenario, model uncertainties, etc.), see BGE (2022), Nummi (2019), Röhlig et al. (2012), IAEA (2012), IAEA (2013). The topical uncertainty considered in this chapter comprises all aspects of model uncertainty.

Model uncertainties are generally identified by comparison of model results with experimental results. A comparison with independent model results can also help to identify model uncertainties. Specifically, the uncertainty of a strongly simplified model representation (maybe 1D) can be compared with a more detailed and complex, time-dependent model. Results of complex models are not necessarily “better” than those of simplified models, but differences are a general hint to model uncertainties. Analysis of the origins of these uncertainties requires detailed investigations and can become a challenging task. Model uncertainties occur in numerical calculations both on the process level and the integrated level.

Model uncertainties uncertainty can be identified by comparing model results with the reality or different models with regard to the consequences they calculate. The latter is done in benchmarking and code validation investigations like DECOVALEX (LaForce et al., 2022; LaForce et al., 2024) as well as comparison of underlying databases.

Model uncertainties are, in general, hard to quantify, but for specific effect and process models, one can at least compare their predictions with experimental results or observations in nature. Examples are measurements of bentonite or bedrock properties or of the host rock environment. Natural analogues often provide a good means to test models and assess their uncertainties. Even complex long-term models like those for climate evolution can, to a certain degree, be compared with the actual evolution.

The safety relevance of the uncertainty results from the fact that people tend to relying on the validity of model results. It is important to analyse model uncertainty properly and to make clear, when presenting model results, that they are subject to such uncertainty.

(2) Characterisation

Whether or not a model represents the reality "correctly" depends, on the one hand, on the physical understanding of the underlying processes and their couplings and, on the other hand, on the intentionally applied simplifications. Therefore, model uncertainties can arise from inexact description of the nature, but also from simplification, neglection of influences or couplings, and from the numerical code itself. They arise in all kinds of numerical calculations both on the process level and the integrated level and in all scales.

Codes can contain programming errors or algorithms that are inappropriate for a specific problem. Errors occurring only in rare situations can never be excluded. Such uncertainties are typically hard to capture since the error situations are unknown. They can, however, lead to faulty or even wrong calculation results and, in extreme cases, to severe consequences.

Uncertainties due to simplification of the physical problem are hard to assess. A more detailed, higher-dimensional model does not necessarily provide the correct solution of the physical problem. There is danger of over-detailing: the model might describe the system more accurately than it can be justified under the actual circumstances and knowledge and pretend an exactness of results that does not match the actual prediction accuracy. Results can look more reliable in that they are stable and robust, but in fact do not actually represent the situation to be modelled. This is specifically relevant for long-term investigations, as, due to unforeseen developments, the situation or its boundary conditions may change over time with the consequence that the detailed model is no longer correct.

A typical characteristic of model uncertainties is that they can hardly be quantified, as one neither knows what might be wrong with the model, nor what consequences can follow.

Model uncertainty has to be distinguished from parameter uncertainties. The latter have influence on the results but not on the model itself, which only defines how the parameters act together to produce some kind of prediction. So, the uncertain factors that affect model uncertainty are not parameters but part-models for specific effects and their kind of combination. Such factors are, for instance:

- thermal, hydraulic, mechanical and chemical (THMC) models for:
    - reactive gases,
    - solute diffusion in EBS,
    - solute diffusion from EBS to host rock,
    - geochemistry,
- coupling of effects,
- uncertainties on integrated and process level,
- uncertainty of input data,
- modelling complexity (1D ... 4D),
- modelling accuracy,
- model scale.

Various modelling exercises, including uncertainty and sensitivity analysis, were done in EURAD WP "Development and improvement of numerical methods and tools for modelling coupled processes" DONUT (Ahusborde et al., 2021).

Modelling issues do not directly affect safety, but nevertheless, model uncertainties have can safety-relevant effects, as they are used to derive safety statements:

- reliability of safety statement,
- description of barrier performance,
- quantification of risks and consequences.

(3) Classification and associated management actions

The consequences of numerical model uncertainties and how to address them depend on the storage concept. If it is based on the absence of failure or leakage processes, the uncertainties generated by the model may be significant.

Models are realised through software codes, which are made by humans and hold the risk of errors. Such code errors can lead to wrong model predictions, although the model itself is correct. To manage this kind of uncertainty, the probability of code errors should be reduced as far as possible by applying approved measures of QA already during the software development phase, like incremental development, refactoring, two-person integrity, comparison with analytical solution, regression testing, etc. For an overview and further references see (Wikipedia 2023).

The validity of the codes should be checked by validation against experimental results on laboratory and in-situ scale. Validation means a collection of evidence (a strong proof is generally impossible) that the model is suitable for its intended use, for instance by comparing its results or predictions with observations or data not considered in the set-up of the model. This is, however, a general problem for codes designed for predicting long-term developments, as experiments over thousands or millions of years are not possible. Therefore, overall validation of integrated-level performance assessment (PA) codes can only be done by comparison with independent calculation results. Benchmarking exercises are a means of managing this kind of uncertainty. Such exercises should include a variety of differently conceptualised codes with different degrees of complexity and dimensionality but addressing the same real situation.

Model calibration is a means of reducing model uncertainty. By applying a model to predict known datasets that were not used for developing the model one can get valuable hints on weaknesses that would allow model improvement.

For mitigation of the effects of model uncertainties, one can try to use conservative assumptions. This shifts the effects of the uncertainty to a range of calculation results which is less safety relevant. In nonlinear systems, however, it is not always possible to identify an assumption as uniquely conservative, so this approach should be used with care. Over-conservatism can weaken or even completely destroy the safety statement of a performance assessment.

The effects of model uncertainties can possibly be mitigated by applying several models independently. This approach means that a specific repository concept is analysed by different groups, each using their own models and tools. For instance, one group could use a highly simplified 1D model and perform a number of calculations, varying many parameters, while another group applies a detailed 4D modelling with only a few variants. Of course, the results cannot be directly compared, but striking contradictions can be a hint to modelling or programming errors.

The German repository safety concept requires the enclosure of the waste in a specifically defined region of the host formation, which provides safety by itself: the containment-providing rock zone (EndlSiAnfV, 2020; EndlSiUntV, 2020). This concept originates from the requirement to generally reduce dependency on models for long-term evolution of the disposal system and is therefore an essential measure to mitigate model uncertainties. A similar effect can be achieved by high quality requirements to canisters or other geotechnical barriers, which are made to provide a high degree of isolation and therefore make radionuclide transport modelling less relevant.

In principle, it is also possible to include model uncertainties in probabilistic analyses. This can be done by assigning probabilities to different models and selecting them by random choice in a set of calculations. The probabilities are more or less arbitrary, as proper quantification of model uncertainties is impossible, but such an approach can reveal how model uncertainties act on the results of a performance assessment.

Due to the different sources of modelling uncertainty, possible actions for reducing either aim at improving process understanding, model refinement and data availability or at increasing confidence in the existing models. Some examples of the first case are:

- site exploration:
    - specification of host rock properties,
    - exploring admissible limits (temperature, pressure, etc.),
- extensive research (DONUT, ACED, HITEC, ...):
    - tracer test experiments,
    - matrix diffusion.

The second case of model uncertainty reduction actions comprises:

- expert judgement:
    - experience-based assessment of the reliability of models and codes,
- Qualification, Verification, Validation (QVV), NEA (2012), IAEA (2016):
    - model validation/benchmarking,
    - code verification,
    - code review and quality assurance:
        - good documentation of assumptions, variability and interactions,
    - code validation/benchmarking,
    - code publication,
    - benchmarking exercises with differently conceptualised and/or differently detailed codes, addressing the same real situation.

The uncertainty can be mitigated by:

- conservative assumptions (if possible, but avoid over-conservatism!),
- independent application of different models and codes,
- isolation concepts:
    - containment-providing rock zone,
    - qualified geotechnical barriers,
- global sensitivity analysis/Monte-Carlo methods,
- Carry out preparatory calculations and sensitivity studies which make it possible to identify essential processes and data in view to simplify the numerical model,
- FEPs approach (Vigfusson et al., 2007; Röhlig et al., 2012).

(4) Representation in safety assessments

As safety assessments are essentially based on radionuclide transport calculations, model uncertainty is an intrinsic component of safety assessment and does not need to be represented in a specific manner. Nevertheless, the uncertainty should be addressed in the evaluation of results. It is relevant for safety insofar as it leads inevitably to uncertainty of the results of a safety assessment, and in case of underestimation it could jeopardise the validity of safety statements.

Conservative model assumptions are often applied to avoid underestimation, but as stated above, conservatism is not always unique.

One possibility to take model uncertainties into account in a safety assessment is to apply different models (or mode variants) and to assess the differences of the results. That can be done deterministically or even in a probabilistic assessment by switching between models from run to run, according to assumed probabilities. Proper quantification of these probabilities, however, is hardly possible. Another possibility is, as mentioned above, to analyse the same system using two or more completely independent model setups by different groups.

(5) Additional comments

Discussions about managing uncertainties associated with models depend largely on the purpose of the modelling, as models must ultimately be shown to be fit for purpose.

A future approach to deal with model/parameter uncertainty might be to deal with virtual twins of a repository, including all kinds of THMCRB processes on multiple scales, using data-driven and physics-based models. Having such tools available, targets like dose limits could be defined; sensitivity analysis on all models' parameters with respect to a defined dose limit could be performed using parameter uncertainties for all parameters. A statistical framework will yield most important or dominating parameters for related parameter uncertainties. Since fully coupled models are used, non-linearities are included in the modelling. No concern about conservative estimates is necessary or has to be defended. Spatial heterogeneities, evolving boundary conditions, etc. can be tested. Model predictions can be used for comparison with experimental data from which data-driven models can be deduced. Surrogate models may help to produce a high number of model realisations to allow good statistical predictions/analysis. Such tools would allow to manage dominant uncertainties according to their mathematical quantification and not according to vague arguments, model simplifications and simplified models.

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

Uncertainties associated with the completeness of FEPs considered in the safety case are not addressed in the context of the near-field uncertainties.

5. Synthesis of the 5th UMAN Workshop dedicated to management options and preferences of different actors regarding near-field uncertainties

5.1 Overall objectives of the UMAN workshops[8]

Workshops organised by UMAN Subtask 4.3 served as an exchange and discussion platform on the different uncertainty management strategies and options, employed by the various actors involved in RWM and participating in WP UMAN, including WMOs, TSOs and REs. The workshops covered five different types of uncertainties considered in WP UMAN, namely uncertainties related to site and geosphere, human aspects, spent nuclear fuel, waste inventory and near-field (see Table 4).

Table 3 - Overview of the workshops organised in the framework of WP UMAN

Workshop	Uncertainty related to	Session 1 (i.e. Day 1)	Session 2 (i.e. Day 2)	Session 3 (i.e. Day 3)	Format	Interactions
Workshop 1	Site and geosphere	19.02.2021	02.03.2021	11.03.2021	Online	EURAD WP FUTURE
Workshop 2	Human aspects	04.06.2021	11.06.2021	23.06.2021	Online	-
Workshop 3	Spent nuclear fuel	09.02.2022	17.02.2022	28.02.2022	Online	EURAD WP SFC; project MICADO
Workshop 4	Waste inventory	06.04.2022	20.04.2022	09.05.2022	Online	IAEA
Workshop 5	**Near-field**	17.05.2023	05.06.2023	29.06.2023	Online	EURAD WP HITEC; project BEACON

The main aim of the UMAN workshops was to identify the preferences of the different actor groups (i.e. WMOs, TSOs and REs) with respect to the management of the above mentioned types of uncertainties, particularly to identify commonalities and differences within the actor´s group as well as among the actor`s groups. It was attempted to explain the rationale behind the identified differences through the different responsibilities, roles and interest of these actors in RWM programme, specificities of the national programmes (including national regulations, types of radioactive waste, repository type, considered host rock(s), repository design and safety concepts), current implementation stage of the national programmes as well as lessons learned.

Further, the workshops contributed to identification of needs for future joint activities and initiatives that could have a character of research and development (R&D), strategic study (StSt) as well as knowledge management (KM) activities.

Moreover, the workshops allowed to verify correctness of the workshops input materials provided by UMAN Subtask 4.2, particularly completeness of the identified uncertainty management options. The outcomes of the workshops provided also material for UMAN Task 5, required for preparation of UMAN seminars. It is recalled that these aspects are not presented in this report.

[8] This section contains passages taken from (Haverkate et al., 2024).

In addition, the workshops fostered the interactions with other EURAD WPs, other eesarch projects and organisations; in case of the 5th UMAN Workshop with EURAD RD&D WP "Influence of temperature on clay-based material behaviour" (HITEC) as well as with EU research project "Bentonite Mechanical Evolution" (BEACON).

The outcome of the first four workshops, which were part of the first phase of UMAN, was presented in Haverkate et al. (2024). The report at hand is dedicated to management of near-field uncertainties and presents the outcome of the 5th UMAN Workshop. Input for the workshop was provided mainly from Subtask 3.6, specifically from a preliminary version of Deliverable D10.18 (Pfingsten et al., 2024), as well as from material produced in Subtask 4.2 extension like the input template shown in Appendix A.

It should be noted that the input provided by the participating organisations through the homework template, particularly with regard to the first two questions, reflects the current implementation stage of the national programme these participating organisations represent.

5.2 Organisation of the 5th UMAN Workshop[9]

The 5th UMAN Workshop was organised and moderated by the Czech National Radiation Protection Institute (SÚRO) in the form of three half-day online sessions on 17 May, 5 June and 29 June 2023. The detailed workshop agenda is provided in Appendix B. It was attended mainly by representants of organisations contributing to Tasks 3 and 4 of WP UMAN. All three groups of actors (WMOs, TSOs, REs), were represented, as well as a wide variety of repository types and concepts and different programme stages.

In Session 1 of the workshop, a general introduction was given, and a homework template was provided to be answered as preparation for detailed discussions in Session 2. Four questions were posed in the template:

1. What is the safety significance of this uncertainty in the view of your organisation as WMO, TSO or RE? How do you expect the safety significance to evolve over time (over the six phases of a disposal programme considered in the EURAD Roadmap)?
2. What is your preferred management strategy? I.e., what is your preference regarding the treatment of the uncertainty in the context of the different elements of the strategy (e.g. analysis of safety relevance; representation and evaluation in safety assessment; actions to reduce, mitigate or avoid the uncertainty; general management principles)? Please substantiate your answer with references and examples. Of particular interest would be examples of pitfalls encountered and lessons learned.
3. Did you identify other management strategies than those already identified in the material provided (i.e., the input from Subtask 4.2) or do you disagree with any statements made? Please also provide references and examples.
4. Do you identify needs for future EURAD activities addressing the management of this uncertainty? If yes, please explain which types of activities would be of interest to your organisation (R&D, knowledge management or strategic study activities).

Very few answers to question 3 were provided, but presenting and discussing them is beyond the scope of this report. Issues related to correctness and completeness of the workshop input materials prepared by Subtask 4.2, summarising available uncertainty management strategies and options, are not addressed in this report.

After the session, 13 homework sheets were returned (5 submitted by WMOs, 5 by TSOs, 3 by REs). In Session 2 of this workshop 4 WMOs, 6 TSOs and 4 REs took part. The targeted number of the participating organisations yielded 4 for the WMOs group, 4 for the TSOs group and 7 for the REs group.

[9] This section contains passages taken from (Haverkate et al., 2024).

Session 2 was the central part of the workshop. Three discussion groups were formed, one for each type of actor, each with a moderator and a rapporteur. Within these groups, possible uncertainty management options in the different phases of the implementation programme (see Figure *4*) and the preferences of the participating organisations were discussed, using the three selected topical uncertainties presented in Section 2.2. The uncertainty management scheme developed in UMAN Subtask 2.1 (Hicks et al., 2023), shown in Figure 7, was used as a basis for the discussions. It should be noted that the input provided by the participating organisations through the homework template, particularly with regard to the first two questions, reflects the current implementation stage of the national programme these participating organisations represent.

In Session 3, the rapporteurs of the three groups presented the discussion results of Session 2 to the full auditorium and differences and commonalities between the groups were discussed.

5.3 Views of the actors' groups

It turned out that the understanding of the uncertainty management categories of reducing, mitigating and avoiding was not quite consistent between the workshop participants. To avoid confusion, in this report we follow the definitions in Section **Erreur ! Source du renvoi introuvable.**.

It should be noted that very few and narrow answers to question 3 (see above) were provided that do not allow meaningful conclusions and are therefore not presented in this report.

5.3.1 Uncertainties related to hydraulic properties of the bentonite

In many concepts, the bentonite buffer assumes a relevant safety function. Re-saturation and swelling pressure evolution "as expected" guarantees mechanical integrity of the near-field and heat transfer from HLW/SNF through the buffer into the host rock.

The safety significance of this topical uncertainty depends on the host rock and the general disposal concept, which widely differ between the participating countries. In salt, bentonite may play a minor role as a seal component but has little safety relevance. In clay, the isolation function is predominantly maintained by the clay formation, while bentonite is used as a technical component with limited safety relevance, compared to that of the host rock. In crystalline rock, however, the bentonite buffer is essential for limiting the water flow to the canister as well as for chemical buffering. Due to coupling of different effects, the uncertainty of evolution of water content, permeability and pressure can become safety significant. Regardless of the host rock, different waste isolation concepts rely on bentonite to different degrees. Consequently, the workshop participants assessed the safety significance rather differently.

Those who saw a certain safety significance widely agreed that at the beginning, the uncertainty plays a minor role as it is expected to have no or little influence on host rock and site selection, but it increases during the early programme phases. Since bentonite is a technical material, its properties are widely independent of site characteristics (except geochemical conditions). During the phases of facility construction, operation and closure, the uncertainty of hydraulic bentonite properties will become more important, depending on the selected concept. Several participants saw highest relevance during facility construction. At the beginning of the post closure phase there may be still some relevance of the uncertainty, as the re-saturation and swelling process can take some time and therefore might have an influence on water movement shortly after closure. It was mentioned, however, that during site characterisation and facility construction more information will become available, so that the uncertainty itself is reduced.

Possible management options, including actions to reduce, mitigate or avoid the uncertainty, were identified in Section 4.4.1. While REs mainly relied on targeted laboratory and field investigations, modelling on different scales and statistical methods, WMOs put more focus on general site exploration and material quality assurance as well as the regulatory basis. For the TSOs, the preferences seemed to depend on the status of the national programmes.

Some specific opinions are compiled in the following (it turned out that the borders between uncertainty avoidance, reduction and mitigation are not always clear):

WMOs:

- It was stated that, to mitigate the uncertainty, the hydraulic behaviour of seals must be optimised to make sure that clay rock formation is the main migration pathway throughout the post-closure phase. Permeability of pure bentonite is not of the concern. The permeability of the clay core of seals has no influence of the amount of water reaching waste packages. Moreover, the tightness duration of the waste package has almost no influence on the post-closure safety.
- Another WMO does comprehensive performance assessment to understand the behaviour and properties of bentonite and bentonite/sand mixture. The hydraulic properties of the bentonite and bentonite/sand mixture are tested well both in laboratory and in-situ conditions. The behaviour of the bentonite material in the whole repository system is studied numerically in details.

TSOs:

- One TSO puts more emphasis on the safe containment principle, especially for clay. In clay, the preferred management strategy would be to mitigate the uncertainty by selecting a site that mainly relies on geological barriers to provide safety. A crystalline rock concept, however, will probably rely on technical and geotechnical barriers. For such a repository concept, the safety significance should be analysed by means of appropriate model investigations including sensitivity analysis.
- Another TSO, due to the advanced national programme, puts more emphasis on quality control in the HLW repository safety. Strict specifications exist as a part of the operating license submission to the regulator. Uncertainty is handled in the licensing documentation.

REs:

- REs generally state that a better understanding can be achieved by performing experiments (short term to ~20 years), sophisticated modelling of these experiments, and later on predicting on repository scales (spatial and time) with special focus on the transients of re-saturation, mechanical (swelling pressure) and hydraulic properties, temperature including heterogeneous bentonite initial distribution, heterogeneous re-saturation, and related consequences for the safety function of the technical barrier.

The participants agreed that further research is necessary to provide more experimental data for bentonite re-saturation and swelling pressure evaluation. This is specifically valid for those organisations that represent early-stage programmes. For future European research, there is high interest in THMC coupling approaches, large-scale re-saturation experiments, as well as better involvement of the Civil Society in understanding the general conditions of repository closure. Identified research activities are compiled in Appendix D.

5.3.2 Uncertainties related to metallic material behaviour

Metallic material is an essential component of every disposal concept, as the canisters are made from metal. The effect has two main aspects with their specific relevance for safety:

- Metal corrosion affects canister lifetime, durability of liners, the source term and chemical effects of corrosion products. It is influenced, among others, by chemical conditions and microbial activity.
- Gas generation can lead to pressure build-up and even affect the mechanical stability of the engineered and natural barriers. Gas pressures that are too small to cause rock damage can nevertheless lead to fluid displacement and radionuclide transport.

The uncertainty comprises a variety of uncertain influences, which are independent of each other. It is relevant for long-term safety and also for waste retrievability and recovery.

The container concept to be used, but also the safety relevance of corrosion processes, depend on the host rock type. Due to the low permeability of rock salt and saturated clay, which does not allow free gas outflow, the uncertainty of gas production and pressure can have a considerable safety relevance in salt and clay concepts. Crystalline host rocks (and maybe some types of clay rock) are more or less permeable for gas, so that high pressures are improbable to occur, but other metal-related effects like sorption on corrosion products can become more relevant. In crystalline, canister corrosion is safety-relevant as the canisters provide an essential barrier for radionuclide retention.

The uncertainty significance was assessed differently, depending on the different disposal concepts and programme stages. Many participants considered it as high or at least medium as the effects have direct impact on the containment safety function of the steel overpack and the time at which the radionuclide release in the disposal system starts. Some organisations representing advanced programmes, however, considered the significance of the uncertainty as low, since their concepts do not rely on long-term canister stability. Quantification of the uncertainty was considered a big challenge.

During the site selection phase, the uncertainty has the potential to be safety significant in that it might have a certain, indirect influence on the selection of host formation, as it acts very differently in different host rocks. During facility planning and construction it can be relevant for the disposal concept. During operation and closure, the uncertainty is often considered less safety significant, as corrosion of metals to be used as canister materials (copper, stainless steel) is a slow process.

The development of the uncertainty significance over the implementation phases is assessed rather differently by the workshop participants, which seems to be hardly influenced by the type of actor (WMO, TSO, RE) but mainly by the specifics of the disposal concepts and programmes they represent, and also by different views on the definition of the uncertainty significance in this case. The wide field of effects subsumed under this uncertainty that do or can play a role causes this inhomogeneous situation.

One member of the TSO group, e. g., sees a generally low significance which slightly increases in the late post-closure phase. This results from general trust in the quality and long-term performance of the canisters, which themselves are considered to have only medium safety relevance in the respective disposal concept. In contrast, another TSO assigns the uncertainty a high significance in the early stages up to facility construction, which decreases in the operational and post-closure phases. This is based on the argumentation that in the respective national concept, the canisters are an important barrier, and the uncertainty of corrosion effects has been influencing decisions since the early programme phases. On the other hand, the WMO from the same country argues that ILW-LLW canisters have no tightness function after closure, and HLW steel containers need to provide tightness during the thermal transient peak, so that there is little relevance of the uncertainty over all phases.

Possible management options, including actions to reduce, mitigate or avoid the uncertainty, were identified in Section 4.4.2. The uncertainty can be reduced and mitigated but, as metal parts are a component of each disposal concept, the only possible strategy to avoid the uncertainty would be to prohibit the contact of metal parts with water. As the uncertainty and its safety relevance depend, to a large extent, on the disposal concept, the same is valid for the management strategy, and the preferences show no clear commonalities between actors of the same type. The views of some specific actors are summarised in the following:

- One TSO puts high confidence in reducing the uncertainty by quality control of the canisters and the deposition holes for the repository design. For the canisters, severe acceptance criteria exist as well for the raw material as for the final product. Deposition holes are rejected if after drilling they turn out not to meet the requirements, including groundwater flow and composition. Since quality control is assumed to be effective, the remaining uncertainty is generally considered low.
- Another TSO investigates alternative repository design concepts with less metal (which could be replaced by ceramics or other alternative materials) or minimising the oxidising transient to reduce the uncertainty.

- One member of the RE group intends to minimise corrosion rates by use of high-pH cementitious material as well as to mitigate the uncertainty by minimising use of highly porous backfill material to provide storage room for gas.

Most participants, regardless of the actor type, agreed that there is need for further research and development, by laboratory investigations and thorough site exploration, to determine the geochemical and hydrological conditions as well as possible. Some current focuses are:

- THMBCR experiments on all scales,
- redox impact on corrosion,
- gas production:
    - irradiation effects,
    - microbial activity influence,
- corrosion experiments (laboratory and in situ),
- canister-host rock interaction,
- investigation of natural analogues (e. g., from archeology),
- development and experimental validation of models for:
    - corrosion rates under various conditions,
    - diffusion of corrosion products and interactions with container surface,
    - water transport to the container.

5.3.3 Uncertainties related to modelling of radionuclide transport

Model calculations are used to find the most suitable site, to describe adequately the site characteristics and to show if legal requirement and limits are fulfilled. Models on the process and integrated level are an essential component of the safety case and generally important for system understanding as well as for demonstrating the safety functions of subsystems and the performance of geological and geotechnical barriers. Since every model is a – more or less drastic – simplification of the reality, it remains uncertain how well the calculated results actually represent the natural conditions and how reliable safety-relevant conclusions are. Due to the wide spatial scale (from millimetres to km scale), THMCBR models are known to have high uncertainty.

As modelling is the only tool for long-term assessment of radionuclide release from a DGR and its possible radiological consequences, there is a wide agreement, at least among TSOs and REs, that all kinds of model uncertainty have a high degree of safety relevance. Underestimation of radionuclide release could lead to adverse impact to human health. Nevertheless, several WMOs considered this uncertainty less relevant. One member of the WMO group, for instance, argues that, since in the national concept the geological environment of the host rock is quite homogeneous and stable and the canister design requires an isolation phase that shifts the begin of radionuclide release to the post-thermal phase, the uncertainty in the degree of transport model abstraction and its safety relevance is relatively small. Another WMO mentioned that models and calculations must not generate uncertainties. Of course, this does not mean that model uncertainties have to be excluded (which would be impossible) but model calculations should always reduce, not enhance the overall uncertainty. Generally, actors of all types tend to assess the safety relevance of the uncertainty lower if they apply well-qualified and validated models and computational tools. It is, however, not always clear if a more detailed or sophisticated model, e. g., a full 3D/4D representation vs. a 1D/2D assessment, is more reliable with respect to safety, as such models require more data, and model uncertainty is simply transformed into data uncertainty. An increase in model detailedness does only make sense if a sufficiently reliable database is available that otherwise could not be utilised. Higher detailedness or dimensionality can create additional uncertainty.

Modelling uncertainty is of some relevance during the site evaluation and site selection phase, as preliminary model calculations have to be performed to compare different sites and concepts. This kind of uncertainty can directly act on the site selection process. During facility design and construction, the uncertainty is still safety significant as model calculations continue being performed in order to optimise individual components of the repository system. During the phase of operation and closure the safety relevance of model uncertainties decreases. The post-closure phase, however, covers the total assessment period and is described exclusively by modelling results. So, modelling uncertainty is mostly assessed as highly significant for this phase. As one can expect an increase of knowledge about the site and the repository components over the phases, the importance of accurate modelling will also increase. Those WMOs that assigned low relevance to modelling uncertainty in general do not see any change over the programme phases.

Possible strategies for uncertainty management were identified in Section 4.5.1. In general, actors of all types agree that research is most important to reduce modelling uncertainty. On the one hand, targeted laboratory and in-situ investigations are expected to increase knowledge about the natural systems to be modelled and improve understanding of the underlying processes and features, which might enable the modellers to improve the models and reduce their uncertainty. Such investigations can also contribute to provision of verified databases, justifying transition from lower-dimensional to higher-dimensional models. On the other hand, confidence in the applied models and codes can be increased by consequent validation and benchmarking exercises. In code development, the probability of code errors should be reduced as far as possible by applying approved measures of QA already during the software development phase.

While REs mainly focused on process investigation and model improvement, favouring an iterative approach, WMOs often mentioned comprehensive site investigation and TSOs proper code qualification as means of uncertainty reduction. This, however, is just a slight tendency, not a clear preference of the different types of actors. A common view of most participants was that the uncertainty should be managed by a combination of measures of all kinds.

Some research activities mentioned by the participants are:

- tracer test experiments,
- model improvement for radionuclide leaching from canisters/radionuclide concentrations as a source term,
- coupling of near-field evolution and radionuclide transport models,
- clear definition of boundary conditions and parameters,
- upscaling of laboratory results.

The following management options for reduction of uncertainty were identified:

- in-depth site exploration,
- expert judgement.

Reduction of model uncertainty by model and code qualification can be achieved through:

- code QA during software development:
  - incremental development,
  - two-person integrity/code review,
  - regression testing,
  - comparison with analytical solutions,
  - publication of codes.
- model QVV:
  - ensure/substantiate that the physical model is fit for its purpose considering phenomenology and uncertainties.
- multiplicity of approaches:
  - benchmarking exercises: application of differently conceptualised codes addressing the same real situation,
  - variety of models used in the safety case,
  - using different methods or approaches for safety assessment.

Most approaches to mitigate model uncertainty aim at minimising the dependence on modelling. With regard to radionuclide transport, that can be reached by conceptual or design measures that minimise the amount of radionuclides released from a limited, isolated region in the repository, e. g., high-quality canisters and / or the containment-providing rock zone according to the German concept. This means replacing model calculations, at least in part, by general arguments. The low significance that some WMOs) assign to modelling uncertainty results from their confidence in the mitigation effectivity of their national concepts.

Another widely used possibility to mitigate the influence of radionuclide transport model uncertainty is to use conservative parameters and assumptions. The principle of conservatism is to shift the uncertainty ranges largely to the "safe" side. All actors applying this approach, however, are aware of the problem of over-conservatism, which in practise can lead to less significant or even useless results. Moreover, it is often unclear whether an assumption is conservative or not.

A widely applied means to handle uncertainties in model calculations is the probabilistic approach. As it does not affect the uncertainties themselves but allows one to better assess their consequences, it can be seen as uncertainty mitigation. An additional use of probabilistic uncertainty and sensitivity analysis (Monte-Carlo methods) is improvement of model understanding. Most actors of all types considered the probabilistic approach an important element of their uncertainty management strategy.

Moreover, the FEPs approach (Vigfusson et al., 2007; Röhlig et al., 2012) was identified as a means for mitigating modelling uncertainties. The use of this approach is mainly a systematic analysis of the influences of the different elements constituting the scenarios to be considered, and with that a better and exacter identification and quantification of their uncertainties.

5.4 Summary of the outcome of the 5th UMAN Workshop

The 5th UMAN Workshop, dedicated to near-field uncertainty management options and preferences of different actors, provided a platform for UMAN participants to present and exchange their specific views with respect to these issues. It turned out that, due to the very different repository concepts with regard to host rock type, canister design, disposal concept and safety strategy, the preferred uncertainty management options are predominantly influenced by the specificities of the national programmes. The individual views depend, understandably, to some extent on the roles and responsibilities of the actors in the national disposal programme. There is, however, a wide agreement that all kinds of uncertainty management play their role.

The key elements identified by the different actors are in line with the generic uncertainty management strategy (Figure 7, left hand side). Management options for all elements of the uncertainty management scheme (Figure 7, right hand side, and Figure 8), that is uncertainty identification, uncertainty characterisation and analysis of safety relevance, were mentioned, but the focus is laid by all actors on the specific actions to reduce, mitigate or avoid uncertainties.

It turned out that the understanding of the measures of reducing, mitigating and avoiding uncertainties and the borders between them is not quite unique. The same (or similar) uncertainty management measures were sometimes assigned to different categories by different participants.

For the topical uncertainty related to hydraulic properties of the bentonite, there is a consent between the actors' groups that further research is necessary to reduce the uncertainty, including laboratory and in-situ investigations as well as THMC and transport modelling, in order to improve understanding of the processes. WMOs and TSOs also mentioned site exploration and material quality assurance. WMOs stated that the use of well characterised bentonite is preferable.

For the topical uncertainty related to metallic material behaviour, predominantly the TSO group mentioned consequent quality control as a measure of uncertainty reduction, while REs are more in favour of investigating material properties in experiments and using statistical methods. The WMO group focused on actions that are not directly related to the metallic materials themselves but on the conditions in their surroundings, like selection of a site with low water content, optimising geochemical and hydrological conditions or implementation of geotechnical barriers.

For the topical uncertainty associated with modelling of radionuclide transport, WMOs and TSOs consider code quality assurance, model validation and benchmarking as important measures for uncertainty reduction, while REs do not, nevertheless admitting that application of different codes is sensible. REs lay the focus on application of statistical methods.

There is some inhomogeneity regarding the assessment of uncertainty significance for safety between organisations representing differently advanced disposal programmes, regardless of the actors' groups they belong to. In countries with more advanced programmes, there is a tendency to assess the safety significance of near-field uncertainties lower than in early-phase countries. This is obviously due to the confidence in the developed concepts and their effectiveness to avoid or mitigate existing uncertainties. Many workshop participants generally assessed the near-field uncertainties less relevant than far-field uncertainties, which is predominantly valid for concepts that rely on the geological barrier.

In general, the views of the actors' groups are consistent and supplement each other. Due to their nature, REs are more focused on research actions, while WMOs have a wider view, putting more emphasis on site selection and characterisation. TSOs often underline quality assurance measures.

In the workshop, future joint activities and initiatives such as research and development, strategic studies and knowledge management were presented by all three actors' groups. These are provided in a tabular form in Appendix D for each topical uncertainty considered in the 5th UMAN Workshop. Note that these identified activities and initiatives are presented as originally formulated and are not prioritised. The following list addresses a few key topics:

- Experimental data from re-saturation and swelling pressure evaluation,
- Uncertainty analysis and optimisation with respect to experimental data and their safety relevance,
- THMC coupling approaches,
- Mechanistic description of chemical and physical perturbations on RN behaviour,
- Large scale experiments to complete the BEACON project,
- Alternative material sources,
- Canister performance for long term:
    - corrosion,
    - understanding of stress corrosion cracking
    - strength resistance,
    - heat resistance,
    - radiation resistance,
- Model and code development, validation and benchmarking,
- Exchanges on the substantiation that models used in the safety assessments are fit for their purpose, considering the viewpoint and expectations of different actors (regulators, civil society, REs, …) and on how to reach a common understanding of model purposes and the meaning/significance of modelling results in the context of the safety case.
- Civil Society involvement to understand the general conditions for closure (technical and societal aspects).

6. Summary and conclusions

In this report an overview was given about possible approaches for handling near-field uncertainties in the safety case and the preferences of the different actors (i.e., WMOs, TSOs and REs) in the light of their roles in the national disposal programme as well as the matureness and specifics of the respective national programmes. This was done using the three topical uncertainties, which were selected from the list of the near-field uncertainties potentially relevant for disposal safety, elaborated by UMAN Subtask 3.6 (Pfingsten, 2024). The selection was based on the assessment of the safety significance of near-field uncertainties that was made by Subtask 3.6, taking into account the views of the different types of actors. The topical uncertainties are:

- uncertainty related to hydraulic properties of the bentonite,
- uncertainty related to metallic material behaviour in different barriers,
- uncertainty related to modelling of radionuclide transport.

In the first part of the report (Chapter 4), it was presented how the uncertainties are identified, characterised and classified with respect to possible management options and how they are represented in safety assessments. The presentation of possible management strategies and options for each of the topical uncertainties included:

- uncertainty identification,
- uncertainty characterisation,
- safety relevance of the uncertainty,
- assessment of the necessity to reduce/mitigate/avoid the uncertainty,
- representation in the safety assessment,
- specific actions to reduce/mitigate/avoid the uncertainty.

The overview was based on the experience of the actors participating in UMAN Subtask 4.2, as well as on the review of existing documentation like regulations, guidelines, national reports. Such documentation is available from national programmes, international initiatives (IAEA, OECD/NEA) and relevant past or ongoing European R&D projects. As such, the overview 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 is limited to a selection of three topical uncertainties and does not aim at providing a complete overview of all possible or existing uncertainty management options or strategies.

In the second part of this report, the views of the different actors' groups were analysed on the basis of the discussions during the 5th UMAN Workshop, including the homework sheets submitted by the participants. As a basis for the workshop, the same topical uncertainties were considered that had been selected for the work of Subtask 4.2.

The safety significance of the topical uncertainties was in addition assessed together with its evolution during the programme phases defined in EURAD. The topical near-field related uncertainties were generally assessed significant for safety. Representants of advanced disposal programmes) however, tend to assess the significance lower, which seems to result from the fact that elaborated facility design concepts already contain various elements appropriate to mitigate the safety significance of near-field uncertainties. Moreover, strict quality assurance and acceptance criteria for canisters and buffer materials reduce the respective uncertainties and/or their safety relevance. Organisations representing concepts that mainly rely on the geological barrier assess the near-field uncertainties less relevant than those associated with the far-field.

The preferred management options of the different actors were presented. It has to be noted that the information provided reflects the current implementation stages of the national programmes the participating organisations represent. The preferences on options to manage near-field uncertainties depend to a large extent on the specific repository concept, first of all on the host rock type. Further, the views on preferred options seem to be influenced to a lesser extent by the type of actor (WMO, TSO, RE) and their roles in the national programmes.

Uncertainty management options can be classified into reducing, mitigating and avoiding of uncertainties (see Chapter **Erreur ! Source du renvoi introuvable.**). It turned out that the understanding of these classes is not quite uniform among the organisations participating in WP UMAN, Subtasks 4.2 and 4.3.

The participants of the 5th UMAN Workshop identified a variety of research – on an individual or a collaborative basis – to further reduce known near-field uncertainties, to elaborate approaches for mitigating and to communicate with the Civil Society. Several of such research activities are recommended for the future partnership EURAD-2.

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Appendix A. Template to gather Input from WP UMAN

• Background

The goal of EURAD-UMAN Subtask 4.2 extension is to compile and review information about possible management options for **near-field**-related uncertainties (MS291). Different types of uncertainty in different programme phase are to be addressed.

This is a template for gathering input from WP UMAN participants. As the core group of this Subtask consists of only four organisations, we would appreciate additional input from other UMAN partners, of course on a voluntary basis.

In UMAN Subtask 3.6 a list of near-field-related uncertainties – or fields of uncertainty – was compiled (https://service.projectplace.com/pp/pp.cgi/r31354269). From this list, three uncertainties were selected for focusing in Subtask 4.2. These will be addressed in detail in MS291 and are therefore the basis of this input template (the numbering refers to the grouping in the document linked above):

- **I-C.6: Uncertainty related to hydraulic properties of the bentonite**
- **II-A.1: Uncertainty related to metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different bariers (waste package, liners…)**
- **III-A.5: Uncertainty related to modelling of radionuclide transport: full 4 D description or 1 D or mixed compartment**

You are kindly asked to provide for the 3 uncertainties, where you do have information available in your organisation, information regarding:

- The
    - identification,
    - characterisation and
    - determination of the safety relevance of the uncertainty.
- The way the uncertainty is managed, or is planned to be managed, in relation to its classification.
- How the uncertainty is represented and dealt with in the safety assessment.
- What its relevance is in the current phase of your programme.
- Any other relevant comment or discussion about this uncertainty.

<u>Please do not concentrate on actors' views and preferences but on possible (i.e. available) management options of near-field related uncertainties</u>, based on following information (so a kind of literature review):

- existing documentation (e.g. regulations, guidelines, handbooks, national reports, list of options, cross-mappings, sets of interrelated or interacting elements)
- international initiatives (IAEA, NEA/OECD)
- relevant past and ongoing European R&D projects
- examples of pitfalls

and also

- UMAN Questionnaire 1 (https://service.projectplace.com/pp/pp.cgi/r1848534081)
- the experience of your organisation.

Insert your answers in the white table cells below, deleting the red instructions. Please do not change the grey cells.

Comprehensive answers are appreciated. It is especially interesting to see:

- specific example(s), experience, innovations, references,
- explanation of advantages / disadvantages, potential pitfalls, etc. w.r.t. the above,
- indications on evolution over phases of program, e.g., targeted minimal accuracy of the predictions, and why this accuracy is thought sufficient,
- particularities w.r.t. different actors.

Please add your references at the end of the document.

Answers should be provided by 10 May 2023.

• General information

Name:		**Actual phase:**		
Type of actor:		**Repository type / host rock:**		

• Possible management options for three near-field-related uncertainties

○ Uncertainty related to hydraulic properties of the bentonite

Uncertainty No. **I-C.6**	**Category** Uncertainties on evolution of disposal system & environment	**Description** Uncertainties related to effects of re-saturation and swelling pressure evolution. Bentonite resaturation is assumed to be homogenous to the expected swelling pressure. Maybe, however, preferential flow paths could develop due to inhomogeneous initial conditions, or material properties.
General safety relevance	Bentonite is supposed to provide a (nearly) watertight barrier after swelling. If this is not or not completely the case, or happens slower than expected, there can be considerable water flow towards the waste package and with that increased metal and matrix corrosion, contaminant release and gas production. This can lead to higher radionuclide release from the repository and is therefore safety relevant.	
Identification of the uncertainty	*How is the uncertainty identified and quantified?*	
Characterisation of the uncertainty	*Characterise the uncertainty in view of your disposal programme. Where does it occur? Which components (or "sub-uncertainties") does it comprise? How does it act on the repository system?*	
Concept-specific safety relevance of the uncertainty	*Explain your point of view regarding the safety relevance of the uncertainty in your specific repository concept*.	
Classification	Uncertainty to be ☐ reduced ☐ mitigated ☐ avoided *Explain your choice (multiple possible)*	
Actions[10] **to manage the uncertainty** (according to classification above)	*Which actions are taken or foreseen to manage the uncertainty?*	

[10] Which can be of different nature (technical, managerial, …)

Representation in safety assessments	*How is the uncertainty taken into account in a safety assessment?*
Relevance at your current phase	
General comments	

Uncertainty related to metallic material behaviour in different barriers

Uncertainty No.	**Category**	**Description**
II-A.1	Uncertainties on evolution of disposal system & environment	All uncertainties related to metal corrosion (steel, copper, copper coated steel, composite, super container, …) and canister lifetime. Metal parts are present in waste packages, liners etc. The field of processes comprises geochemistry (pH-, Eh-evolution), corrosion/degradation (including pit corrosion), colloid formation, gas generation and pressure build-up. Uncertainties can come from metal mass, metal composition, surface structure, geochemical conditions, brine composition, flow conditions, temperature, etc.
General safety relevance	Metal corrosion is the most relevant source of gas in a repository. Gas spreads over parts of the system, influences the pressure and can displace brine, moreover it is a transport medium for volatile radionuclides. This can have significant effects to the radionuclide release from the waste form and from the near field.	
Identification of the uncertainty	*How is the uncertainty identified and quantified?*	
Characterisation of the uncertainty	*Characterise the uncertainty in view of your disposal programme. Where does it occur? Which components (or "sub-uncertainties") does it comprise? How does it act on the repository system?*	
Concept-specific safety relevance of the uncertainty	*Explain your point of view regarding the safety relevance of the uncertainty in your specific repository concept*.	
Classification	Uncertainty to be ☐ reduced ☐ mitigated ☐ avoided *Explain your choice (multiple possible)*	

Actions[11] to manage the uncertainty (according to classification above)	*Which actions are taken or foreseen to manage the uncertainty?*
Representation in safety assessments	*How is the uncertainty taken into account in a safety assessment?*
Relevance at your current phase	
General comments	

Uncertainty related to modelling of radionuclide transport: full 4 D description or 1 D or mixed compartment

Uncertainty No.	**Category**	**Description**
III-A.5	Uncertainties on concepts/models, data, tools and methods	Model uncertainties: reliability of concepts and mathematical models – maybe also in extreme situations –, coupling of models, numerical realisation, exactness of numerical results, possibility of program errors, etc. The often-used 1D RN transport modelling/prediction includes a lot of assumptions / uncertainties – would there be a reduction of uncertainties by 4D?
General safety relevance	Models are used to assess the release of contaminants and hazard to future generations. Errors can lead to misassessment, which can be safety-relevant in case of significant underestimation.	
Identification of the uncertainty	*How is the uncertainty identified and quantified?*	
Characterisation of the uncertainty	*Characterise the uncertainty in view of your disposal programme. Where does it occur? Which components (or "sub-uncertainties") does it comprise? How does it act on the repository system?*	
Concept-specific safety relevance of the uncertainty	*Explain your point of view regarding the safety relevance of the uncertainty in your specific repository concept*.	
Classification	Uncertainty to be ☐ reduced ☐ mitigated ☐ avoided *Explain your choice (multiple possible)*	

[11] Which can be of different nature (technical, managerial, …)

Actions[12] to manage the uncertainty (according to classification above)	*Which actions are taken or foreseen to manage the uncertainty?*
Representation in safety assessments	*How is the uncertainty taken into account in a safety assessment?*
Relevance at your current phase	
General comments	

References

Please feel free to add the references used in your assessment.

[1]…

[12] Which can be of different nature (technical, managerial, …)

Appendix B. Agenda of the 5th UMAN Workshop

UMAN Subtask 4.3

Workshop 5: Management options and preferences of different actors regarding near-field uncertainties

Preliminary Agenda

The overall objective of Task 4 of WP UMAN is to identify, for different phases of a disposal programme and the associated decision-making, a bundle of possible options for:

- representing uncertainties associated with specific topics in the safety assessment (e.g. uncertainty propagation methods, scenario development, stylisation approaches etc.),
- avoiding, reducing or mitigating these uncertainties;
- making a safety case robust vis-à-vis these uncertainties.

The views and preferences of different kinds of actors on these possible options are to be identified, considering their roles in the decision-making process. Task 4 offers also a platform for networking on relevant issues regarding uncertainty management as a part of risk and safety management throughout the implementation of a disposal programme. UMAN Subtask 4.3 contributes to these objectives by:

- synthetizing the preferences of the different actors for uncertainties associated with specific topics, based on the outcomes of UMAN Subtasks 3.6, 4.1, 4.2 and 5.1;
- identifying needs for future RD&D, KM or strategic study activities;
- preparing the material needed by Task 5 to interact with a broader group of actors including Civil Society.

The management options for the different types of uncertainties considered in the task and the preferences of different actors as well as the rationale behind them are to be discussed, analysed and described. Five workshops bringing together organizations contributing to Subtask 4.3, one of the expert groups of Subtasks 3.2 to 3.6 (depending on the addressed topic) as well as other interested EURAD partners, are planned. These workshops provide also an opportunity to interact with R&D WPs of EURAD, addressing the same uncertainties and to understand their contribution to the management of these uncertainties.

The goal of this fifth workshop is to foster exchanges and uncover the views of WMOs, TSOs and REs with regard to the management of key uncertainties related to near-field*. In particular, uncertainties associated with the following topics are focused on:

1. **Uncertainty related to hydraulic properties of the bentonite** (related to the effects of re-saturation and swelling pressure evolution)

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Bentonite is supposed to provide a (nearly) watertight barrier after swelling. If this is not or not completely the case, or happens slower than expected, there can be considerable water flow towards the waste package and with that increased metal and matrix corrosion, contaminant release and gas production. Bentonite resaturation is considered to be homogenous, to the expected swelling pressure, but preferential flow paths could also develop. This can lead to higher radionuclide release from the repository and is therefore safety relevant. Uncertainty regarding hydraulic properties of the bentonite is also one of the uncertainties considered in part I "Uncertainties associated with the processes governing or altering radionuclide migration and the performance of disposal system components", sub-part C "Uncertainties associated with flow properties through barriers" in the Questionnaire on Near-Field Uncertainties by UMAN Subtask 3.6.

2. **Uncertainty related to metallic material behaviour** (steel, copper, copper coated steel, composite, super container etc.) in different barriers (waste package, liners etc.)
   Metal corrosion is the most relevant source of gas in a repository. Gas spreads over parts of the system, influences the pressure (pressure build-up) and can displace brine, influences pH-, Eh-evolution, pit corrosion, colloid formation (continuous or step functions?) and other degradation processes, moreover it is a transport medium for volatile radionuclides. This can have significant effects to the radionuclide release from the waste form and from the near field and lifetime of storage/disposal packaging set.
   It is one of the uncertainties considered in part II "Uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers", subpart A in the Questionnaire on Near-Field Uncertainties by UMAN Subtask 3.6.

3. **Uncertainty related to modelling of radionuclide transport:** full 4 D description or 1 D or mixed compartment (considered as uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems)
   Models are used to assess the release of contaminants and hazard to future generations. Errors can lead to misassessment, which can be safety-relevant in case of significant underestimation. The often used 1D RN transport modelling/prediction includes a lot of assumptions / uncertainties – would there be a reduction of uncertainties by using 4D modelling? Direct comparison is difficult to perform because of long computational times in the case of 4D modelling. Confirmation of simplification - How big is the uncertainty associated with this?
   It is one of the uncertainties considered in part III "Uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems", subpart A in the Questionnaire on Near-Field Uncertainties by UMAN Subtask 3.6.

* Starting with the waste/waste matrix and surrounding waste container, the near-field is the third technical barrier for radionuclides before they may enter the natural barrier, which is the host rock. The near-field is the area with the largest material heterogeneity (metal, bentonite, clay or crystalline rock and concrete). There are the largest temperature, hydraulic and stress gradients (related to the materials properties), and also the largest chemical gradients between different pore water compositions (e.g., cement – clay). Therefore, a complex evolution of the near-field has to be expected, which needs to keep its barrier functionality for radionuclides in the very long term". (Questionnaire on Near-Field Uncertainties by UMAN Subtask 3.6)

These uncertainties were identified as safety significant by respondents to the questionnaire prepared by Task 3 of UMAN on near-field uncertainties and by the Expert Group based on available information from national programmes and international initiatives (IAEA, NEA/OECD etc.), and relevant past and ongoing European RD&D projects (e.g. ACED, GAS and HITEC as well as ConCorD and MAGIC). They belong to the different categories of uncertainties identified in UMAN (i.e. programme

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uncertainties, uncertainties associated with initial characteristics, uncertainties in the evolution of the disposal system & its environment and uncertainties associated with data, tools & methods used in the safety case)
Therefore, they were selected as key topics for the work performed in Task 4 of UMAN dedicated to uncertainty management options and preferences of different actors across the various programme phases. The workshop will also allow checking the completeness of the management options identified in Subtask 4.2.

The workshop will take place in several stages:

Workshop Day 1
Kick-off, scope and goals of the workshop. Explanation of the work to be done by the participants between Day 1 and Day 2 in preparation of Day 2 click here to join the meeting
Workshop Day 2
Actor groups WMO, TSO and RE discuss possible management options and their preferences click here to join the meeting
Workshop Day 3
Presentation from each actor group, discussion on differences and commonalities between the different groups of actors click here to join the meeting

The participants will be asked to do some work on their views of the different topics between Day 1 and Day 2 of the workshop. These views will be presented and discussed during one of the parallel sessions dedicated to the three actor groups on Day 2 of the workshop.

The workshop is going to be held online. This will be done in **MS Teams sessions** for every day. Invitations to these sessions will follow.

We would like to pay your attention to other materials related to near-field, developed in EURAD:

- MS252: SOTA from RD&D CONCORD WP as input to UMAN Subtask 3.6 (available here)
- MS262: SOTA from RD&D MAGIC WP as input to UMAN Subtask 3.6 (available here)
- MS282: UMAN Draft D10.18 as input to workshop and Tasks 4 and 5 (available here)

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Workshop Day 1
Date: May 17, 2023
Introduction and goals of the workshop

13:00 **Welcome of participants**

13:10 **General introduction to UMAN & types of uncertainties** – *Daniela Diaconu (RATEN)*

13:30 **UMAN Task 4 objectives & approach –** *Agnieszka Strusińska-Correia (BGE)*

13:50 **Discussion and questions**

14:05 **Selection of the key uncertainties related to near-field** – *Wilfried Pfingsten (PSI)*

14:30 Break

14:45 **Options for near-field uncertainties management** – *Dirk-Alexander Becker (GRS)*

15:10 **Evolution of appreciation of near-field uncertainties and their management –** Thermo-hydro-mechanical properties of the bentonite and related uncertainties *(What we don't know and how will WP HITEC and BEACON help) – Jiří Svoboda (CTU in Prague)*

15:30 **Discussion and questions**

15:45 **Expected input from workshop participants + explanation of the homework in preparation of Day 2**

16:00 **Discussion and questions**

16:15 *End of Day 1*

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Workshop Day 2
Date: June 5, 2023
Presentations of participants input

9:00 **Welcome and introduction to workshop Day 2**

9:15 *Three parallel sessions for WMOs, TSOs and REs*

9:25 **Participants homework (Presentations and discussions)**

10:10 *Break*

10:25 **Participants homework (Presentations and discussions) - continuation**

11:40 **Discussions and synthesis**

12:10 *End of parallel sessions*

12:15 **Closing of workshop Day 2**

12:30 *End of Day 2*

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Workshop Day 3
Day: June 29, 2023
Synthesis of participants input

9:00 **Introduction to workshop Day 3**

9:05 **Objectives of the workshop** – *Jitka Mikšová (SURO)*

Topic 1: Uncertainty related to metallic material behaviour (steel, copper, copper coated steel, composite, super container etc.) in different barriers (waste package, liners etc.)
9:10 TSO synthesis on Topic 1
9:25 RE on Topic 1
9:40 WMO synthesis on Topic 1

9:55 Discussion of the results of Topic 1

10:15 *Break*

Topic 2: Uncertainty related to hydraulic properties of the bentonite (the latter related to the effects of re-saturation and swelling pressure evolution)
10:30 TSO synthesis on Topic 2
10:45 RE synthesis on Topic 2
11:00 WMO synthesis on Topic 2

11:15 Discussion of the results of Topic 2

Topic 3: Uncertainty related to modelling of radionuclide transport: full 4 D description or 1 D or mixed compartment (considered as uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems)
11:35 TSO synthesis on Topic 3
11:50 RE synthesis on Topic 3
12:05 WMO synthesis on Topic 3

12:20 Discussion of the results of Topic 3

12:40 Concluding remarks on the outcome of the workshop – *Daniela Diaconu (RATEN)*

12:55 Closing of workshop Day 3

13:00 *End of Day 3*

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Appendix C. Homework template

- **Topic 1: Uncertainty related to hydraulic properties of the bentonite** (related to the effects of re-saturation and swelling pressure evolution)

- **Your view on the safety significance of this uncertainty**
- What is the safety significance of this uncertainty in the view of your organization as TSO, RE or WMO?
- How do you expect the safety significance to evolve over time (over the six phases of a disposal programme considered in the EURAD Roadmap)?
- If you have already answered these questions in the UMAN Task 3 questionnaire, feel free to reuse your answer.
- Your answers.
- Your answers.

- **Topic 1: Hydraulic properties of the bentonite** (related to the effects of re-saturation and swelling pressure evolution)

- **Preferred management strategy**
- What is your preference regarding the treatment of the uncertainty in the context of the different elements of the strategy (e.g. analysis of safety relevance; representation and evaluation in safety assessment; actions to reduce, mitigate or avoid the uncertainty; general management principles)?
- Please substantiate your answer with references and examples. Of particular interest would be examples of pitfalls encountered and lessons learned.
- Your answers.
- Your answers.

- **Topic 1: Hydraulic properties of the bentonite** (related to the effects of re-saturation and swelling pressure evolution)

- **Other identified strategies**
- Please also provide references and examples
- **Points of disagreement with material from Subtask 4.2**
- Please also provide references and examples
- Your answers.
- Your answers.

- **Topic 1: Hydraulic properties of the bentonite** (related to the effects of re-saturation and swelling pressure evolution)

- **Identified future EURAD activities**
- Do you identify needs for future EURAD activities addressing the management of this uncertainty? If yes, please explain which types of activities would be of interest to your organization (R&D, knowledge management or strategic study activities).
- Your answers.

- Your answers.

Appendix D. Tabular summary of identified joint activities and initiatives

List of future joint activities and initiatives (research and development R&D, strategic studies StSt, knowledge management KM, not specified NS) identified in the 5th UMAN Workshop dedicated to management options and preferences of different actors regarding near-field uncertainties

Uncertainty related to	No.	Ideas for future joint activities and initiatives	Actor	Activity type
Hydraulic properties of the bentonite	1.1	EURAD-2: Technical WPs should provide output regarding uncertainties. Uncertainty questionnaires could also be resolved with technical WPs. Count on this activity already in the financial proposal for technical WP. Have uncertainties as part of the WP output.	WMO	NS
	1.2	Providing conservative conclusions for properties of bentonite.	WMO	NS
	1.3	Experimental data from re-saturation and swelling pressure evaluation.	TSO	R&D
	1.4	EURAD-2: Bentonite WP under development • THMC coupling approaches • High interest for large scale experiments to complete the BEACON project	TSO	R&D
	1.5	EURAD-2: Strategic Study OPTI-HLW • Civil Society involvement to understand the general conditions for closure (technical and societal aspects)	TSO	StSt
	1.6	Uncertainty analysis with respect to experimental data and their safety relevance	TSO	R&D
	1.7	BEACON follow-up: include geochemistry	RE	R&D
Metallic material behaviour in different barriers,	2.1	EURAD-2: Technical WPs should provide output regarding uncertainties. Uncertainty questionnaires could also be resolved with technical WPs. Count on this activity already in the financial proposal for technical WP. Have uncertainties as part of the WP output.	WMO	NS
	2.2	EURAD-2: Innovative and new Container/canister materials under disposal field conditions: Manufacturing feasibility and improved Durability	WMO	R&D
	2.3	Investigation of alternative materials	TSO	R&D
	2.4	Modelling of canister corrosion, corrosion of non-porous materials (electrochemical vs geochemical, moving boundaries, effect of corrosion products on near-field geochemistry/clogging etc…)	TSO, RE	R&D
	2.5	Investigation of mechanical material properties	TSO	R&D
	2.6	Understanding of stress corrosion cracking	TSO	R&D
	2.7	Investigation of canister performance in the long term (life-time, corrosion, strength resistance, radiation resistance, heat resistance, process interaction)	TSO	R&D
	2.8	Improvement of understanding of interface processes including experiments related to geochemical and microbial influences on degradation/corrosion products/speed and related modelling	RE	R&D
Modelling of radionuclide transport.	3.1	Exchanges on the substantiation that models used in the safety assessments are fit for their purpose, considering the viewpoint and expectations of different actors (regulators, civil society, REs,…) and on how to reach a common understanding of model purposes and the meaning/significance of modelling results in the context of the safety case.	WMO	NS
	3.2	EURAD-2 proposal: Radionuclide mobility under perturbated conditions	WMO	R&D
	3.3	Mechanistic description of chemical and physical perturbations on RN behaviour	TSO	R&D
	3.4	Proposal of parallel calculation models that could be used for special processes evaluation (robust, special – e. g. THMC, short term, long term), and for use in validation tasks	TSO	NS
	3.5	Improved/up-to-date modelling and experiments and virtual repository twins	RE	StSt