Deliverable 10.12: UMAN - Preferences of different actors on uncertainty management

Work Package 10

Uncertainty Management multi-Actor Network (UMAN)

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Executive Summary

This report[1] presents the work of Subtask 4.3 of the strategic study "Uncertainty Management multi-Actor Network" (UMAN), initiated in the framework of the European Joint Programme on Radioactive Waste Management (EURAD). The context is Radioactive Waste Management (RWM) programmes for near-surface and geological disposal of radioactive waste. The Work Package (WP) UMAN is focused predominantly on developing a common understanding among the different actors involved on strategies and approaches for uncertainties management by sharing knowledge and experience. These actors are Waste Management Organisations (WMOs), Technical Safety Organisations (TSOs), and Research Entities (REs) but also Civil Society (CS).

Within Subtask 4.3 five workshops have been organised in particular to identify preferences of the participating actors´ groups with respect to the uncertainty management strategies and options as well as the resulting similarities, differences and the rationale behind them. These aspects were discussed for selected examples of uncertainties related to five uncertainties types considered in WP UMAN, i.e. uncertainties related to site and geosphere, human aspects, spent nuclear fuel, waste inventory and near-field. However, the results of the workshop regarding the near-field uncertainties are however not under the scope of this report and are provided in Becker et al. (2024). The outcome of Subtask 4.3 served also as an input for the pluralistic dialogue carried out in Task 5 as part of the UMAN seminars, in which the uncertainty management aspects were discussed in a larger group of actors, including CS, regulators, representatives of international organisations and other uncertainty-specific invited actors in addition to WMOs, TSOs and REs.

In each workshop the preferred management strategies and options were discussed for several concrete uncertainty examples (termed as “topical uncertainties”), which belong to the uncertainty types considered in WP UMAN as mentioned above. These topical uncertainties were as follows:

- **uncertainties related to site and geosphere** (focus of the 1st UMAN Workshop):
  - hydraulic conductivity of the host rock (and other geological units),
  - sorption capacity of the host rock (and other geological units),
  - homogeneities of the host rock (and other geological units),
  - fault locations, detection and reactivation,
  - climatic evolution (focus on glaciations and permafrost),
- **uncertainties related to human aspects** (focus of the 2nd UMAN Workshop):
  - public acceptance of the repository at potentially suitable or projected locations,
  - schedule to be considered for implementing the different phases of the disposal programme,
  - adequacy of safety-related activities during construction for the implementation of safety provisions,
  - “new” knowledge,
- **uncertainties related to spent nuclear fuel (SNF)** (focus of the 3rd UMAN Workshop):
  - fuel history data, reactor operation and irradiation conditions,
  - nuclear data,
  - performance of spent nuclear fuel during (dry) interim storage,
- **uncertainties related to waste inventory** (focus of the 4th UMAN Workshop):
  - physico-chemical conditions in the storage or disposal facility,
  - radionuclide activity (including the scaling factor),
  - chemical composition (with a special attention to organic content).

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

The participants of the UMAN workshops were predominantly the organisations involved in WP UMAN, contributing to Tasks 3 (Characterisation and significance of uncertainties for different categories of actors) and 4 (Uncertainty management options and preferences of different actors across various programme phases). These organisations belong to the three EURAD actor groups and represent EU Member States with different national disposal programmes in different implementation phases. In addition to these actors, a representative of CS from UMAN Task 5 took part in the workshops as an observer for the purposes of a preparation of the UMAN seminars. In case of existing thematic overlapping, EURAD WPs of RD&D character, representatives of past European R&D projects and international organisations outside EURAD were also invited to the workshops in order to foster interaction and to gain a different perspective on the topical uncertainties and their management.

To reach the workshops purpose, the participants were assigned to three discussion groups according to their responsibilities, roles and interest in RWM programme. These three discussion groups corresponded to the three above mentioned actors´ groups involved in EURAD. Each workshop consisted of three, half-day sessions. In order to facilitate the discussions on the preferred uncertainty management strategies and options in the three actors’ groups, specific questions were prepared in advance in so called “homework templates”, circulated among the workshop participants.

The workshops started with an introductory session (i.e. Day 1) followed by a discussion in the three actors groups based on the individual responses to the homework templates in session 2 (i.e. Day 2). Finally, the results of the discussions in session 2 were presented by a rapporteur in session 3 (i.e. Day 3), which forms the basis for this report.

Hence, the present report synthetises the first four workshops with focus on the views of the actor’s groups on safety significance of the topical uncertainties and its evolution over the programme phases, preferred uncertainty management options and strategies, potential future joint activities and initiatives, including research and development, strategic studies and knowledge management.

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Abbreviation List

BAT	“Best available technology” principle
BEACON	European research project “Bentonite Mechanical Evolution”
BWR	Boiling water reactor
CS	Civil Society
COWAM	Community Waste Management
DHC	Delayed-hydride cracking
DiD	Defence-in-depth principle
DGR	Deep geological repository
DT	Design target
DTM	Difficult-to-measure
EBS	Engineering barrier system
ECZ	Effective containment zone
EDZ	Excavation damaged zone
EGOS	Expert Group on Operational Safety
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
EURATOM	European Atomic Energy Community
FEPs	Features, Events and Processes
FUTURE	EURAD Work Package “Fundamental understanding of radionuclide retention”
G	Guidance
GAS	EURAD Work Package “Mechanistic understanding of gas transport in clay materials”
GDF	Geological Disposal Facility
GEOSAF II	Second phase of an International Intercomparison and Harmonisation Project “Demonstrating the safety of geological disposal”, initiated by the International Atomic Energy Agency (IAEA)
HazID	Hazard Identification tool
HIDRA	IAEA project “Human Intrusion in the Context of Disposal of Radioactive Waste”
HITEC	EURAD Work Package “Influence of temperature on clay-based material behaviour”
HLW	High level waste
i.a.	among others
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IRF	Instant Release Fraction
IMS	Integrated Management System
KM	Knowledge Management

LLW	Low level waste
MICADO	European research project “Model Uncertainty for the Mechanism of Dissolution of Spent Fuel in a Nuclear Waste Repository”
MS	Milestone document
NPP	Nuclear power plant
NS	Not specified
PA	Performance assessment
PREDIS	EU project “Pre-disposal management of radioactive waste”
QA	Quality Assurance
QC	Quality Control
R&D	Research and Development
RD&D	Research, Development and Demonstration
RE	Research Entity
RWM	Radioactive Waste Management
SA	Safety assessment
SC	Sorption capacity
SE	Safety envelope
SFC	EURAD Work Package “Spent fuel characterisation and evolution until disposal”
SITEX	Sustainable Network for Independent Technical Expertise on Radioactive Waste Management
SNF	Spent nuclear fuel
SoK	State of Knowledge
SCC	Stress-corrosion-cracking
SOTA	State of the art report
SSH	Social Science and Humanities
StSt	Strategic Study
TRL	Technology Readiness Level
TSO	Technical Safety Organisation
UMAN	EURAD Work Package “Uncertainty Management multi-Actor Network”
WAC	Waste Acceptance Criteria
WMO	Waste Management Organisation
WP	Work Package
w.r.t.	With respect to

1. Introduction

1.1 Background

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) along the programme and its stages. It 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 national RWM programmes, 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 relevant 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 views and preferences of three actors´ groups (namely WMOs, TSOs and REs) on uncertainty management options 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,
- making a safety case robust vis-à-vis these uncertainties.

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.

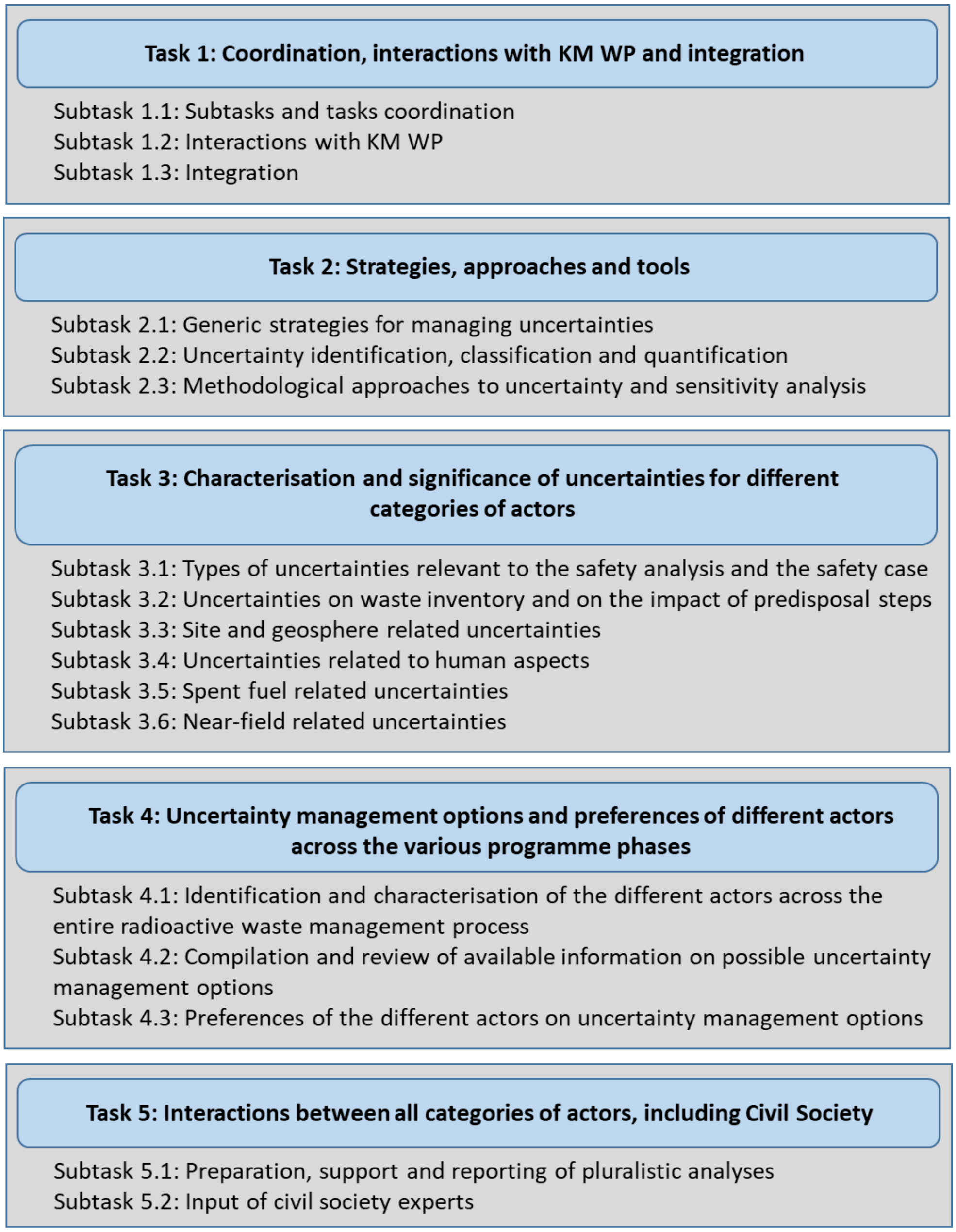

Figure 1 – Structure of WP UMAN

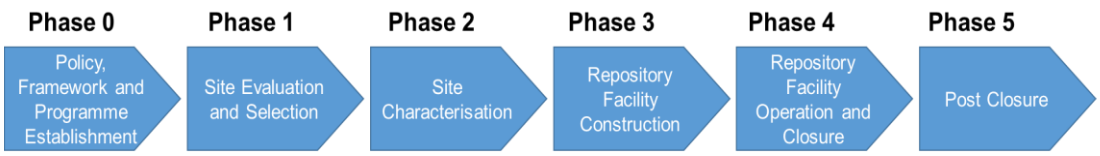

Figure 2 – Phases of a Radioactive Waste Management programme (RWM) referring to the EURAD Roadmap

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.

The present report was prepared with the aim of presenting and discussing the results of the UMAN workshops, which represented the core activities of this subtask.

1.2 Objectives

This report provides a summary of the outcomes of the UMAN workshops organised by Subtask 4.3, 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. Further, the future joint activities and initiatives (of a character of research and development R&D, strategic studies StSt and knowledge management KM), identified by the different actors´ groups, are also provided in this report.

These above mentioned aspects are discussed for selected examples (termed topical uncertainties) of uncertainties related to five uncertainties types considered in WP UMAN, i.e. uncertainties related to site and geosphere, human aspects, spent nuclear fuel, waste inventory and near-field, following the five UMAN workshops, each dedicated to one of the above-mentioned uncertainty type. The management aspects of uncertainties associated with near-field are however not the scope of this report and are provided in Becker et al. (2024).

The outcome of Subtask 4.3 served also as an input for Task 5 organising UMAN seminars, in which the uncertainty management aspects were discussed pluralistically, in a larger group of actors, including CS, regulators and other uncertainty-specific invited actors in addition to WMOs, TSOs and REs.

1.3 Scope and approach

As elucidated in Sections 1.1 and 1.2, this report summarises the results of the first four UMAN workshops, which were organised by Subtask 4.3. The main objective of the workshops was to foster exchange and uncover views of the different participating actors´ groups with regard to uncertainty management. These actors included WMOs, TSOs and REs, which represented organisations contributing to WP UMAN as well as, depending on the considered topic, other interested EURAD partners from other WPs and organisations outside EURAD. A more detailed description of the objectives of the UMAN workshops is provided in Chapter 2.

The uncertainties considered in this report represent the following four of the five uncertainties types addressed in WP UMAN, whose management aspects were discussed separately in the dedicated four UMAN workshops:

- **uncertainties related to site and geosphere**, representing the scope of the **1st UMAN Workshop** and including the following selected topical uncertainties: hydraulic conductivity of the host rock (and other geological units); sorption capacity of the host rock (and other geological units); homogeneities of the host rock (and other geological units); fault locations, detection and reactivation; climatic evolution (focus on glaciations and permafrost),
- **uncertainties related to human aspects**, representing the scope of the **2nd UMAN Workshop** and including the following selected topical uncertainties: public acceptance of the repository at potentially suitable or projected locations; schedule to be considered for implementing the different phases of the disposal programme; adequacy of safety-related activities during construction for the implementation of safety provisions; “new” knowledge,
- **uncertainties related to spent nuclear fuel**, representing the scope of the **3rd UMAN Workshop** and including the following selected topical uncertainties: fuel history data, reactor operation and irradiation conditions; nuclear data; performance of spent nuclear fuel during (dry) interim storage,

- **uncertainties related to waste inventory**, representing the scope of the **4th UMAN Workshop** and including the following selected topical uncertainties: physico-chemical conditions in the storage or disposal facility; radionuclide activity (including the scaling factor); chemical composition (with a special attention to organic content).

Details on the uncertainties selection and their classification adopted are provided in Chapter 2.

Further, different types of radioactive waste and their disposal solutions in different host rocks (rock salt, claystone and crystalline rock) were considered in the first four UMAN workshops, reflecting the specificities of the national programmes represented by the participating organisations.

This report presents and summarises several selected aspects discussed in the framework of the UMAN workshops. The main scope of this report is to identify the preferences of the different actors´ groups with respect to the management of the above-mentioned topical uncertainties and to analyse them in terms of similarities, differences and the possible reasons for them. A detailed description of the views on these aspects within each actors´ group is not the scope of this report. Further, the views on safety significance of the topical uncertainties and its expected evolution over the programme phases are compared in a similar manner, i.e. among the three actors´ groups. 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. It 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 basis for this report are generally 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 homeworks) submitted by the participating organisation as well as oral statements made in the direct discussions within the actors´ groups. More details on the workshops´ organisational issues are provided in Chapter 2.

1.4 Report structure

This report describes the outcomes of the first four workshops organised by Subtask 4.3 in the framework of the WP UMAN.

Chapter 1 provides first a general description of the WP UMAN and the UMAN Subtask 4.3, responsible for the organisation of the workshops. The objectives of this report are described whereafter in more details together with the report scope and the adopted approach. Finally, the structure of this report is presented.

In Chapter 2 the overall objectives of the UMAN workshops are elucidated as well as the uncertainties addressed in the workshops, organisational issues and the overall adopted methodology.

Chapters 3 to 6 provide a synthesis of the first four UMAN workshops.

The summary and conclusions, based on the outcomes of these four UMAN workshops, are provided in Chapter 7.

2. UMAN workshops

2.1 Overall objectives of the UMAN workshops

Workshops organised by UMAN Subtask 4.3 served as an exchange and discussion platform on the different uncertainty management strategies and options, applied by the various actors involved in RWM and participating in WP UMAN, representing 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 1). This report is however focused on the first four workshops and the corresponding uncertainties; the outcome of the 5th UMAN Workshop, dedicated to the preferred management options for near-field related uncertainties, is provided in Becker et al. (2024).

Table 1 - 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

* Not scope of this report. Outcome of the 5th UMAN Workshop is presented in Becker et al. (2024)

In the first four UMAN workshops different waste types, host rocks covering claystone, crystalline rock and rock salt, resulting in different safety concepts and repository design, as well as different disposal types were considered. With respect to the latter the main focus was however on deep geological disposal.

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. An attempt was made to explain the rationale behind the differences identified 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 identified and collected 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 (shown in Table 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.

In addition, the workshops fostered the interactions with RD&D WPs initiated in the EURAD, WP "*Fundamental understanding of radionuclide retention*" (FUTURE) and WP "*Spent fuel characterisation and evolution until disposal*" (SFC), as well as with organisations outside the EURAD, e.g. with the International Atomic Energy Agency (IAEA).

Table 2 - Overview of input from UMAN Task 3 and Subtask 4.2, required for preparation of the UMAN workshops.

Uncertainty related to	**Input material from individual subtasks of Task 3**		**Material from Subtask 4.2**
Site and geosphere	Subtask 3.3	MS22: UMAN Preliminary list of uncertainties from UMAN from UMAN Subtask 3.3 to Subtask 4.2 MS76: UMAN Draft D10.7 as input to Tasks 4 and 5 Diaconu et al. (2023)	MS89: UMAN Compiled and reviewed information about possible management options for site and geosphere related uncertainties as input to Subtask 4.3 Kaempfer et al. (2023)
Human aspects	Subtask 3.4	MS23: UMAN Preliminary list of uncertainties from UMAN Subtask 3.4 as input to Subtask 4.2 MS101: UMAN Draft D10.8 as input to Tasks 4 and 5 Dumont et al. (2023)	MS113: UMAN Compiled and reviewed information about possible management options for uncertainties related to human aspects as input to Subtask 4.3 Kaempfer et al. (2023)
Spent nuclear fuel	Subtask 3.5	MS54: UMAN Preliminary list of uncertainties from UMAN Subtask 3.5 as input to Subtask 4.2 MS111: UMAN Draft D10.9 as input to Tasks 4 and 5 Detilleux et al. (2024)	MS118: UMAN Compiled and reviewed information about possible management options for uncertainties related to spent fuel as input to Subtask 4.3 Kaempfer et al. (2023)
Waste inventory	Subtask 3.2	MS92: UMAN Preliminary list of uncertainties from UMAN Subtask 3.2 as input to Subtask 4.2 MS143: UMAN Draft D10.6 as input to Tasks 4 and 5 Bielen et al. (2023)	MS145: UMAN Compiled and reviewed information about possible management options for uncertainties related to waste inventory as input to Subtask 4.3 Kaempfer et al. (2023)

2.2 Overview of the addressed uncertainties and their classification

The preferred management strategies and options were discussed for several concrete uncertainty examples (termed hereafter "topical uncertainties"), which belong to the uncertainty types considered in WP UMAN, namely uncertainties related to site and geosphere, human aspects, spent nuclear fuel and waste inventory (note that those related to near-field are out of the scope of this report). These topical uncertainties were as follows:

- **uncertainties related to site and geosphere** (focus of the 1st UMAN Workshop):
  - hydraulic conductivity of the host rock (and other geological units),
  - sorption capacity of the host rock (and other geological units),
  - homogeneities of the host rock (and other geological units),
  - fault locations, detection and reactivation,

  - climatic evolution (focus on glaciations and permafrost),
- **uncertainties related to human aspects** (focus of the 2nd UMAN Workshop):
  - public acceptance of the repository at potentially suitable or projected locations,
  - schedule to be considered for implementing the different phases of the disposal programme,
  - adequacy of safety-related activities during construction for the implementation of safety provisions,
  - “new” knowledge,
- **uncertainties related to spent nuclear fuel (SNF)** (focus of the 3rd UMAN Workshop):
  - fuel history data, reactor operation and irradiation conditions,
  - nuclear data,
  - performance of spent nuclear fuel during (dry) interim storage,
- **uncertainties related to waste inventory** (focus of the 4th UMAN Workshop):
  - physico-chemical conditions in the storage or disposal facility,
  - radionuclide activity (including the scaling factor),
  - chemical composition (with a special attention to organic content).

These topical uncertainties were selected from lists of uncertainties potentially significant for safety, considering the outcomes of the 2nd UMAN Questionnaire provided by the corresponding documents from Task 3 (i.e. unpublished milestone documents for internal use and published deliverables, shown in Table 2).

Several criteria were considered when selecting the topical uncertainties. The topical uncertainties were those whose significance for disposal safety was rated as “high” by the respondents to the 2nd UMAN Questionnaire (i.e. WMOs, TSOs and REs). Details of this analysis are presented separately for each uncertainty type in the corresponding deliverables from Task 3, listed in Table 2.

Further, where appropriate, an attempt was made to select topical uncertainties to represent different categories of uncertainties according to matrix developed in WP UMAN (see Figure 3). This matrix was intensively used especially in case of the 2nd UMAN workshop, focused on uncertainties associated with human aspects.

The uncertainties matrix combines two different uncertainty classification schemes. The first classification scheme represents generic types of uncertainties relevant for safety as identified by actors WMOs, TSOs and REs through the 1st UMAN Questionnaire developed by Subtask 3.1 (Grambow, 2023). This scheme covers following five categories of uncertainties, shown also in Figure 4:

- programme uncertainties, associated with the RWM programme and other prevailing circumstances (societal, resources, etc.),
- uncertainties associated with the initial characteristics of the disposal system and its environment (e.g. waste, site, engineered components),
- uncertainties associated with 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 SNF) 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.

	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 3 – Uncertainties matrix developed in WP UMAN

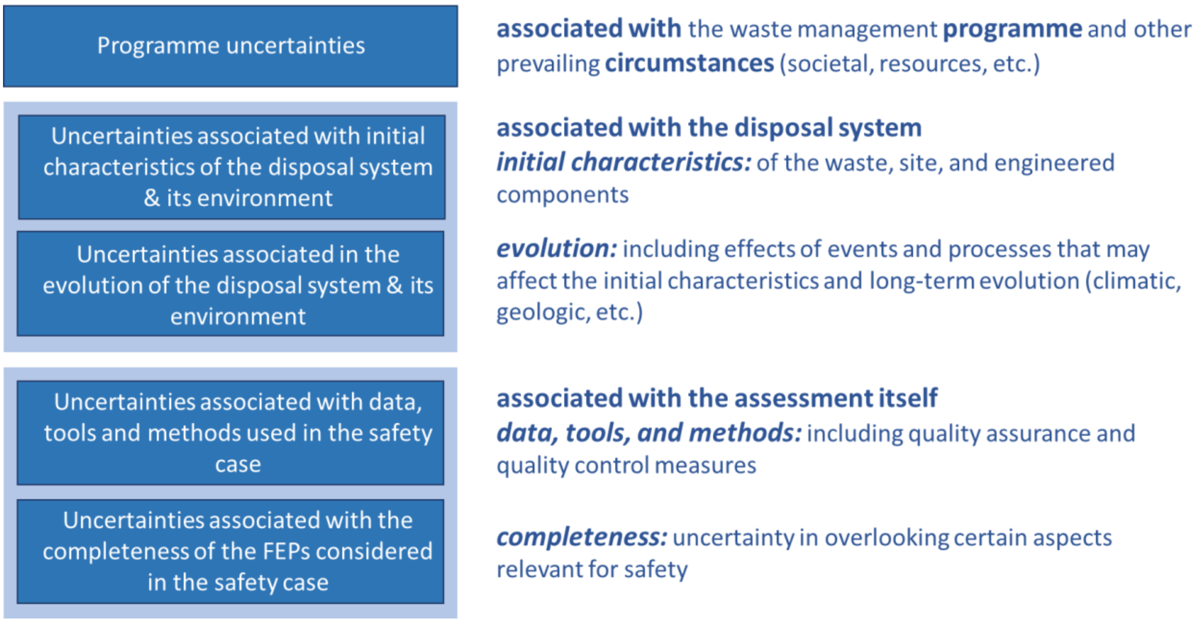

Figure 4 – Generic uncertainties identified in WP UMAN, representing also the first level of the multi-level uncertainty classification scheme depicted in Figure 5

The above mentioned generic categories/groups of uncertainties represent the first level of a multi-level uncertainty scheme depicted in Figure 5. The different uncertainties types considered in WP UMAN (i.e. uncertainties related to site and geosphere, human aspects, spent nuclear fuel and waste inventory) represent indirectly the second classification level of this scheme. The last level of this classification scheme is represented by uncertainties that were identified by Subtasks 3.2 – 3.5 as potentially significant for disposal safety, based on analysis of responses to the 2nd UMAN Questionnaire (Bielen et al., 2023; Diaconu et al., 2023; Dumont et al., 2023 and Detillieux et al., 2024). They include the topical uncertainties selected for the purposes of the UMAN workshops, schematically illustrated in Figure 5. For the purposes of a clarity of the multi-level classification scheme depicted in Figure 5, the assignment of the topical uncertainties to the second and the first level of the three-level uncertainty classification scheme is shown graphically in Figures 9, 10, 11 and 12 in Sections 3.1, 4.1, 5.1 and 6.1, separately for each of the considered uncertainty type. Further, a simplified assignment of the topical uncertainties, solely to the first level of the multi-level uncertainty classification scheme, is provided in Table 3.

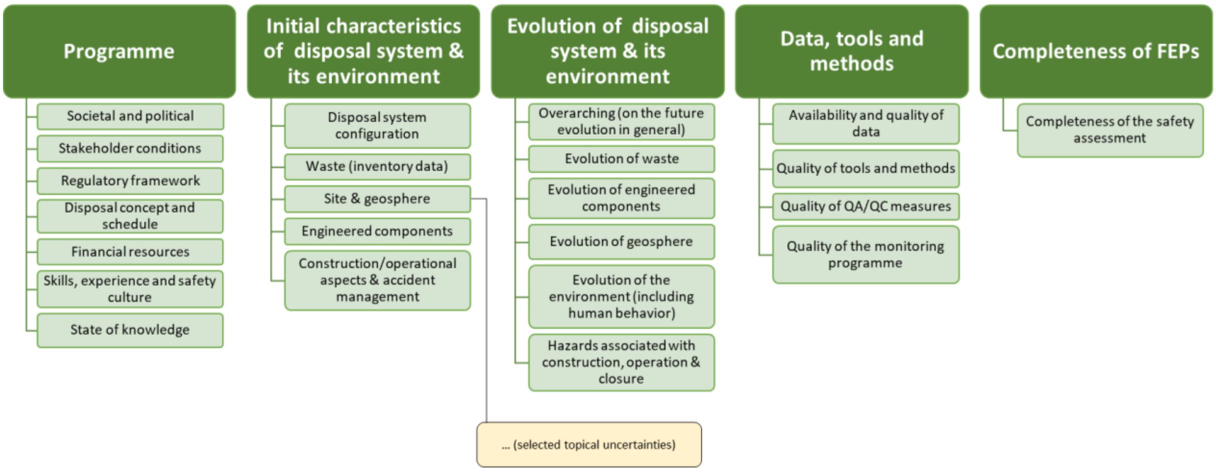

Figure 5 – Multi-level uncertainty classification scheme developed in WP UMAN. Note that the last level, representing the topical uncertainties selected for the discussion in UMAN workshops, is shown schematically for uncertainties related to site and geosphere.

The second uncertainty classification scheme constituting the uncertainty matrix, presented in Figure 6, categorises uncertainties with respect to availability and use of knowledge into:

- 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.

Similarly to the previous uncertainty classification scheme, an attempt was made (if applicable) to select topical uncertainties representing these three different uncertainty categories.

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

For the purposes of work consistency in Task 4, the same topical uncertainties were generally considered by Subtask 4.2 (which provided an overview of possible uncertainty management options, required for preparation of the UMAN workshops) and by Subtask 4.3 (responsible for organisation of the UMAN workshops). One exception was made in case of topical uncertainty “Performance of spent nuclear fuel during final disposal (e.g., radionuclides critical in safety assessment, radionuclides contributing to fast/instant release)” related to spent nuclear fuel. This topical uncertainty was considered solely by Subtask 4.2 upon suggestions made at the 3rd UMAN Workshop to shift the discussion focus from pre-disposal to disposal aspects.

Table 3 - Assignment of the topical uncertainties 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 site and geosphere					
Hydraulic conductivity		×			
Sorption capacity		×		×	
Heterogeneities		×		×	
Fault		×	×		
Climatic evolution			×		×
Uncertainties related to human aspects					
Public acceptance	×				
Schedule	×				
Adequacy of safety-related activities during construction		×			
"New" knowledge			×		
Uncertainties related to spent nuclear fuel					
Fuel history data		×	×		
Nuclear data				×	
Performance of spent nuclear fuel during (dry) interim storage			×	× (grey)	
Uncertainties related to waste inventory					
Physico-chemical conditions			×		
Radionuclide activity		×			
Chemical composition		×			

2.3 Workshops´ organisation and adopted approaches

The participants of the UMAN workshops were predominantly the organisations involved in WP UMAN, contributing to Tasks 3 and 4. These organisations belong to the three EURAD actor groups (i.e. WMOs, TSOs and REs) and represent EU Member States with different national disposal programmes (i.e. national regulations, waste types, host rock(s), repository types, safety concept) in different implementation phases. In addition to these actors, a representative of CS from UMAN Task 5 took part in the workshops as an observer for the purposes of a preparation of the UMAN seminars. In case of existing thematic overlapping, EURAD WPs of RD&D character, representatives of past European R&D projects and international organisations outside EURAD were also invited to the workshops in order to foster interaction and gain a different perspective on the topical uncertainties and their management.

To reach the workshops purpose, the participants were assigned to three discussion groups according to their responsibilities, roles and interest in RWM programme. In this manner it was expected to affect the preferred uncertainty management options in addition to the different frameworks of the national disposal programmes. These three discussion groups corresponded to the three actors groups involved in the EURAD, namely WMOs, TSOs and REs.

Each workshop consisted of three, half-day sessions (see also Table 1):

- Session 1 (i.e. Day 1): an introductory session, providing the workshop participants with the information necessary for a successful participation in workshop Session 2 (such as workshop goal, selection process of the topical uncertainties, possible management options identified by Subtask 4.2, explanation of homework template to be answered as a preparation for Session 2);
- Session 2 (i.e. Day 2): discussions of preferred management strategies and options for the selected topical uncertainties in three actors groups (i.e. WMOs, TSOs and REs), based on individual responses to the homework templates;
- Session 3 (i.e. Day 3): presentation of the results from the discussions in Session 2 for each actors group as well as identification of similarities and differences (including rationale behind them) among the actors groups.

Detailed agendas of the first four UMAN workshops are provided in Appendices A1 – A4, respectively.

The number of submitted homeworks as well as the factual number of participating organisations in the Sessions 2 of the first four UMAN workshops, are provided in Table 4. The targeted number of participating organisations in the WMOs group were 5, in the TSOs group 3 and in the REs group 3.

Table 4 - Number of submitted homeworks and factual number of participants in Sessions 2 of the first four UMAN workshops

Workshop	Uncertainty related to	WMOs	TSOs	REs
Workshop 1	Site and geosphere	Homeworks: 4 Organisations: 6 (including two observers)	Homeworks: 4 Organisations: 4	Homeworks: 4 Organisations: 7 (including 1 observer)
Workshop 2	Human aspects	Homeworks: 6 Organisations: 6	Homeworks: 3 Organisations: 3	Homeworks: 3* Organisations: 4* *including one organisation outside EURAD
Workshop 3	Spent nuclear fuel	Homeworks: 4 Organisations: 5	Homeworks: 3 Organisations: 4 (including two organisations from EURAD WP SFC)	Homeworks: 4 Organisations: 7 (including three observers from EURAD WP SFC)
Workshop 4	Waste inventory	Homeworks: 6 Organisations: 6	Homeworks: 3 Organisations: 3	Homeworks: 3 Organisations: 4

In order to facilitate the discussion on the preferred uncertainty management strategies and options in the three actors groups, specific questions were prepared in advance in so called “homework templates”, circulated among the workshop participants. The questions were identical for all the selected topical uncertainties and arranged in following four blocks:

- 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)?
- 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)?
- Material provided by Subtask 4.2 on identified uncertainty management options and strategies:
  - Other identified strategies (than in material from Subtask 4.2).
  - Points of disagreement with material from Subtask 4.2.
- 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, KM or StSt activities).

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.

An example of a homework template for topical uncertainty “hydraulic conductivity of the host rock (and other geological units)”, representing an uncertainty related to site and geosphere, is provided in Appendix B. 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.

The evolution of uncertainty significance for safety was discussed on a basis of the following phases of a RWM programme adopted in EURAD, depicted also in Figure 2:

- Phase 0: Policy, framework and programme establishment,
- Phase 1: Site evaluation and selection,
- Phase 2: Site characterisation,
- Phase 3: Repository facility construction,
- Phase 4: Repository facility operation and closure,
- Phase 5: Post closure.

Uncertainty management scheme, developed by Subtask 2.1 (Hicks et al., 2023), was employed in the UMAN workshops to discuss the preferred uncertainty management options. The elements of this uncertainty management scheme, shown in Figures 7 (right) and 8, are as follows:

- uncertainties identification,
- uncertainties characterisation,
- assessment of safety relevance,
- identification of uncertainties to be reduced, mitigated or avoided,
- specific actions for:
  - uncertainties reduction,
  - mitigation of consequences,
  - uncertainties avoidance,
- representation of (remaining) safety-relevant uncertainties in safety assessment (SA).

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

Common generic management principles and strategies, identified by Subtask 2.1 (Hicks et al., 2023), were also adopted for the workshop purposes. These principles and strategies, illustrated in Figure 7 (left), cover the following elements:

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

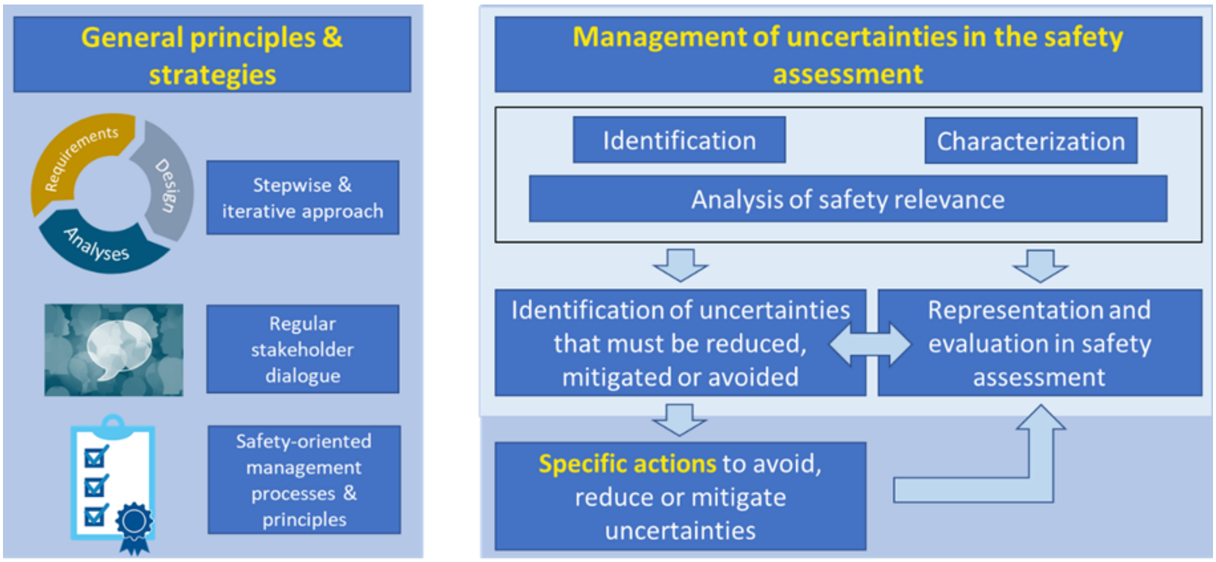

Figure 7 – Generic uncertainty management principles and strategies (left) and uncertainty management scheme (right)

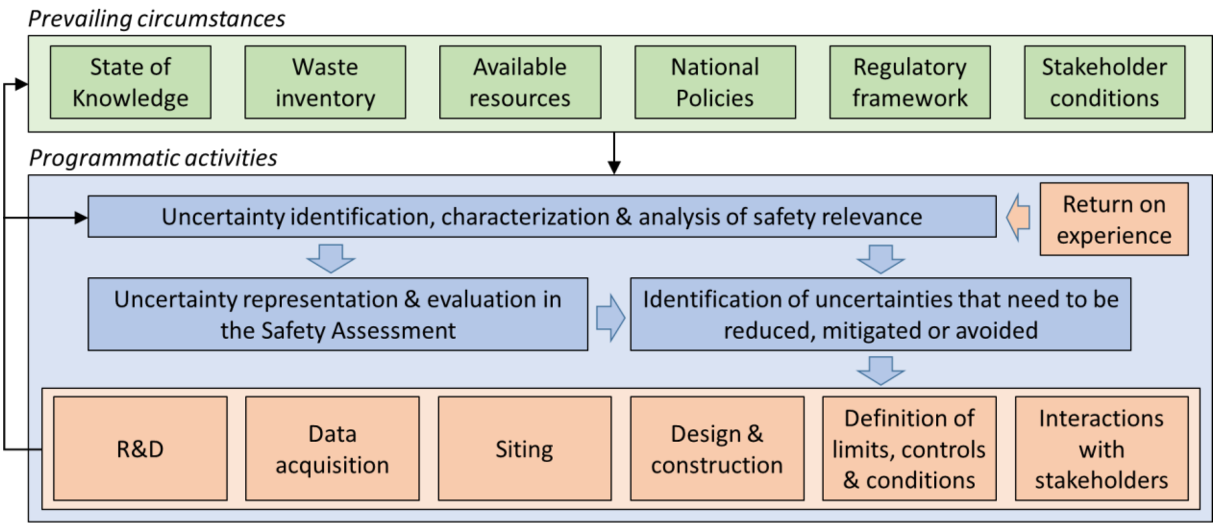

Figure 8 – Uncertainty management scheme with examples of specific options for uncertainty reduction, mitigation and avoidance, set up in the context of prevailing circumstances as well as return of experience

The material provided by Subtask 4.2, summarising the identified uncertainties management options and strategies, is listed in Table 2. Note that at the time of organisation of the UMAN workshops, solely milestone documents were available.

3. Synthesis of the 1st UMAN Workshop dedicated to management options and preferences of different actors regarding site and geosphere related uncertainties

In this chapter the outcome of the 1st UMAN Workshop, dedicated to the management options and preferences of uncertainties related to site and geosphere, is presented. The commonalities and differences with respect to the management of these uncertainties among the different participating actors (i.e. WMOs, TSOs and REs) are discussed. In case of the identified differences, it was attempted to analyse the reasons behind the different actors' perspectives.

The objectives of the workshop as well as the overall organisational issues and adopted methodology are described in details in Chapter 2. The agenda of this workshop is provided in Appendix A1.

3.1 Considered uncertainties

Uncertainties related to site and geosphere, which are relevant to safety and decision-making process, were identified in Diaconu et al. (2023) in the framework of UMAN Subtask 3.3, based on the 2nd UMAN Questionnaire. Due to the fact that only a few topical uncertainties could be addressed at the workshop, a few uncertainties out of the uncertainties presented in Diaconu et al. (2023) were selected under consideration of the criteria described in Section 2.2 of this report. For the purpose of work consistency in UMAN Task 4, the selected uncertainties were identical to those considered in UMAN Subtask 4.2 when identifying available management options and strategies (see Kaempfer et al., 2023).

The following five topical uncertainties were addressed during the 1st UMAN Workshop:

- uncertainties related to **hydraulic conductivity of the host rock (and other geological units)** as example of uncertainty related to the initial state of the disposal system and its environment; The host rock of a disposal facility is an important, if not the most important, barrier. The properties related to the flow regime in this host rock (from which hydraulic conductivity is a key parameter) are of fundamental importance and directly related to the safety functions attributed to the host rock. Uncertainties on the hydraulic conductivity are thus potentially relevant with respect to the post-closure safety.
- uncertainties related to **sorption capacity of the host rock (and other geological units)** as example of uncertainty related to the initial state of the disposal system and its environment as well as uncertainty related to data, tools, and methods.
  Beside the hydraulic conductivity, the radionuclide retention capacity of the host rock is also an important property as it impacts the safety function related to retention of radionuclides. Variations in sorption parameters are regularly identified as having a major impact on the results of the radiological impact calculations (for several nuclides) in the long-term safety assessment.
- uncertainties related to **homogeneities of the host rock (and other geological units)** as example of uncertainty related to the initial state of the disposal system and its environment as well as uncertainty related to data, tools, and methods.
  Due to their nature and formation history, all host rocks are inherently heterogeneous. These heterogeneities can be encountered at different scales (from microscopic to multi-meter scale). These heterogeneities, and the uncertainties related to them, are as well important when defining a representative elementary volume of the host rock, as when extrapolating local properties to a larger scale. Uncertainties related to the homogeneity of the host-rock characteristics can thus influence different important safety properties of the host rock.
- uncertainties related to **fault locations, detection and reactivation** as example of uncertainty related to the initial state as well as evolution of the disposal system and its environment.
  Fault locations can be detected by different means such as a (natural or human created) outcrop or surface or subsurface imaging (e.g. by seismic investigations). Due to resolution detection limits or absence of significant fault heave, uncertainties on the location of a fault can become significant. Fault reactivation over time is dependent on stress state evolution of the geosphere

and can be influenced by erosion and tectonic evolution. Faults are features that can have significant impact on the disposal facility performance (preferential flow pathway, earthquake source, etc.) and their potential future reactivation might entrain changes in the facility outline and hydrogeological situation. Uncertainties related to fault locations and their reactivation can impact several safety related properties and features of the disposal facility.

- uncertainties related to **climatic evolution (focus on glaciations and permafrost)** as example of evolution-related uncertainty and allowing to address the arguments completeness (FEPs, scenarios).
  Future glaciations and permafrost might have an important and potentially disruptive influence on the disposal facility, due to e.g. stress state changes, glacial erosion, hydrogeological/groundwater flow changes, isostatic movements with earthquakes. Uncertainties on these features are potentially safety relevant, such as uncertainties on the timing of a glaciation, extent of the ice sheet, depth of permafrost, uncertainty on groundwater flow changes.

For an extensive overview of the potential management options and strategies for the afore-mentioned topical uncertainties, reference is made to Kaempfer et al. (2023).

The aforementioned assignment of the topical uncertainties to the different types of the generic uncertainties identified in UMAN (see Section 2.2) is illustrated in Figure 9. One can notice that some of the topical uncertainties are classified as more than one type of the generic uncertainty. This is mainly due to the broad nature of the defined uncertainty: e.g. uncertainties on fault locations (and detection) are a part of the initial characteristics of the site, whilst uncertainties on fault reactivation represent the evolution of the disposal system.

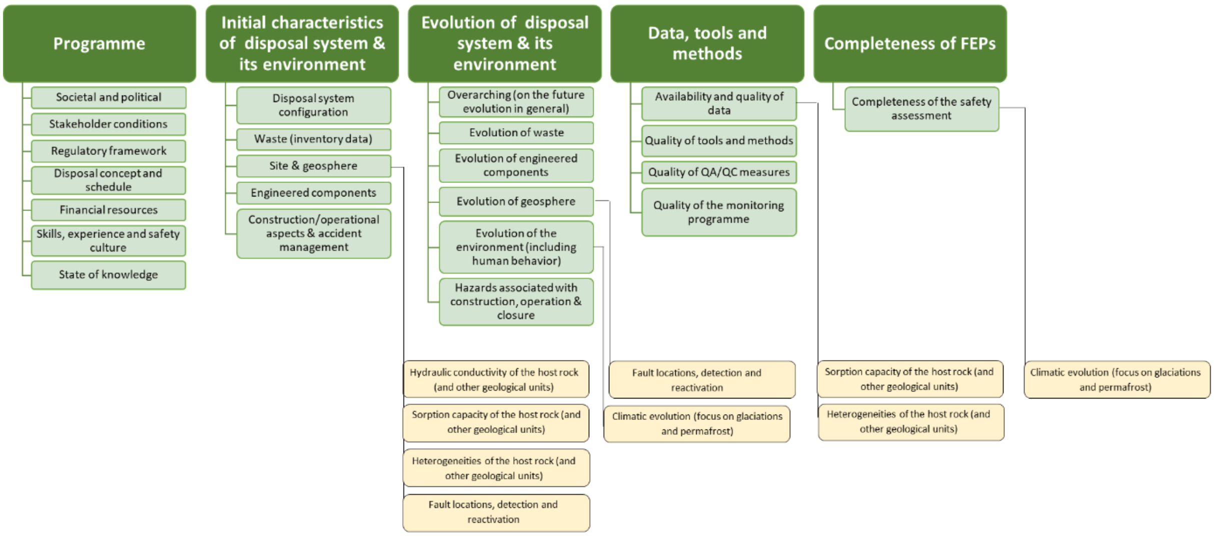

Figure 9 – Multi-level uncertainty classification scheme developed in WP UMAN for uncertainties related to site and geosphere

3.2 Views of the actors´ groups

3.2.1 Uncertainties related to hydraulic conductivity of the host rock (and other geological units)

The safety significance of the uncertainty on the hydraulic conductivity varies with the phases of the disposal facility. The safety significance in the initial programme phases (0 – 2) is generally considered to be higher than in the later phases. This is due to the fact that during the initial phases i.a. selection of host rock will take place, for which hydraulic conductivity can be a key parameter, possibly related to a site selection criterion. Also, the uncertainty in the early phases might have a profound influence on the initial outcome of the early SA (using more simplified models) and influences the repository conceptualisation. It has to be mentioned that during the construction of the repository, the uncertainty on the hydraulic conductivity can increase due to the potential influence of the Excavation Damaged Zone (EDZ) and due to the influence of the disposed waste such as high level waste (HLW) dissipating heat in the host rock.

Safety relevance of this uncertainty is also seen to be different for different types of host rocks (rock salt, claystone, crystalline rock). For (intact) salt host rock for example, due to its extreme low hydraulic conductivity, the uncertainty is seen as not important, while for other host rocks such as clay, the uncertainty can influence important elements such as the host rock selection.

The importance for safety is obviously also dependent on the knowledge of the characteristics of hydraulic conductivity itself, where small uncertainties due to good knowledge will be seen as less important than high uncertainties, which are due to a lack of knowledge.

The representation of this topical uncertainty in the SA depends on the goal of the assessment, and might make in that view use of more realistic or more conservative assumptions. Generally, two different strategies emerge, being the consideration of the uncertainty using probabilistic/stochastic modelling or using bounding cases (e.g. supposed high bounding conductivity).

The preferred management strategy of this uncertainty for WMOs, TSOs and REs is to avoid the uncertainty or to reduce it.

The selection of a (relatively) homogeneous site/host rock would allow reducing (or avoiding) variability of the hydraulic conductivity and therefore avoiding that the uncertainty could become large and highly safety significant.

The reduction of the uncertainty for a selected host rock mostly takes place during the early phases of site selection and characterisation, when more data on hydrogeology and hydraulic properties are collected, and models are further validated. It should also be noted that even with a detailed site exploration programme the uncertainty will not be fully reduced, and as mentioned earlier, it can increase during construction phase and after waste emplacement.

Specific techniques to reduce the uncertainty on hydraulic conductivity are:

- exploration (borehole, measurements, lab test on borehole samples, etc.),
- correlations with other more continuous parameters, e.g. granulometry.

There are many similarities between WMOs, TSOs and REs, in the appreciation of importance for safety and the preferred management options. Some differences however were noticed, although not fundamental.

The REs underlined that the uncertainty does not necessarily reduce over time, which is only true when statistical uncertainties are considered, but not when the evolution of the repository surroundings due to excavation or waste emplacement is taken into account.

The TSOs placed emphasis on the avoidance of the uncertainty through host rock selection, and also disagreed with the statement that it is usually strived for to use best estimate values for hydraulic conductivity in the reference scenario or reference cases, as the choice of a best-estimate, probabilistic or conservative approach is dependent on the objective of the assessment.

The differences between TSOs, WMOs and REs are mostly amongst the identification of other strategies than the ones identified by Kaempfer et al. (2023):

- TSOs mentioned the use of "stress tests" which would allow assessing available safety margins through a range of (hypothetical) hydraulic conductivities from the actual hydraulic conductivity up to levels actually leading to undue risks (similar to 'what-if scenarios'). This approach would demonstrate the robustness of the disposal system if it shows a sufficiently large margin between the most pessimistic or bounding scenario and the level where undue risks occur.

- WMOs mentioned the use of complementing arguments that diffusive transport is important (tracer profiles, pore water chemistry), the use of « simple » models (analytical, semi-analytical) to demonstrate the (small) influence of hydraulic conductivity in the repository system for communication with external stakeholders, and the identification of specific values that allow a statement on geological barrier´s safety function, e. g. use of hydraulic resistance instead of hydraulic conductivity/permeability, barrier´s thickness and area. Then the individual parameters can be varied, and their sensitivity assessed.

3.2.2 Uncertainties related to sorption capacity of the host rock (and other geological units)

The safety significance of the uncertainty on the host rock sorption capacity varies with the advancing programme phases. Generally, the safety importance is the highest during the early phases (0 – 2) and specifically during the siting phase, as the feature is very important w.r.t. the radionuclide retention by the host rock. With advancing programme phases and increasing knowledge, the uncertainty is reduced and subsequently of lesser safety significance.

The safety significance of this topical uncertainty depends on the type of host rock, too. For the salt rock type, the uncertainty is not seen as important, as the impermeable tight nature of this host rock limits the need to rely on its sorption capacity in the safety demonstration. The uncertainty is more important for other host rock types.

It is worth mentioning that facility construction, the presence of an EDZ, the interaction between the repository, the EBS, the waste and the host rock might lead to chemical alteration of zones of the host rock with potential impact on sorption capacity, which might increase the uncertainty associated with this parameter.

The representation in the SA depends on the goal of the assessment, and might make in that view use of more realistic or more conservative assumptions. Generally, two different strategies emerge, being the consideration of the uncertainty using probabilistic/stochastic modelling or using bounding cases (e.g. supposed high bounding conductivity).

Different strategies can be envisaged, including (partially) avoiding of the uncertainty, reducing it or applying a mitigation strategy.

The selection of a homogeneous site/host rock would allow avoiding the variability and therefore would strongly reduce the uncertainty. This would count for a part of the uncertainty, but does not cover the whole uncertainty, e.g. related to disturbance of host rock through EDZ or barrier/host rock interactions.

There is a general agreement that this uncertainty needs to be adequately reduced through increasing knowledge, research and development (R&D) measures (during site selection and further characterisation), e.g. better characterisation of the pore water chemistry and chemical conditions at the actual site, and ongoing work on better definition of sorption competition effect. Specific issues relevant for sorption may also need further study (e.g. organic material).

Knowledge improvement can be achieved through experimental tests on rock samples, form laboratory tests to large-scale in-situ tests in underground laboratories, all combined with subsequent model calibration.

It is also worth mentioning that some uncertainties could be mitigated through complementary measures at the level of the engineered barrier system, according to defence-in-depth (DiD) principle, or technical-organisational measures.

There are no real fundamental differences among WMOs, TSOs and REs. Although all actors´ groups acknowledged the need to reduce the uncertainties, the TSOs also put emphasis on avoiding the uncertainty through (homogeneous) host rock selection. In addition, TSOs and WMOs considered the possibility of mitigation through EBS choices (following the DiD principle) or technical-organisational measures.

WMOs also identified the following other strategies to reduce uncertainties:

- optimising the modelling strategy to reduce model uncertainty of sorption coefficient (Kd) approach, e.g. bottom-up approach (Bradbury and Bayens, 2011) or smart Kd concept (Stockmann et al., 2017),
- identification of specific values that allow for a statement on barrier´s safety function, e.g. if sorption is included in an "extended hydraulic resistance", this specific value covers hydraulic conductivity/permeability, thickness, area, and sorption. Then the individual parameters can be varied and their sensitivity assessed.

TSOs also mentioned stress tests as other option (see also Section 3.2.1), and pointed out that some uncertainty will remain due to the fact that most values of sorption coefficients are chosen by analogy with other radionuclides and uncertainties associated with the use of a Kd model will remain. TSOs also noted w.r.t. representation in the SA that where simplifications are necessary (e.g. when a Kd approach is used), the implementer should substantiate the validity of the simplifications with respect to the intended use of the model (as part of the model verification and validation process).

REs remarked that host rock includes a part, which is chemically altered by the repository construction and waste emplacement (perturbations). Most safety relevant nuclides (actinides, Tc, Ni, etc.) are transported only few centimetres to meters in clay, so only the perturbed part of the host rock is relevant for them in clay. In crystalline rock the chemical alteration of host rock might be less important.

3.2.3 Uncertainties related to homogeneities of the host rock (and other geological units)

The safety significance of the uncertainty on the homogeneity of the host rock evolves with advancing programme phases. Generally, the safety importance is seen as the highest during the early phases (0 – 2), as the feature is seen important during the host rock selection and siting process. With the advancing phases and increasing knowledge, the uncertainty becomes smaller and subsequently less important.

However, the importance and evolution of the uncertainty is also depending on the type of host rock. Specifically for crystalline rocks, uncertainties regarding heterogeneities and concerning hydraulic, mechanical or thermal properties might also be of relevance during the operational period, e.g., they can strongly influence the choice of an excavation method and the dimensioning of the proposed repository.

Regarding representation in the SA, a variety of options have been identified. This would be dependent on the targeted objective. Probabilistic/stochastic modelling using statistical approach, or the use of bounding cases (conservative approaches) can be used to demonstrate the available safety margin. Alternative conceptualizations (e.g. supposing an undetected inhomogeneity such as a fault presence) can be used too, in a form of altered evolution scenarios or what-if scenarios, allowing to assess the robustness of the system.

There was a general agreement that these uncertainties are to be reduced, during the early phases of the host rock selection and site selection, through an increasing knowledge based on exploration activities (i.e. geophysical methods simultaneously accompanied by detailed geological mapping). This will also allow for a selection of a (relatively) homogeneous volume of host rock that can host the facility, termed effective containment zone (ECZ). Other approaches for further reduction of the uncertainties are geostatistical approaches, and determination of relationships between different parameters.

The approaches were mostly similar among WMOs, REs, TSOs, although some smaller differences were encountered.

Another strategy identified by WMOs was further extension of specific values that allow a statement on barrier´s safety function, e.g. the "extended hydraulic resistance" can be arranged in parallel as well as in series to capture zones of different homogeneity. Then the individual parameters can be varied and its sensitivity assessed.

TSOs mentioned stress tests as an important strategy (see Section 3.2.1). TSOs also noted that possible approaches to represent the uncertainty could be compared and treated through different “assessment cases”, so as to treat model uncertainty.

REs did not identify specific aspects other than the ones identified as being common for all actors´ groups as mentioned in the text above.

3.2.4 Uncertainties related to fault locations, detection and reactivation

This topical uncertainty is generally seen as important, as it may, under some circumstances, facilitate radionuclide transport and hence impact the safety functions of the host rock related to “limitation of water flow” and “radionuclide retention”. The safety significance of the uncertainty is however evolving with time and can also be different for different types of host rock.

The safety significance of the uncertainty is generally seen to be highest during phases 1 – 2 as it is often applied as a criterion to a site selection process. It is expected to decrease during later phases due to increasing data/knowledge, based on site characterisation (borehole, seismic data, etc.). However, for crystalline rocks, uncertainties regarding faults might also be of relevance during the operational period, e.g., they can strongly influence the choice of an excavation method and the dimensioning of the proposed repository.

The way the uncertainty is represented in the SA is again variable. The remaining uncertainties can be addressed through sufficiently conservative boundary conditions and other conservative assumptions (i.a. regarding the fault activation or reduction of transport pathway length) or through probabilistic modelling. In addition, altered evolution scenarios or what-if scenarios can be defined to explore the robustness of the system e.g. in case of undetected features.

Three types of treatment of this uncertainty are identified: avoiding the uncertainty, reducing it and mitigation.

Avoiding of the uncertainty can be done during the site selection, i.e. through selectin of an area/disposal volume that has no present (or potential future) hydraulic conductive faults (i.e. through application of exclusion criteria).

Uncertainty reduction can be achieved through exploration, using geophysical methods simultaneously accompanied by geological mapping of problematic parts of the territory. Also R&D (e.g. modelling) can contribute to reduction of this uncertainty. This will increase the knowledge on the fault locations and their potential for reactivation in the future. More data will also be gained during the construction activities.

These uncertainties could be mitigated to some extent through the self-sealing capacity of these host rock (e.g. for clays), complementary measures at the level of the EBS and adaptation of the architecture of the repository in case of suspected fault (e.g. done in crystalline rock).

There are no large differences between WMOs, TSOs and REs.

WMOs also identified the need for avoiding some specific human activity (like geothermal energy stations), which can help to avoid seismicity on/reactivation of present faults. Further, they also mentioned the use of complementing arguments: e.g. self-sealing of clay that would limit the impact of fault reactivation. In their opinion technical-organisational measures represent a potential option to mitigate the uncertainties.

TSOs put emphasis on the differences in strategies when facing different host rocks, and emphasise the stress tests (see Section 3.2.1) as an important strategy.

REs did not identify specific aspects other than the ones identified as being common for all actors´ groups as mentioned in the text above.

3.2.5 Uncertainties related to climatic evolution (focus on glaciations and permafrost)

Climate evolution (particularly glaciations and permafrost) can impact safety in many ways, as future climate changes can have a substantial impact on the aquifers and on the biosphere and hence on the dose in many ways (e.g. increase in concentration of radionuclides due to changing/decreasing flow rates, change in geosphere and biosphere pathways, different irrigation needs). Glaciation-induced erosional processes could cause removal of parts of geological layers, which could lead to (partial) disruption of isolation and/or containment of the waste (e.g. loss of barrier, decompaction disturbances such as porosity changes). The relevance of uncertainties associated with permafrost depends on the depth of the containment zone that is considered and the vulnerability to permafrost.

The view on the importance of the uncertainties associated to the glaciations and permafrost is quite variable among the different actors´ groups and even within one group. The importance clearly depends on many factors, such as climatic zone/latitude and altitude of the country/site, depth of the ECZ. The view on its evolution is also mixed and depends on the estimation of the global importance of the phenomenon. A common view on the importance during the different phases cannot be deduced, and the determination of the importance is something to be looked at case by case, site per site.

In order to represent this uncertainty in SA, generally a stylised approach/bounding case for low-probability scenarios is applied (altered evolution scenarios, what-if-scenarios). This includes conservative/bounding assumptions regarding possible radionuclide pathways. The scenarios could cover a range of possible climate evolutions. These scenarios should be able to show that safety is not jeopardized/the safety margin remains sufficient.

The main management strategy seems to be avoidance/mitigation of the uncertainty by choosing a sufficiently deep or thick ECZ or a site location, where glaciation will not occur or can be excluded as a low probability event or will not be able to significantly impact the host rock/geosphere.

In case of the impact on the biosphere, the representation in a stylized way of the biosphere was identified as a way of coping with this uncertainty (even a way for reducing its importance, according to WMOs).

Some differences exist among WMOs, TSOs and REs, but as already mentioned, these differences originate predominantly from the different climatic zone/latitude and altitude of the country/site.

WMOs mentioned also technical-organisational measures as an option to mitigate the uncertainties.

TSOs identified as a complementary strategy the requirement to assess available safety margins through (hypothetical or what-if) cases, where there would be an impact of glaciation at disposal depth, e.g. what is the impact on safety if the disposal site is violated by a glacial valley ("stress test").

REs identified the investigation of the relation between disposed waste streams/inventory and host rock isolation and confinement requirements, considering the different timescales for radiotoxicity decline:

- e.g. relaxing the co-disposal option to disposal at different depths/sites,
- separation of radionuclides with high radiotoxicity (option pursued by the Partitioning and Transmutation community in order to mitigate uncertainties at the very long term). For clay host rocks, it is acknowledged that this has no effect on normal evolution-type scenarios. It is only relevant to scenarios, where the radiological impact is proportionate to the disposed radiotoxicity. Depending on the hypotheses, this could be the case for glaciation scenarios (as well as certain human intrusion scenarios).

4. Synthesis of the 2nd UMAN Workshop dedicated to management options and preferences of different actors regarding human aspects related uncertainties

In this chapter the outcome of the 2nd UMAN Workshop, dedicated to the management options and preferences of uncertainties related to human aspects, is presented. The commonalities and differences with respect to the management of these uncertainties among the different participating actors (i.e. WMOs, TSOs and REs) are discussed. In case of the identified differences, it was attempted to analyse the reasons behind the different actors' perspectives.

The objectives of the workshop as well as the overall organisational issues and adopted methodology are described in details in Chapter 2. The agenda of this workshop is provided in Appendix A2.

4.1 Considered uncertainties

Uncertainties related to human aspects, which are relevant to safety and decision-making process, were identified in Dumont et al. (2023) in the framework of UMAN Subtask 3.4, based on the 2nd UMAN Questionnaire. Due to the fact that only a few topical uncertainties could be addressed at the workshop, a four topical uncertainties out of the uncertainties presented in Dumont et al. (2023) were selected under consideration of the criteria described in Section 2.2 of this report. For the purpose of work consistency in UMAN Task 4, the selected uncertainties were identical to those considered in UMAN Subtask 4.2 when identifying available management options and strategies (see Kaempfer et al., 2023).

These selected topical uncertainties, considered in the 2nd UMAN Workshop, are as follows:

- uncertainties related to **public acceptance of the repository at potentially suitable or projected locations** as example of programme uncertainties,
- uncertainties related to **schedule to be considered for implementing the different phases of the disposal programme** as example of programme uncertainties,
- uncertainties related to **adequacy of safety-related activities during construction for the implementation of safety provisions** as example of uncertainties associated with initial characteristics of the disposal system and its environment,
- uncertainties related to **"new" knowledge** as example of uncertainties associated with the evolution of the disposal system and its environment.

The first topical uncertainty addresses also the estimation of the public acceptance, including methods to measure the acceptance level and to determine when a sufficient level of acceptance is enough.

The second topical uncertainty is related among others to insufficient support and acceptance by the public as well as political changes in the phases of site selection and site characterisation, regarding decisions on the location of a disposal facility and its construction. Further, the schedule may also be affected by uncertainties related to the provision of sufficient financial and raw material resources, the availability of technologies at the appropriate readiness level (TRL) and resources for evaluation. It affects the timing of the agreement on the completeness of safety case.

The third topical uncertainty was originally considered in the 2nd UMAN Questionnaire and in Dumont et al. (2023) for phases of site evaluation and selection, site characterisation, construction as well as operation and closure. In the workshop however, the aspect of safety-related activities was limited solely to the construction phase in order to enable focused discussions.

The fourth topical uncertainty was originally defined in the 2nd UMAN Questionnaire and in Dumont et al. (2023) as "uncertainty related to reliability of monitoring results and safety analysis". However, for the purposes of the workshop this uncertainty was redefined and interpreted in a much wider context to address any "new" knowledge that will become available in the course of implementation of a RWM programme through e.g. RD&D activities, technology development, monitoring, etc. (corresponding to unknown unknowns) Furthermore, “new” knowledge covers any knowledge that is either new to or was ignored by certain actors (corresponding to unknown knowns and ignored knowns, respectively).

The aforementioned assignment of the topical uncertainties to the different categories of the generic uncertainties identified in UMAN (see Section 2.2) is illustrated in Figure 10 and summarised in Table 3. 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 5). Detailed description of the uncertainties matrix can be found in Section 2.2.

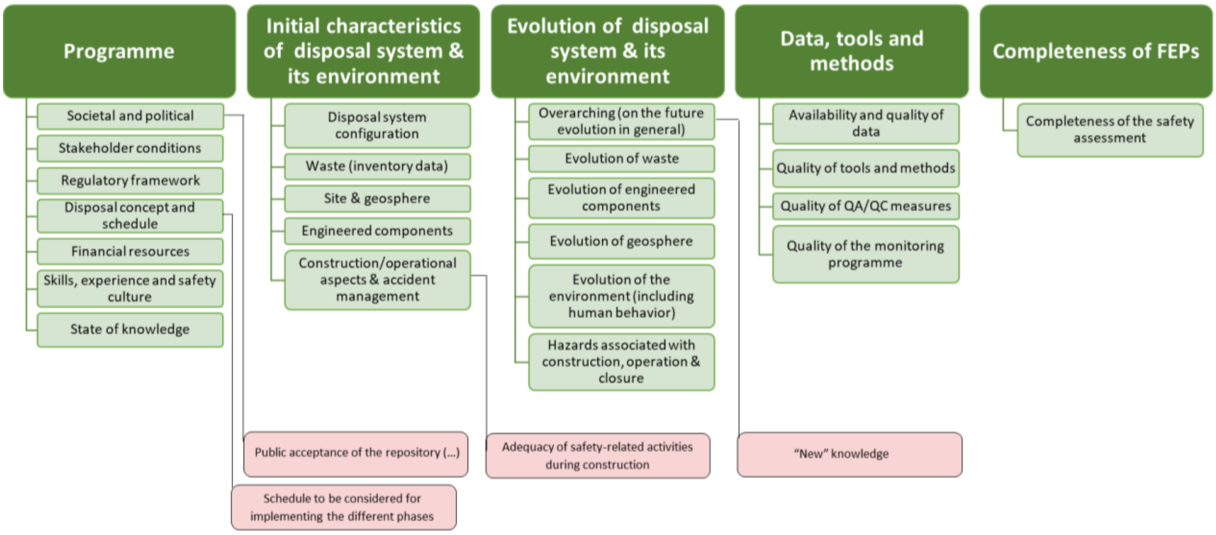

Figure 10 – Multi-level uncertainty classification scheme developed in WP UMAN for uncertainties related to human aspects

Table 5 - Uncertainties matrix developed for topical uncertainties related to human aspects

Generic types of uncertainties	Selected topical uncertainties	Known Unknowns	Unknown/Ignored Knowns	Unknown Unknowns
1. Programme uncertainties	Public acceptance of the repository at potentially suitable or projected locations	e.g. conditions set by a community for accepting the project on its territory		e.g. unconceived negative decision of a community
	Schedule to be considered for implementing the different phases of the disposal programme	e.g. duration of the licensing process	e.g. ignored lack of financial resources	e.g. unconceived political instabilities
2. Uncertainties associated with initial characteristics of the disposal system & its environment	Implementation of safety provisions in construction → characteristics of the built components	e.g. uncertainties in as-built repository components (due to construction errors)		
3. Uncertainties in the evolution of the disposal system & its environment	“New” knowledge		e.g. ignored possible magnitudes of disturbing events (e.g. Fukushima)	e.g. really new knowledge, unexpected, with possible impact on the safety case
4. Uncertainties associated with data, tools & methods used in the safety case			e.g. ignored mistakes in methods for implementing safety-related activities (e.g. 2nd WIPP incident)	

5. Uncertainties associated with completeness of FEPs considered in the safety case				

4.2 Views of the actors´ groups

4.2.1 Uncertainties related to public acceptance of the repository at potentially suitable or projected locations

All actors acknowledged the importance of this uncertainty for a successful implementation of a radioactive waste disposal programme. REs emphasised the necessity to develop a process looking for public consensus and attributes certain power to involved key actors. This would allow to avoid implications that on one side there is a group responsible for a development of a disposal concept (engineers, scientists, etc.) and on the other side there is a group of people that shall accept. TSOs recalled Article 10.2 of Council Directive 2011/70/EURATOM, which treats about the necessary opportunities for an effective public participation in the decision-making process. With respect to that directive and the aforementioned statement of the REs, TSOs remarked that a high degree of competencies of the key actors is very crucial for decision-making. Further, in TSOs opinion, site acceptance can never be definitively achieved if reversibility of the decisions/process is given.

Both REs and WMOs indicated that public consent/public acceptance may change under the influence of certain factors such as cultural, societal and political ones, due to changes of individual/community preferences, changes of word views and concerns for future generations, upon information and communication as well as a result of unexpected nuclear events.

REs stated that public acceptance itself is not an issue relevant for the safety of a RWM programme, however according to TSOs this could be debatable, depending on the definition of safety. In general, two aspects of safety significance of this uncertainty were considered by the three actors:

- delays of decision-making and even abruption of a national RWM programme, which are relevant for:
    - interim storage safety (in terms of facility capacity, facility ageing but also in terms of modification of nuclear waste properties due to extended interim storage, which in turn would impact repository design). However in the view of REs, such delays may have rather indirect impact on safety.
    - operational and disposal safety, if, as underlined by TSOs, such delays occur during construction, operational or closure phases,
    - long-term safety (in terms of results of post-closure monitoring and waste recoverability),
    - potential loss of resources (e.g. raw material, human and/or financial resources) with possible consequences of poor execution of future activities, early closure or abandonment of a facility as mentioned by TSOs.
- additional requirements set by stakeholders that may result in both positive and negative implications for safety of a disposal facility:
    - positive implications triggered by public concerns on safety, leading to more redundancy to certain safety functions of an already safe concept as mentioned by REs. This aspect depends on the perception and understanding of risk and these vary between individual stakeholders (individuals, community, etc.) and experts involved in RWM. While it is not possible to account for the perceived risks of all stakeholders, public confidence will rely on the establishment of an informative, traceable and democratic dialog.
    - negative implications such as e.g. provision of inspection rooms, incorporation of reversibility of decision-making, post-closure monitoring (intrusive versus remote measurements techniques) or waste retrievability (length of galleries, choice of backfill materials, accessibility that is not neutral with respect to operational safety, etc.). Such

specific provisions are expected to increase public acceptance but on the other hand cannot impair the overall safety as underlined by WMOs.

The opinions on the evolution of the safety significance of this uncertainty varied among the actors and in case of WMOs, also inside the actors´ group. At a global level, there was generally good agreement among the WMOs regarding the assessment of safety significance of this uncertainty, being rated as rather high in all programme phases. It was however noted that the safety significance could be reduced under some circumstances, e.g. by a proper consideration of consequences resulting from the delays caused by this uncertainty (e.g. ageing of waste during extended interim storage) or by a site selection process driven by safety criteria. Some nuances among WMOs were identified, particularly with respect to a time point, at which safety significance is expected to decrease – by some WMOs already after site selection or after construction/operation licensing. On the other hand some other WMOs expected an increase of the safety significance of this uncertainty at facility closure, if waste retrievability and monitoring provisions are given. According to TSOs, it is difficult to predict the evolution of the safety significance of this uncertainty; on the other hand they expect this uncertainty to re-appear at each decision point in the national RWM programme. REs drew attention to the fact that both public consent and the meaning of safety evolve. REs do not expect the safety significance of this uncertainty necessarily to decrease over the phases of a national RWM programme and instead they indicated certain peaks of safety significance in phases 0, 1, 3 and 4 when starting emplacement of radioactive waste.

With respect to uncertainty management, all actors emphasised that the overall management strategy should be based on a transparent and participative decision-making process. In addition, from the WMOs point of view this process should be science-based, safety-oriented and self-questioning, with development of regulations governing public involvement, while REs underlined that the process should help building and maintaining trust among the stakeholders. Also TSOs saw the necessity of building trust and increasing participation willingness through continuous actions such as opinion surveys, socioeconomic and social studies, development of participation and communication methodology. With respect to the latter issue, WMOs preferred continuous, intense dialogue with stakeholders, particularly with civil society, that is in addition science-based and conducted using a suitable communication strategy, addressing key aspects such as multifaceted communication (multiple channels and multiple stakeholders), uncertainties, etc. Other strategy elements were also mentioned by TSOs, e.g. flexibility of the process in terms of RWM options and schedule as well as the fact that no decisions/preferences shall be made in advance.

This uncertainty can be addressed in SA through a specific scenario of postponing/abruption of facility construction as indicated by TSOs or by assessing the risk associated with this uncertainty as mentioned by both TSOs and REs.

A question whether this uncertainty can be reduced, mitigated or avoided was discussed intensively by all actors. In TSOs and REs view, this uncertainty cannot be avoided. However, WMOs pointed out a correct interpretation, namely what we try to avoid is lack of public acceptance. Some of the WMOs expected that this uncertainty can be avoided for example through appropriate knowledge management, including lessons learned. Further, WMOs argued that no real mitigation of this uncertainty is possible, unless unacceptance is only partial. All actors agreed that this topical uncertainty can be reduced. However, REs stated that this uncertainty cannot be reduced by conducting more research and communication on safety, but through building and maintaining trust among the key actors, as indicated by the lessons learned (e.g. re-start of national RWM programme in some countries). Such a process should be continuous and with clearly defined rules, powers, and responsibilities of all involved actors, should be initiated in advance and should be conducted independently from future decision points as a long-lasting dialog. This statement was contradictory to WMOs opinion on the relevance of research for reduction of this uncertainty (e.g. transdisciplinary research to capture socio-technical issues, ethical and societal studies and even citizen science), including popularisation of science and educational measures (e.g. summer schools, visits to advanced facilities/universities/schools, change of paradigm "geology decides, not emotions", transforming negative symbols such as Tchernobyl, Fukushima into positive ones). In the context of research, TSOs underlined the importance of transparency, accessibility and understandability of research results in addition to the participative and transparent decision-making process, as mentioned before. WMOs presented some other specific options such as a possibility of developing of local partnerships when regions are preselected, door-to-door discussions, assessment of public acceptance by surveys, knowledge management addressing lessons learned to avoid repeating mistakes from the past, organisations of different discussion formats at different scales (e.g. public debates, formal conferences).

An overview of the preferred management strategies and options for this uncertainty is provided in Table 6 for all actors groups; in this overview the management options common for the actors are listed in the same line.

Table 6 - Preferences of the different actors (WMOs, TSOs and REs) on the management strategies and options for uncertainty related to public acceptance of the repository at potentially suitable or projected locations

Elements of uncertainty management strategy	WMOs	TSOs	REs
Identification	-	-	-
Characterisation	-	-	-
Representation in SA	-	Assessment of the risks associated with this uncertainty in the safety case in order to identify possible mitigation actions and to provide input for informed decision-making Scenario where the disposal facility construction is finally postponed or abandoned	Assessment of risk associated with this uncertainty
Actions to avoid, reduce or mitigate uncertainties	Transparent, participative, science-based, safety-oriented and self-questioning site selection process Continuous, intense dialogue with CS (suitable communication strategy, science- and solid knowledge- based) Reduction by R&D (transdisciplinary research, ethical and societal studies, citizen science) Popularisation of science/educational measures (focus on new generations; change of paradigm geology decides, not emotions) Development of local partnerships when regions are preselected Door-to-door discussions Public acceptance assessment through dedicated surveys Knowledge management addressing lessons learned Organisation of different discussion formats at different	Transparent and participative decision-making process Continuous actions to build trust and participation willingness (opinion surveys, socioeconomic and social studies, development of methodology for of communication)	Continuous, transparent and rule-based process of stakeholder engagement, aiming at building and maintaining trust

	scales (e.g. public debates, formal conferences)	Transparency, accessibility and understandability of research results No decisions/preferences made in advance Flexibility in terms of timetable and RWM options (including pre-disposal) to mitigate possible consequences of this uncertainty	

4.2.2 Uncertainties related to schedule to be considered for implementing the different phases of the disposal programme

In the view of the all actors, the actual schedule for implementation of a disposal programme depends on different factors including provision of sufficient resources (i.e. financial, human and raw material resources), technical constraints (e.g. availability of appropriate technologies), strategies of the different actors with sometimes opposite interests, lack of public acceptance, detection of previously undetected features (faults, water pathways, etc.) during construction phase, accidents during repository construction and operation and some other factors (e.g. war, financial crisis) of arbitrary nature of their impact and occurrence possible in any programme phase.

With respect to significance of this uncertainty for safety, the following negative implications for safety were addressed by the actors:

- delays in certain programme phases, delays in decision-making and even stop or abruption of a national RWM programme, which are relevant for:
    - transport safety,
    - interim storage safety (in terms of facility capacity, facility ageing but also in terms of modification of nuclear waste properties due to extended interim storage, which in turn would impact repository design). However, in the view of REs, such delays may have rather indirect impact on safety.
    - provision of long-lasting maintenance (in particular due to ageing processes) and active measures to ensure safety and security of the facilities (both storage and disposal facilities) as well as associated costs, burdens on future generations, increased overall risks (due to possible loss/lack of resources, records or skills, political instabilities, ageing); increased exposure times for workers and the higher number of exposed workers,
    - mining safety (WMOs),
    - operational safety with respect to e.g. local stability problems caused by delayed provision of stabilising measures (WMOs),
    - post-closure safety related e.g. to barrier effectiveness in the post-closure phase that could be affected by delayed provision of stabilising measures;
    - construction of a disposal facility when facing delays in decisions/authorisations with respect to construction of a nuclear power plant (NPP) (WMOs),
    - poor execution of future activities due to lack of resources, caused by increased costs (TSOs),
    - lack of continuity in the field, including loose of information and data on radioactive waste and site (REs), maintenance of skills and knowledge (WMOs),
    - keeping the site for radioactive waste disposal purposes if the local community changes preferences with respect to the site utilisation,
- potential increase if a risk of a lower quality or induction of errors as a result of a tight schedule (WMOs),

- changes in the programme when a better waste management option becomes available (TSOs).

Safety significance of this uncertainty was discussed mostly by WMOs and TSOs, most probably due to the fact that this uncertainty falls into their responsibilities. Opinions with respect to safety significance varied among the WMOs: some assessed it as being generally low with respect to operational and post-closure safety, however with a possible peak in phases 3 and 4 caused by economic constraints; for some WMOs safety significance was expected to be high in the first programme phases, for others only up to facility construction in phase 3 with expected decrease to medium in the construction and operational phases. On the other hand, a number of WMOs postulated that this uncertainty should be considered already in phase 2 to cover feasibility of a repository construction and found it highly relevant in both phases 3 and 4. With respect to delays in/postponing of repository closure, upon the provision of monitoring and waste retrievability, some WMOs expected safety significance to become high again in this phase. TSOs distinguished between safety significance for interim storage safety and disposal safety. Safety significance of this uncertainty for interim storage is expected to increase with time until waste emplacement; while there is no safety significance for disposal before the start of facility construction. Moreover, it was stated that significance for safety of the delays in construction, operation or closure of a disposal facility is dependent on several factors such as e.g. impact of ageing or the ability to retrieve the waste safely, if necessary. In the view of REs this uncertainty may evolve in a different manner, depending on the nature of the triggering factor, presented at the beginning of Section 4.2.2.

Options for identification, characterisation and representation in safety were presented primarily by TSOs. In their view the uncertainty related to the schedule of implementation of programme phases can be represented and analysed in terms of related "prevailing circumstances", following the framework introduced by International Commission on Radiological Protection (ICRP) with respect to the principle of optimisation of radiation protection. These prevailing circumstances define programme boundary conditions (e.g. waste to be disposed of, available sites, available financial resources, regulatory framework, stakeholder conditions) and thus represent programme and contextual uncertainties such as:

- the societal support of the decisions made in the programme (discussed already in Section 4.2.1),
- socio-political factors with the possible consequences of early closing or abandonment of the installation,
- loss of know-how, possibly leading to a poor execution of future activities, early closure or abandonment of the installation,
- lack of resources (including financial resources), possibly resulting in a poor execution of future activities, early closure or abandonment of the installation,
- changes in the production of nuclear waste, possibly impacting repository size,
- changes in the safety framework with the possible consequence that the repository no longer complies with this framework.

The uncertainty on the schedule of programme phases implementation can be identified through identification of the above-mentioned associated programme and contextual uncertainties using risk analysis (e.g. risk matrix, risk register, hazard identification tool HazID, scenario analysis).

Characterisation of this uncertainty is generally difficult as stated by TSOs, however it could be based on the framework discussed above, in which the related programme and contextual uncertainties are considered.

This framework can be also applied for representation of this uncertainty in SA as it was presented on example of LLW disposal facility in Dessel, Belgium (NIRAS, 2019). Analysis of the risk associated with "prevailing circumstances" should be performed regularly, throughout the disposal programme. This approach would allow to identify specific measures for reduction and mitigation of this risk during subsequent programme phases and periodic safety reviews as well as to foster a risk-informed decision-making. Moreover, specific scenarios addressing potential consequences of changes in programme implementation schedule can be considered in SA, such as e.g.:

- risk of collapse in case of extended duration of operation or delayed backfilling,
- accelerated degradation of materials,
- pessimistic extent (or absence of self-sealing) of EDZ,
- accelerated process of immediate repository closure,
- absence or a partial construction of some system components.

In an extreme case of non-respecting the schedule, “abandoned repository” can be considered as a stylised scenario as presented by WMOs.

At a global level, there was a common view among the three actors on the classification of this uncertainty with respect to the specific actions for uncertainty reduction, mitigation and avoidance. REs stipulated that reduction, mitigation and avoidance of this uncertainty is difficult in general. In both WMOs and TSOs opinion, this uncertainty can be reduced and even mitigated. Additionally TSOs pointed out that the specific measures for uncertainty reduction and mitigation are dependent on the different factors impacting the schedule, presented at the beginning of Section 4.2.2. With respect to uncertainty avoidance, there were slightly different opinions: TSOs stated that this uncertainty cannot be avoided, while WMOs provided some options for uncertainty avoidance, admitting at the same time that development of realistic time schedules, which could be used for these purposes, is challenging.

All actors recognised stepwise, participative process as the key management element of this uncertainty and drew attention to other important aspects such as continuous dialog with stakeholders and proactive communication with respect to planning (WMOs), flexibility and transparency (TSOs), iterative and trust-building process with a stepwise management strategy based on socio-technical criteria (REs). Further, in opinion of TSOs, a sound management system shall be developed and implemented for mitigation of this uncertainty.

The second important option, common for WMOs and TSOs, is a robust and flexible planning of time schedule as well as all required resources as noted by TSOs. When it comes to time schedule, analysis of interdependencies between the programme phases and also regular re-assessments of time plans are necessary according to WMOs. Schedule optimisation can be achieved in different ways as emphasised by WMOs: (i) by testing of methods, tools and approaches in advance before their direct application in order to verify their correctness/applicability, (ii) to analyse different scenarios and techniques for application in phases 3 and 4 (e.g. backfilling of disposal galleries, disposal segments, sequencing of waste packages emplacements) as well as design alternatives, and (iii) by implementation of an industrial pilot phase.

A particular attention was drawn by TSOs to robustness of a repository design under consideration of aging processes. It is generally favoured to use basic and robust materials, which in addition are expected to be available in the future.

As remarked by WMOs, uncertainties related to the schedule for implementation of the programme phases can be considered through analysis of safety-related risk (such as risk associated with operational safety, long-term safety and radiological protection), using e.g. risk matrix. In cases, where critical situations related to mining safety cannot be avoided, graded actions plans are required to determine thresholds as well as necessary actions and procedures in advance.

Knowledge management culture and related knowledge ecosystem were postulated by WMOs to be an important option for efficient and rapid knowledge circulation among various actors, allowing for mitigation of schedule delays (including also delays resulting possibly in loss of expertise). This statement supported the opinion of REs that keeping competences at a level of a team involved in site characterisation and SA is crucial. Another aspect related to knowledge management was raised by REs, namely the importance of updating databases as well as improving developed models.

Monitoring provisions represented a preference option common for WMOs and TSOs. With this respect WMOs underlined its importance in phases 3 and 4 for monitoring of time-sensitive constructions steps (e.g. stabilisation measures), while TSOs considered it as a mean for flexibility enhancement and support of decision-making (e.g. on waste retrievability due to safety or “societal” reasons).

An overview of the preferred management strategies and options for this uncertainty is provided in Table 7 for all actors´ groups; in this overview the management options common for the actors are listed in the same line.

Table 7 - Preferences of the different actors (WMOs, TSOs and REs) on the management strategies and options for uncertainty related to schedule to be considered for implementing the different phases of the disposal programme

Elements of uncertainty management strategy	WMOs	TSOs	REs
Identification	-	Analysis of risk associated with programme uncertainties related directly to this uncertainty	-
Characterisation	-	Through consideration of programme uncertainties related directly to this uncertainty	-
Representation in SA		Analysis of risk associated with programme uncertainties related directly to this uncertainty	-
	In extreme case of non-respecting the schedule, “abandoned repository” can be considered as a stylised scenario	Scenarios resulting from changes in the programme schedule: (i) risk of collapse in case of extended duration of operation or delayed backfilling (ii) accelerated degradation of materials, of pessimistic extent (or absence of self-sealing) of EDZ (iii) accelerated process of immediate repository closure (iv) absence or a partial construction of some system components	
Actions to avoid, reduce or mitigate uncertainties	Stepwise approach involving at each step the various stakeholders, including continuous dialog with stakeholders and proactive communication w.r.t planning	Implementation of a participative and transparent decision-making process; RWM programme with sufficient flexibility	Stepwise management strategy considering both social and technical criteria. In case of delays caused by lack of public acceptance: continuous, iterative, trust-building process involving stakeholders
	Robust time schedule with buffer and analysis of interdependencies between the programme phases; regular re-assessment and flexibility/adjustment of time schedule	Robust and flexible planning, including planning of the necessary resources	
		Implementation of a sound management system	
	Knowledge management culture and knowledge ecosystem		
			Keeping competences at the level of a team involved in site characterisation and safety assessment

			Keeping updated database and improving models
	Testing methods/tools/approaches before their application		
	Analysis of different scenarios/techniques and design alternatives, including their consultations with external experts		
	Introduction of an industrial pilot phase in order to learn and to get feedback before starting the "real" project		
		Robustness of the design with respect to ageing processes	
		Use of basic, robust materials and components that are not expected to become rare	
	Consideration of schedule issue as a safety risk (e.g. operational or long-term safety)		
	Establishment of graded actions plans		
	Monitoring of time-sensitive construction steps	Strong monitoring provisions to enhance the flexibility and to support the decisions (e.g. on waste retrievability)	

4.2.3 Uncertainties related to adequacy of safety-related activities during construction for the implementation of safety provisions

All three actors agreed that this topical uncertainty is relevant for both operational, conventional, radiological and long-term safety, which could be impacted negatively through various factors such as inadequate construction activities, processes and raw materials, any deviation from the intended procedures, accidents caused by geomechanical movements, unexpected local environment during excavation works (e.g. local changes of rock properties, geomechanical issues, unexpected presence of fluid), parallel phases of repository construction and waste emplacement, etc.

Examples of negative impacts on the operational safety can include violation of radiological or conventional safety due to induced local instabilities (e.g. roof falls, collapse of drift face), while negative impacts of long-term safety can influence long-term safety functions of the individual components of the barrier system.

Both WMOs and REs emphasised the role the safety culture plays in provision of safety-related activities, bearing in mind possible different perception of safety among different employees groups. Specific measures such as capacity building, capacity planning, QA measures and Integrated Management System (IMS) are expected to improve safety awareness.

In the view of REs safety significance of this topical uncertainty is strongly linked to the relevance of the construction works for the barrier system as well as local heterogeneity of host rock properties. According to WMOs this uncertainty has to be addressed early, in phase 2, in order to develop and establish safety culture. All actors assessed the safety significance of this uncertainty as high in phases 3 (as indicated by the formulation of this topical uncertainty) and 4 (due to the fact that some types of construction works will be executed in the subsequent phase). However, some implications for safety can be expected also in phase 5. WMOs postulated that the safety significance of this uncertainty could be reduced to medium providing appropriate management of this uncertainty.

WMOs addressed several options allowing for uncertainty identification, which included (i) establishment of a self-questioning and learning organisation/process, takin into account available experience from previous phases and other similar construction activities (in other disposal facilities or in other fields), (ii) monitoring systems and inspections of accessible parts of a disposal facility and (iii) review and oversight.

According to TSOs characterisation of this topical uncertainty is often difficult, however in some cases it can be quantified e.g. as percentage of defects that cannot be detected.

With respect to representation of this uncertainty in SA, WMOs and TSOs shared the same view that specific scenarios or assessments cases (e.g. early canister failure, unfavourable chemical conditions, failing seals) can be applied for this purpose. TSOs indicated additionally that FEPs database could be extended by considering a special FEPs category, addressing a poor quality construction. WMOs emphasised that this uncertainty can be bounded with respect to Design Target (DT), while TSOs indicated the option of using conservative assumptions and parameter values. Further, WMOs mentioned that it is important to integrate “good processes”/”good analysis” into SC in order to demonstrate that this uncertainty was treated adequately (e.g. QA system, clear roles).

Both WMOs and TSOs agreed that there are available options for avoidance, reduction and mitigation of this topical uncertainty. REs provided a few preferred options, however without classifying them into these measures.

Development of a strong safety culture in the organisation was the common key element in managing this uncertainty for the three actors´ groups. According to WMOs and REs, safety culture has to account for the different perspectives on safety among different employee groups (e.g. mining safety versus radiological protection). This measure shall be accompanied by strong oversights and audits (e.g. by regulator, its TSO, and/or by independent quality certification auditors with expertise in different fields such as SA, mining, civil engineering), which could accompany each step of a stepwise design process as postulated by WMOs.

REs and TSOs found establishing of a learning organisation (with a resilient structure)/experience feedback programme very important for the management of this topical uncertainty. The management strategy should in addition account for the socio-technical character of this uncertainty and be supported by an appropriate knowledge management strategy as presented by REs.

In the view of WMOs identification of specific components and activities relevant for safety could be a part of safety management. In this framework some specific issues such as compatibility of materials of supporting and stabilising structures with barriers material with long-term safety functions could be addressed and considered. This statement covers also the issue of selection of appropriate technologies, raised by TSOs. Following the Best Available Technology (BAT) principle would make an advantage of using proven technologies. In case of new technologies, their applicability should be confirmed through a qualification programme. Development of an R&D programme addressing construction issues as well as its regular update, as mentioned by TSOs, would be very important also in the context discussed above.

There were several other options mentioned by WMOs and TSOs, which could be applied to the design of the disposal system in order to manage this topical uncertainty. The common option was the DiD strategy, which includes, as elaborated by TSOs, (i) measures preventing from deviations (e.g. developed control measures and procedures to prevent defects and damage during construction), (ii) maintenance of performance of system components when subjected to construction errors e.g. through safety margins in the design, (iii) design of a multi-barrier system and (iv) detection of deviations, defects or damage to the barrier system (e.g. developing quality control measures during construction based on conformity criteria/quality requirements, periodic testing and inspections). Further options such as robustness, diversity and spatial separation of the barriers constituting multi-barrier system as well as multiple lines of reasoning were mentioned by WMOs.

An important issue discussed in the workshop with respect to this uncertainty was verification of the actual (i.e. after construction) and the target safety functions/characteristics of the barrier system. According to TSOs monitoring provisions should be applied to control performance of safety relevant constructions. This statement complied with the one by WMOs on the use of the concepts of Safety Envelope (SE), Design Target (DT) and As Built State, developed in framework of a project GEOSAF II. Also REs see these concepts relevant for the preparation of any corrective measures in case of identified deviations between DT and As Built State.

Moreover, TSOs pointed out that the choice of appropriate management actions is determined by the nature of this uncertainty – ignored/unknown knowns versus known unknowns. In case of ignored/unknown knowns, measures such as staff training and qualification are applicable.

The preferred management options with respect to this topical uncertainty are provided for each actors group in Table 8; in this overview the management options common for the actors are listed in the same line.

Table 8 - Preferences of the different actors (WMOs, TSOs and REs) on the management strategies and options for uncertainty related to adequacy of safety-related activities during construction for the implementation of safety provisions

Elements of uncertainty management strategy	WMOs	TSOs	REs
Identification	Self-questioning, learning from previous stages and from similar construction activities (other disposal facilities or other fields)	-	-
	Monitoring systems		
	Inspections of accessible parts of the facility		
	Review and oversight		
Characterisation	-	Quantification (e.g. % of defects that cannot be detected)	-
Representation in SA		Inclusion of a poor quality construction FEPs category in the FEPs database	-
	Appropriate scenarios or assessment cases (e.g. early canister failure; unfavourable chemical conditions, failing seals)	Specific scenarios	
	Bounding the uncertainties w.r.t. DT		
	SC needs to demonstrate "good processes"/"good analysis", addressing that the uncertainties were dealt with adequately (e.g. QA system, clear roles)		
		Conservative assumptions and parameter values	
Actions to avoid, reduce or mitigate uncertainties	Strong safety culture with mutual understanding of safety from different perspectives (mining versus radiological protection)	Implementation of a Safety Culture Development Programme	Strong safety culture with mutual understanding of safety from different perspectives (mining versus radiological protection)
	Several design steps accompanied by expertise of licensing authorities in different fields (SA, mining, civil engineering)	Audits by the regulator, its TSO, and/or by independent quality certification auditors	Strong oversights, audits

	QA measures, including audit of QA system		
		Experience feedback programme	
			Learning organisation with resilient structure
			Treatment of this uncertainty in context of a socio-technical system
			Knowledge management
	Safety management based on the identification of the specific components and activities that are important w.r.t. safety		
	Consideration of special issues e.g. compatibility of materials of supporting and stabilising structures with barriers material with long-term safety functions		
		Use of proven technologies (BAT principle); demonstration of new technologies through a qualification programme	
		Regular updating and implementation of R&D programme addressing construction issues	
	DiD and multiple lines of reasoning	DiD principle: - Prevention from deviations e.g. by developing control measures and procedures to prevent defects and damage during construction - Maintenance of performance of system components when subjected to construction errors e.g. through safety margins in the design - Multi-barrier system - Detection of deviations, defects or damage to barrier system (including developing quality control measures during construction based on conformity criteria/quality requirements; periodic testing and inspections)	
		Monitoring of the performance of safety relevant constructions	
	Use of concepts of SE, DT and As Built State, developed in GEOSAF II with pitfalls regarding quantification of all criteria		Preparation of corrective measures in case of identified deviations between DT and As Built State
	Application of the principles of robustness, diversity and spatial separation to design of a (multi) barrier system		
		For related ignored/unknown knowns - training, staff qualification, etc.	

4.2.4 Uncertainties related to “new” knowledge

The context of “new” knowledge, discussed in the workshop, varied among the actors. WMOs underlined that “new” knowledge may cover different aspects and that there are different ways to generate it, for example through confirmation, optimisation or alternatives. One important aspect of new knowledge, discussed by WMOs, were new technologies and developments, raising a dilemma of choosing between old, well-proven technologies that belong to state-of-the-art and new technologies promising potentially better solutions, while keeping in mind that disposal of radioactive waste should promote new technologies/developments. Application of Technology Readiness Level (TLR) is believed to be helpful when assessing the suitability and readiness of available technological solutions for the purposes of radioactive waste disposal. TSOs considered “new” knowledge in the framework of unknown/ignored knowns and unknown unknowns (based on Figures 3 and 6 in Section 2.2), underlining the necessity of developing an appropriate uncertainty management strategy to assure that at the end of the decision-making process, no remaining uncertainty can potentially jeopardize disposal safety. REs on contrary focused on new scientific findings, which will be continuously generated in different disciplines, providing sufficient resources. REs emphasised the importance of the management of new knowledge and its systematic incorporation into SC/SA.

When it comes to the assessment of relevance of this topical uncertainty for safety, WMOs remarked that “new” knowledge helps to consolidate the existing knowledge and thus contributes to reduction of uncertainties, including better quantification of safety margins developed in SC. On the other hand, “new knowledge” may lead to possible adaptations, modifications and optimisation of exemplarily SC/SA, facility design or even of a regulatory framework. Such changes would require a revision of SC and facility design and may impact negatively time schedule of implementation of a national disposal programme as well as interim storage of radioactive waste. Further, WMOs noted that at the policy-level, “new” knowledge is a basis for reversibility of a decision-making process, posing necessity for continuous technological watch and even for a re-assessment of the process. With respect to the latter it would be required to establish specific criteria to support the decision-making and justification of the decisions in order to ensure that changing the process is indeed worth when facing new developments (i.e. when do we know enough to ensure safely disposal solution in order not to get stocked in optimisation for nothing). REs in turn distinguished between “new” knowledge relevant and irrelevant to disposal safety. If not ignored, “new” knowledge would contribute to increase of confidence in safety. On the other hand some of the “new” knowledge may be insignificance for the safety if e.g. the expected change in the foreseen repository behaviour remains within bounding cases and safety margins. They also remarked that “new” knowledge is presented rather from a negative perspective (i.e. having a negative impact on safety), while in fact it may have also a positive impact (i.e. by increasing confidence in safety).

In the WMOs view, safety significance of the uncertainties related to “new” knowledge is rather low in all programme phases because of stepwise approach and robustness by design. However, given reversibility of decisions, retrievability and/or recoverability of the waste, “new” knowledge in terms of new materials/technologies can play a role in phases 3 to 5. TSOs stated that safety significance of unknown/ignored knowns is high in all programme phases as the return on experience shows that past accidents/incidents are often associated with this uncertainty. For unknown unknowns it is difficult to assess their safety significance due to their “unknown” nature. However, it is expected that the extent and quality of the knowledge on disposal facility behaviour will increase over time, resulting in reduction of the associated uncertainties. REs postulated that safety significance of the uncertainty related to “new” knowledge cannot be known a priori and therefore it is rated as being high. However, this uncertainty is safety significant in all programme phases.

The overall management strategy reflects the different aspects of “new” knowledge considered by the actors: WMOs mentioned that radioactive waste disposal should be promoted as new technologies and challenges, TSOs pointed out a stepwise, flexible decision-making process, while REs underlined the importance of knowledge management. Additionally TSOs underlined the fact that uncertainty management strategy should ensure that, at the end of the decision-making process, no remaining uncertainty can potentially jeopardize the safety. Preferred management options were provided for certain elements of the uncertainty management.

Options for uncertainty identification were discussed solely by WMOs – here international exchange, checking the completeness of FEPs catalogues and 3D modelling were mentioned.

In case of uncertainty representation in SA, several options were provided by WMOs and TSOs, including systematic FEPs management and use of conservative approaches (mentioned by TSOs), principle of "good analysis" and robustness demonstration (mentioned by WMOs) as well as what-if scenarios, common for these both actors.

All three actors expect that this uncertainty can be reduced (as far as reasonably possible) in the course of the implementation of the national programme e.g. through incorporation of "new" knowledge into SC. In addition, WMOs stated that this topical uncertainty could be avoided. REs on the other hand underlined that missing knowledge can be mitigated through definition of additional, conservative safety margins. TSOs provided a very detailed description of the specific options, depending on the uncertainties nature. In their view, unknown unknowns can be reduced and avoided through:

- R&D activities,
- data acquisition (e.g. site characterisation, monitoring),
- site selection (e.g. criterion on the complexity of the host rock),
- design and construction (e.g. use of well proven methods and materials),
- interactions with stakeholders,

unknown knowns and ignored knowns can be reduced and even "minimised" by applying the following options:

- sound management system, which includes knowledge and record management, staff qualification, systematic FEPs management and peer reviews,
- periodic safety reviews,
- experience feedback programme,
- safety culture,
- interactions with stakeholders (including regulatory reviews).

while the remaining/emerging uncertainties should be mitigated through:

- programme flexibility,
- interactions with stakeholders,
- defence-in-depth principle.

The option common for all three actors was development of a transdisciplinary R&D programme, focused i.a. on investigation of new components and materials. International exchange (e.g. with advanced programmes) was mentioned by both WMOs and REs.

There were several common options for WMOs and TSOs identified, starting with the need for a strong safety culture, which, in the view of TSOs, could be fostered through a sound management system. Further common elements included interactions with stakeholders, experience feedback programme, periodic safety reviews as well as design of a robust disposal system.

Management of the "new" knowledge, which will be generated over the next 50 – 100 years, as well as its systematic incorporation into SC/SA were identified by REs as necessary actions to be well planned. Appropriate knowledge management was also supported by TSOs.

WMOs mentioned in addition the advantage of implementing an industrial pilot phase before starting a "real" construction, while TSOs found the DiD principle relevant together with development of a stepwise, flexible and reversible decision-making process.

The preferred management options with respect to this topical uncertainty are provided for each actors´ group in Table 9; in this overview the management options common for the actors are listed in the same line.

Table 9 - Preferences of the different actors (WMOs, TSOs and REs) on the management strategies and options for uncertainty related to "new" knowledge

Elements of uncertainty management strategy	WMOs	TSOs	REs
Identification	International exchange	-	-
	Completeness of FEPs catalogues		
	Issues identified through 3D modelling		
Characterisation	-	-	-
Representation in SA		Systematic FEPs management	-
	What-if scenarios	What-if scenarios	
	„Good analysis" principle		
	Robustness demonstration		
		Conservative approach	
Actions to avoid, reduce or mitigate uncertainties	R&D programme (including trans-disciplinary research and investigation of new components/materials)	R&D programme (including trans-disciplinary research)	R&D programme (including trans-disciplinary research)
	International exchange		Exchange with advanced programmes
		Knowledge management	Knowledge management
			Systematic incorporation of "new" knowledge into SC/SA
	Strong safety culture	Sound management system fostering a strong safety culture	
	Multi-facetted interactions with stakeholders	Interactions with stakeholders	
	Experience feedback programme	Experience feedback programme	
	Periodic safety reviews	Periodic safety reviews	
	Strong regulator		
	Robust disposal system	Robust disposal system	
		Defence-in-depth (DiD) principle	
		Stepwise, flexible decision-making process with reversibility	
		Safety margins	Additional, conservative safety margins
	Industrial pilot phase before "real" construction		

5. Synthesis of the 3rd UMAN Workshop dedicated to management options and preferences of different actors regarding spent nuclear fuel related uncertainties

In this chapter the outcome of the 3rd UMAN Workshop, dedicated to the management options and preferences of different actors regarding spent nuclear fuel (SNF), is presented. Depending on individual back-end country strategies, SNF can be considered for direct geological disposal, for reprocessing and may face very long-term interim storage. For all cases, a proper characterisation of SNF is required. The commonalities and differences with respect to the management of these uncertainties among the different participants (i.e. WMOs, TSOs and REs) are discussed. The reasons behind the different actors' perspectives were analysed in case there were any identified.

The objectives of the workshop along with the overall organisational issues and adopted methodology are described in details in Chapter 2. The agenda of this workshop in provided in the Appendix A3.

5.1 Considered uncertainties

Uncertainties related to SNF, which are relevant to safety and decision-making process, were identified in Detilleux et al. (2024) in the framework of UMAN Subtask 3.5, based on the 2nd UMAN Questionnaire. Due to the fact that only a few topical uncertainties could be addressed at the workshop, a few uncertainties out of the uncertainties presented in D10.9 were selected under consideration of the criteria described in Section 2.2 of this report. Note that in UMAN Subtask 4.2 (see Kaempfer et al., 2023) another uncertainty related to performance of SNF in geological disposal was considered additionally after conduction of the 3rd UMAN Workshop. This was due to the fact that the 3rd UMAN Workshop did not cover uncertainties related to final disposal of SNF, in particular the behaviour of SNF in geological disposal.

These selected topical uncertainties, considered in the 3rd UMAN Workshop, are as follows:

- uncertainties related to **SNF history data, reactor operation and irradiation conditions** as example of uncertainties associated with initial characteristics of the fuel as well as its evolution,
- uncertainties related to **nuclear data** as example of uncertainties associated with data, tools and methods,
- uncertainties related to **performance of SNF during (dry) interim storage** as example of uncertainties associated with evolution and to some extend also to data tools and methods.

While the first two topical uncertainties are analysed separately in this workshop for the sake of identifying key uncertainties, it is clear that they belong together, as the properties of SNF in terms of inventory assessment (neutron, gamma-ray emission, decay heat, radionuclide inventory, elemental content) depend on nuclear data and irradiation history.

The first topical uncertainty is related to waste inventory data, including for instance composition of fresh or burned fuel, or cladding. The initial fuel composition, reactor operation and irradiation conditions as for example burnup history and linear power and cooling time are key variables, to which the preferred uncertainty management strategy is related.

The second topical uncertainty is related to the data, tools and methods. Initial fuel isotopic composition and its uncertainties including trace elements, nuclear data (for instance cross-sections, fission product yields or decay chain data) have an overall safety significance for the post-closure phase. All issues related to the availability and quality of nuclear data is known at the beginning of the storage. This uncertainty is important for the overall safety case. It is related to long-term safety concerning potentially migrating radionuclide inventories. It is also of importance to potential criticality in the disposal site.

The third topical uncertainty addresses the mechanisms of degradation and their impact on SNF handling for conditioning in the view of disposal, which is more relevant for the design of the final repository than for the interim storage.

The afore mentioned assignment of the topical uncertainties to the different types of the generic uncertainties identified in UMAN (see Section 2.2) is illustrated in Figure 11. 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 10). Detailed description of the uncertainties matrix can be found in Section 2.2.

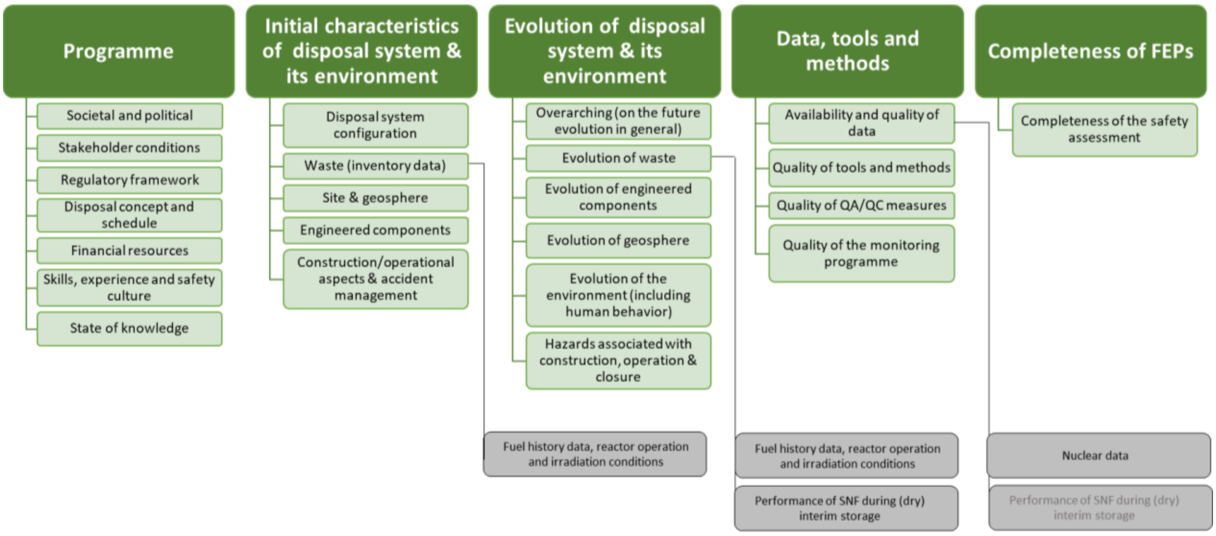

Figure 11 – Multi-level uncertainty classification scheme developed in WP UMAN for uncertainties related to spent nuclear fuel

Table 10 – Uncertainties matrix developed for topical uncertainties related to spent nuclear fuel

Generic types of uncertainties	Selected topical uncertainties	Known Unknowns	Unknown/Ignored Knowns	Unknown Unknowns
1. Programme uncertainties	SNF performance during interim storage (disposal)	Duration of dry storage; EC policies	New types of nuclear fuels, higher burnup (UO2, MOX, ATF, etc.)	
2. Uncertainties associated with initial characteristics of the disposal system & its environment	Fuel history data, reactor operation and irradiation conditions	Impurities level, irradiation conditions, burnup	New types of nuclear fuels, higher burnup (UO2, MOX, ATF, etc.)	Over extended life time, unexpected irradiation conditions
3. Uncertainties in the evolution of the disposal system & its environment	SNF performance during interim storage Attention: long-term evolution of SNF during disposal and the corresponding fuel structure were not addressed in this workshop	Ageing effects on cladding integrity under storage conditions	Conditions increasing aging rate during (extended) storage	
4. Uncertainties associated with data, tools & methods used in the safety case	Nuclear data	Cross sections, fission yield, decay data	Numerical errors of computer codes	Use of neural models, quantic computers
5. Uncertainties associated with completeness of FEPs considered in the safety case				

5.2 Views of the actors´ groups

5.2.1 Uncertainties related to fuel history data, reactor operation and irradiation conditions

All actors considered that this uncertainty, in conjunction with uncertainties in nuclear data (see Section 5.2.2), is important for nuclide inventories, thermal load, source term and impact assessment, including long-term evolution and criticality, but it is considered well taken into account in the safety cases, and their robustness (safety margins). The safety relevance of the remaining uncertainties is therefore considered low. This is also true for uncertainties in nuclear data (see Section 5.2.2). Higher uncertainties might be encountered in some early stage programmes, were the safety case is not fully developed yet. WMOs stated that most effective reduction of the uncertainty is at the beginning of the programme, e.g., by ensuring that the data is captured well. Safety significance can be reduced by (fundamental) design choices.

All actors agreed that uncertainties might also be higher for certain uncommon fuel types or burnups, like fuel from new reactor concepts, or of unprocessed SNF concerning certain issues like burnup-credit. They considered that unprocessed SNF in the closed fuel cycle is a small fraction of the overall waste, so that the significance of this uncertainty in such term is still considered as low.

The uncertainties in fuel radionuclide inventories and impact on criticality are influenced by the initial composition of the fresh fuel, its impurity levels, its isotopic composition, its operation condition in the reactors and operation history in the reactor (loading strategy, burnup, linear power) as well as the interim storage (cooling) time. REs added, that with the accumulation of data from the fuel fabrication process and post-irradiation investigations of SNF and accumulation of operational experience, the uncertainty will further decrease in time. Acknowledging that uncertainties in fuel history data occur, all actors agreed that the corresponding uncertainties are generally well managed and safety margins are sufficient and these issues therefore have low relevance for the safety case.

For all actors, and in particular for WMOs, it is important to reduce the fuel history uncertainty by developing a strategy for data and records management. Clear management principles must be established as early as possible. This includes clear definition, collection, transfer, storage and conservation of all necessary information and data. Also, this uncertainty can be reduced by RD&D or in-depth characterisation programmes for instance in key nuclides (C-14, Cl-36) and their instant release fraction (IRF), not treated in this workshop. REs added that experimental analysis of Cl impurities in fresh fuel and cladding can for example reduce uncertainties of calculated Cl-36 inventories. Similar approach exists for C-14 concerning stable N and C analyses.

All actors agreed that safety relevance and management options depend on the phenomena and view point of interest listed below (which typically are satisfactory treated in the safety cases):

- decay heat that dimensions disposal architecture and might in extreme cases damage the multi-barrier system,
- degradation mechanisms that may reduce cladding performance,
- nuclide inventory as source term for consequence analyses,
- criticality analyses (e.g., proof of subcriticality).

TSOs stated that uncertainties in the decay heat production are less relevant for them. The largest uncertainties appear when addressing new reactors, not yet covered in the safety case, where one encounters uncertainty in prediction of total SNF inventory. Remaining uncertainties of fuel and cladding compositions could be evaluated carefully, for example by means of parametric studies.

WMOs pointed out that safety relevance must be low before starting the operating phase. This can and must be achieved by design measures. The uncertainty impacts optimisation in general (feasibility, cost, acceptance and safety). The criticality topic seems in this regard to be somehow less advanced than the other topics and therefore the impact of uncertainties is somehow higher concerning this topic. This was confirmed for all participants.

In REs opinion the significance of these uncertainties will decrease over time due to knowledge and experience accumulation. However, implementation of disposal programmes can disclose issues that were not considered before with sufficient low uncertainty.

All actors agreed that, while the safety significance of these uncertainties is low, their importance might increase for certain actors, depending on the stage of the programme and the impact of implementation needs.

In the view of WMOs and most of the other actors, nuclide inventory has enough robustness (safety margins), so that the safety significance of the corresponding uncertainties is in general low. Remaining uncertainties of importance depend on the safety topic: e.g. in post-closure long-term safety, relevance of remaining inventory-related uncertainties depends on the host rock and is linked to few key nuclides like Cl-36, C-14, Se-79, I-129, Ni-59, Tc-99, Ra-226. It is not only important to know the inventory, one must also know, which fraction of the inventory is easily releasable from the disposed fuel (instant release fraction, IRF). However, long migration times, for example in clay rock, decreases the significance of these uncertainties. Uncertainties in IRF values were not addressed in this workshop.

Concerning decay heat, WMOs assumed as well that if disposal system has enough robustness (safety margin), safety significance is low; but some uncertainty will remain due to retrievability aspects. All actors agreed that the impact of the uncertainty can be fully controlled by design (e.g., using conservative assumptions to determine canister loading; remaining uncertainty itself is estimated to be rather small). However, when optimising packaging density or criticality margins in a repository, over-conservative safety margins could hinder an optimal use of repository space. An option could be to reduce uncertainties even further. Alternatively, sufficient distances between disposed waste packages can be foreseen to manage this uncertainty safely.

WMOs agreed with the other actors on the fact that subcriticality is seen as one of the most prominent safety aspects linked to SNF, in particular if estimates use the burnup credit method. However, in subcriticality assessments, uncertainty on fissile content might be dominated by other uncertainty, e.g., on evolution scenarios, regarding (the absence of) regulatory guidelines, etc.

The assessment of the safety significance by the actors depends less on their roles and responsibilities and more on the considered repository concept, disposal canister vs dual-purpose canister vs the option of direct disposal of transport containers as well as considered host rocks (e.g., temperature resistance, salinity,…).

An overview of the preferred management strategies and options for this uncertainty is provided in Table 11; in this overview the management options common for the actors are not necessarily listed in the same line. All actors were the same opinion that no specific management strategy for the treatment of these uncertainties is necessary. The actors shared also another common opinion that with a sensitive analysis, experimental investigations, conservative approaches and improvement of simulation models the uncertainties themselves will further decrease.

Table 11 – Preferences of the different actors (WMOs, TSOs and REs) on the management strategies and options for uncertainty related to fuel history data, reactor operation and irradiation conditions

Elements of uncertainty management strategy	**WMOs**	**TSOs**	**REs**
Identification	-	-	-
Characterisation	-	-	-
Representation in SA	Representation of remaining uncertainty in safety assessment: conservatism. Uncertainty on nuclide inventory: conservative assumptions, upper bounds	Graded approach should be considered in the management strategy. Analysis of safety relevance, representation and evaluation in safety assessment.	Assessment of risk associated with this uncertainty. Conservatism.

	Uncertainty on decay heat: keep in check by conservative design (upper bound assumptions) Uncertainty on criticality: e.g. shifting loading-curves (e.g. because uncertainty in burnup credit)	Safety assessment is processed for nearly maximum burnup. Conservative approach. Preference: imply a balance consideration of various aspects, such as identification of parameters, assessing their impact and try to put in place possible measures. All safety relevant uncertainties are mandatorily evaluated in safety case. Sensitivity analysis of uncertainties in spent fuel. Conservatism.	
Actions to avoid, reduce or mitigate uncertainties	Management principles must be established as early as possible in the programme. Clear definition of all necessary information/ data is needed to ensure collection, transfer, and storage of all required data, e.g., Nuclear Waste Logistic platform in Germany Reduce uncertainty by RD&D programmes (many of them are ongoing, also future activities have been identified e.g. on key nuclides C-14, Cl – 36 and their IRF, impurities (link to C-14)) Studies of criticality safety and burnup credit	As principal part of SNF comes from NPP with various burnup, safety assessment is processed for nearly maximum burnup values. Irradiation and SNF composition clarified by producers. Reduce uncertainty associated to inventory evaluation by improving models, codes based on comparison with measurements made on SNF elements from reactor. Experimental investigation of cladding leak tightness and computer simulations	With the increase of knowledge and experience it is expected that safety significance will decrease over time. However, implementation of disposal programmes can disclose issues that were not considered in details before.

All actors agreed that the representation of remaining uncertainty in safety assessment is governed by conservatism (safety margins):

- for uncertainties related to nuclide inventory: conservative assumptions, upper bounds,
- for uncertainties related to decay heat: keep in check by conservative design (upper bound assumptions),
- for uncertainties related to criticality: shifting loading-curves (e.g., because of uncertainty in burnup credit).

Further all actors emphasised that all planned disposal system have enough robustness (safety margin, conservativism).

All actors agreed on the need for RD&D as well as for SNF characterisation programmes, covering both destructive and non-destructive analyses. This is potentially more important for WMOs because at the end this uncertainty provides margins to reduce over-conservatisms linked to high costs. In general, safety cases and systems are deemed robust enough so that remaining uncertainty related to SNF can be coped with, however the aim should be to achieve the same robustness with less conservatism.

5.2.2 Uncertainties related to nuclear data

This uncertainty is largely discussed together with the uncertainties related to fuel history data, reactor operation and irradiation conditions (see Section 5.2.1). Correctness and accuracy of SNF radionuclide inventory and their characteristics (activities, neutron and gamma sources, decay schemes and residual decay heat) are crucial for SNF transport, storage, and criticality and disposal safety cases. This highly depends on nuclear data libraries that are used in calculations of inventories, together with fuel history data.

Since the nuclear data libraries are continuously tested by benchmarks, revised and updated by providing more accurate values, the uncertainties are well documented and tend to reduce over time. Nuclear data libraries consider also the completeness of the data on presence of activation products and other radionuclides that are important in the long-term safety analysis of the repository.

There was consensus that due to the high quality of data, uncertainties on nuclear data, in general, are considered of lower impact than the uncertainties associated with the fuel history and reactor operation/irradiation conditions (presented in Section 5.2.1). Indeed, for WMOs fuel history uncertainty often dominates over nuclear data uncertainty or other parameters in a deep geological repository (DGR) system. As the data quality further increases over time, the corresponding uncertainty will therefore decrease.

As in case of the topical uncertainty on fuel history data, reactor operation and irradiation conditions (see Section 5.2.1) one needs to distinguish safety significance with respect to:

- nuclide inventory,
- decay heat,
- subcriticality (including burnup credit).

All actors agreed that nuclear data is very important but the level of safety-significance of this uncertainty is between low or medium.

As far as long-term safety (biosphere dose calculations) is concerned, the inventories of only a limited number of mobile radionuclides (like Se-79, Cl-36, I-129, Ni-59 Tc-99) are significantly affecting the corresponding uncertainties. Acknowledging that uncertainties in radionuclide inventories are important for the disposal assessment, TSOs considered that uncertainties in nuclide inventories due to nuclear data uncertainties are much smaller than uncertainties in the expected transport time in geosphere. The remaining uncertainties in nuclear data concern the concentrations of long-lived safety-relevant radionuclides, potentially to be found in accessible environments after hundreds of thousand millions of years. With this regard, the safety significance of nuclear data uncertainties is in overall low.

In general, (and especially in applications with safety relevance), the impact of the uncertainty in nuclear data is less significant than the impact of the uncertainty associated with fuel history. This indicates that the safety significance of this topical uncertainty is expected to remain constant throughout all programme phases.

All this drives to the point that safety significance is focused on the post-closure phase. From long time perspective the significance of this uncertainty will continuously remain low. It can even gradually decrease with increasing scientific knowledge.

All actors agreed that no specific management strategy is necessary due to the low significance of uncertainties on nuclear data for the safety of a disposal system, as all relevant uncertainties are mandatorily evaluated in the safety case. REs recalled that there is no direct link between the uncertainty on nuclear data and the evolution of the waste management programme as nuclear data evolves with the progress made in nuclear physics.

REs argued that correctness and accuracy of SNF radionuclide inventory and its characteristics are crucial for SNF transport, storage and disposal safety cases. This highly depends on nuclear data libraries that are used in calculations. However REs agreed that the uncertainties should tend to reduce since the nuclear data libraries are continuously revised and updated by providing more accurate values. Nuclear data libraries shall also be evaluated for the completeness of the data concerning the presence of activation product and other radionuclides that are important in the long-term safety analysis of the repository. However, many studies on this topic have been already conducted. In some cases, the results of older studies provide indeed solid/sufficient basis that could be employed instead of performing new analyses and repeating work.

While REs did not provide position whether any special management strategy is needed or other uncertainties in safety assessment are of higher relevance, they agreed that a sensitivity analysis of nuclear data on SNF characteristic is necessary in order to ensure that the latest nuclear libraries and data are used. Usage of different data libraries (e.g. ENDF/B, JEFF, JENDL) in modelling and comparison of the results may help to mitigate and reduce the uncertainty.

According to TSOs no specific management strategy is necessary due to low significance of uncertainties on nuclear data for the safety of a disposal system. This is also due to the fact that all relevant uncertainties are mandatorily evaluated in the safety case. TSOs agreed about the need for common benchmarks.

WMOs argued that sensitivity analyses and uncertainty analyses performed to identify significant uncertainty and assess the impact of remaining uncertainty consistently indicate a low safety significance (always captured by other parameters). As the safety significance of this uncertainty is low, they stated that no special management is required. Some WMOs confirmed that they have no-ongoing or currently planned activities to decrease or mitigate the nuclear data uncertainties even further.

It is important to contextualise the uncertainties in the overall safety analyses. As only few nuclides are dose limiting, only these are important to assess the impact of inventories uncertainties. As the overall uncertainties in safety analyses are large, the inventory uncertainties of dose limiting radionuclides relative to nuclear data are not the key uncertainties, as agreed on by all actors. This statement is important to understand the points of view of the actors´ groups and the management strategy.

The key management strategy is to perform a thorough sensitivity analysis and common benchmarks as well as to employ the up-to-date libraries and nuclear data, with focus on the relevant radionuclides. An overview of preferred management strategies and options for this uncertainty is provided in Table 12 for all the actors´ groups; this overview the management options common for the actors are not necessarily listed in the same line.

Table 12 – Preferences of the different actors (WMOs, TSOs and REs) on the management strategies and options for uncertainty related to nuclear data

Elements of uncertainty management strategy	**WMOs**	**TSOs**	**REs**
Identification	-	-	-
Characterisation	-	-	-
Representation in SA	By conservatism	Management by conservative choices relative to final dose of key nuclides. Safety significance of remaining uncertainties focuses on the post-closure phase	By conservatism
	Nuclide inventory: conservative assumptions, upper bounds	They concern the concentrations of long-lived radionuclides potentially to be found in accessible environments after hundreds of thousands of years	Accurate nuclear data with “as low as achievable” uncertainties represent a key-point for accurate fuel inventory calculations, affecting various safety issues in the steps of disposal, allowing to determine more precisely doses to personnel, decay heat vs. time, re-criticality events and evolution scenarios.
	Impact assessment on criticality analyses (including burnup credit)	Some important uncertainties concern Se79 for which nuclear	Key radionuclides – their activity in the repository is decisive input in safety assessment

		cross-section and decay data are less known as well as Sn126	
Actions to avoid, reduce or mitigate uncertainties	Increases scientific knowledge to reduce uncertainty	Total adsorption spectroscopy can be used to experimentally reduce uncertainties in nuclear beta decay data	Analysis of safety relevance. Sensitivity analysis of SNF inventory. Sensitivity analysis of nuclear data on the inventory. Understanding of coupled phenomena needs to be increased in the community
	Sensitivity analysis	Record keeping on data on fuel composition and irradiation history, to allow re-evaluation of waste composition when new or more detailed nuclear data become available	The identification of most reliable nuclear data and some programmes addressing the issue of improving cross-sections and fission yields data accuracy, sensibly reducing the uncertainties when possible, would be helpful.
	Evaluation of the inventory		Common benchmarks oriented to applications in SNF handling and disposal in order to evaluate the most reliable nuclear data, after comparison of calculations with some experimental outcomes, would be beneficial and would go in the direction of uncertainties reduction and impacts on critical issues mitigation
	The cross-section and decay data of some radionuclides are less known, to focus on improving nuclear data and reduce uncertainty for these key radionuclides		
	Dosimetric libraries keep update	Dosimetric libraries keep update	Dosimetric libraries keep update. Using the latest libraries and nuclear data, with focus on the relevant radionuclides
	R&D projects at the international level	R&D projects at the international level	R&D projects at the international level

5.2.3 Uncertainties related to performance of spent nuclear fuel during (dry) interim storage

Interim dry storage of SNF is foreseen in some countries for 40 to 50 years prior to transport it to a final repository site for disposal. The safety significance of this topical uncertainty could evolve, from the point of view of REs, if storage time is extended due to delay in implementation of the disposal programme. As the storage containers are in most cases not considered suitable for disposal, repackaging from storage to disposal containers might be necessary. While there are very little to no uncertainties associated with radionuclide release during dry storage, uncertainties due to transportability of SNF (including transport legislation) and to stability during potentially necessary repackaging might be a safety concern. The characteristics of SNF (activities, neutron and gamma sources, decay schemes and residual decay heat) and potential degradation mechanism during dry storage (such as hydrogen embrittlement, creep, etc.) need therefore to be assessed for SNF transport, storage, and criticality. In the view of all the actors´ groups this uncertainty is important but it can be reduced by some measures.

WMOs suggested to distinguish between the uncertainty for operation of interim storage and the resulting effects on disposal.

TSOs pointed out that storage containers may degrade over time. REs argued that this effect will be minor due to the high corrosion resistance for example of the used CASTOR containers and the day-to-day validation of container tightness during storage. TSOs agreed that after a correct encapsulation, degradation would have little effect. SNF handling may nevertheless pose risk during encapsulation process. This needs to be taken into account in a layout of a potentially necessary encapsulation plant. The safety impact of this uncertainty was therefore considered as being low.

REs also considered the safety significance of this uncertainty as being low. They evaluated that design of the casks ensures, and safety assessments demonstrate, that SNF performance issues will not occur during the scheduled interim storage period (typically ~ 50 years). This issue shall be also considered in the safety case of SNF transportation from the storage site to the encapsulation/disposal site, as well as for assessment of long-term processes in the repository. In REs opinion fuel and cladding degradation mechanisms have low probability of occurrence during interim storage but it might be difficult to formally exclude such mechanisms. This means that these mechanisms might need to be considered when planning transport of SNF from the interim storage to the encapsulation and disposal facilities. However, understanding of the degradation process under storage conditions is expected to improve in the next years and thus both the uncertainty and its significance for safety will decrease.

WMOs did not share a common view with respect to the assessment of the safety significance of this uncertainty. Some WMOs considered the significance of this uncertainty as being low because it does not lead to deviation from standard procedures, while other WMOs considered medium impact on the safety because some uncertainties might be relevant, for instance uncertainty on hydrogen embrittlement and hydride reorientations. Further, some WMOs even considered high safety significance because of potential impact during operational phase or pre-disposal steps (e.g. container design). All WMOs agreed that the DGR systems are deemed robust so that safety relevance of remaining uncertainty is limited. The evaluation depends on the repository concept.

In the view of WMOs and REs, the uncertainty itself may increase due to prolonged interim storage:

- Hydride formation and reorientation in long-term storage may lead to cladding cracking during transport.
- Chemical and thermomechanical cladding stability are important for interim storage and transport, but not during final disposal. In the phase of waste emplacement, cladding failure may not be entirely excluded, however the container prevents any risk in this phase of the disposal. After repository closure, no credit is taken from cladding stability, hence the uncertainty is not relevant for long-term safety.

The preferred management strategy for REs is to work with conservative assumptions on the cladding failure. REs saw the need to characterise hydride reorientation and associated embrittlement during long-term interim storage as well as to understand thermomechanical effects (creep) on cladding stability, although many studies had been already performed on this topic.

TSOs pointed out that the management strategy passes through periodical monitoring of containers with respect to possible corrosion and decisive degradation processes. REs argued that this periodic inspection might be difficult or even impossible, as typical interim storage facilities may not have equipment required for opening the casks and handling SNF safely.

WMOs stated that the uncertainty management options depend on the phenomena of interest. In their opinion, this uncertainty can be reduced by improving the understanding of the different degradation mechanisms e.g. through participation in international RD&D. The topics of particular interest were as follows:

- hydrogen embrittlement (process understanding and safety impact),
- drying process and impact on cladding,
- fuel characterisation (real fuel versus experimentally investigated rods),
- sufficient coverage of parameter range by experiments and transferability of results to other materials and operating conditions.

Many actors participated in programmes on Transport Shock and Vibration Test. Investigations indicated that SNF can be stored and transported safely, even after extended periods of storage

(Pantram, 2019). Long-term integrity of storage containers may be (in case of dry storage) an issue, however this aspect was not covered by this topical uncertainty.

An overview of preferred management strategies and options for this uncertainty is provided in Table 13 for all the actors´ groups; in this overview the management options common for the actors are not necessarily listed in the same line.

Table 13 – Preferences of the different actors (WMOs, TSOs and REs) on the management strategies and options for uncertainty related to performance of spent nuclear fuel during (dry) interim storage

Elements of uncertainty management strategy	**WMOs**	**TSOs**	**REs**
Identification	-	-	-
Characterisation	-	-	-
Representation in SA	Representation of remaining uncertainty in safety assessment: conservatism	Uncertainty determined by uncertainty of release of long-lived fission products	Conservatism
	Repository concept design	Conservatism	For disposal one can assume a scenario assuming a certain or a total fraction of the claddings have failed. The standard scenario of all SA today is that the cladding has failed immediately after repository closure: no credit from cladding is taken. However, in case of transfer from a storage to encapsulation in a disposal container, the number of failed cladding is expected to be very low and well known. In case of SA of the SNF encapsulation, the cladding failure needs to be considered, including the impact on fission gas release. This is also necessary for plant layout/design
Actions to avoid, reduce or mitigate uncertainties	Strategy and tools for data and records management	Monitoring	Characterise hydride reorientation and associated embrittlement during long-term interim storage
	Wider scope: material types, temperature ranges, higher burnups, fuel types (especially MOX)	Key role covered by in-situ monitoring of decisive degradation processes	Programmes on transport shock and vibration test
	Key radionuclides (Impurities C-14, Cl-36)	Encapsulation process	Extending storage time
	Uncertainty impact on (Sub) criticality assessment	Storage time	Understanding of the degradation processes during storage conditions
	Activities focusing on the practical recommendations	Benchmarks to test reliability of data and codes	R&D on adoption, validation and verification of fuel performance codes for SNF dry storage conditions, transportation
		Study and testing of SNF in interim storage conditions	Investigation of aging effects during long-term storage – combined effect of DHC, creep, SCC
		Testing handling of degraded SNF	
		Defining strategies for handling degraded SNF	

6. Synthesis of the 4th UMAN Workshop dedicated to management options and preferences of different actors regarding waste inventory related uncertainties

This chapter provides outcome of the 4th UMAN Workshop, dedicated to the management options and preferences of uncertainties related to waste inventory. The commonalities and differences with respect to the management of these uncertainties among the different types of participating actors (i.e. WMOs, TSOs and REs), identified during the workshop, are discussed. In case of the identified differences, it was attempted to analyse the reasons behind the different actors´ perspectives.

The objectives of the workshop as well as the overall organisational issues and adopted methodology are described in details in Chapter 2. The agenda of this workshop is provided in Appendix A4.

6.1 Considered uncertainties

About 20 uncertainties related to waste inventory, relevant to safety and decision-making, were identified and described in Bielen et al. (2023) in the framework of UMAN Subtask 3.2, based on the 2nd UMAN Questionnaire. However, during the workshop only limited number of topical uncertainties could be addressed. Therefore, the uncertainties for consideration in the 4th UMAN Workshop were selected based on an additional short survey performed in the framework of UMAN Subtask 4.2. The survey was undertaken in order to identify the uncertainties that are of the highest safety relevance among the UMAN participants as well as members of the EU project "*Pre-disposal management of radioactive waste*" (PREDIS) (see Kaempfer et al., 2023). Based on this survey, the following uncertainties were selected for the purpose of the 4th UMAN Workshop:

- uncertainties related to **physico-chemical conditions in the storage or disposal facility** as an example of uncertainties associated with the evolution of the disposal system,
- uncertainties related to **radionuclide activity (including the scaling factor)** as an example of uncertainties associated with the initial characteristics,
- uncertainties related to **chemical composition (with a special attention to organic content)** as an example of uncertainties associated with the initial characteristics.

It should be also noted that in Bielen et al. (2023), uncertainty associated with the radionuclide activity and uncertainty associated with the scaling factors were treated as two separate uncertainties related to waste radiological properties. However, due to high relevance and interest among the UMAN participants as well as other interested EURAD partners, these two uncertainties were combined into one for discussions in the 4th UMAN Workshop. Similarly, the uncertainty on chemical composition covered uncertainty associated with chemical composition and uncertainty on the cellulose content in organics-bearing waste.

The assignment of the topical uncertainties to the different types of the generic uncertainties identified in UMAN (see Section 2.2) is illustrated in Figure 12.

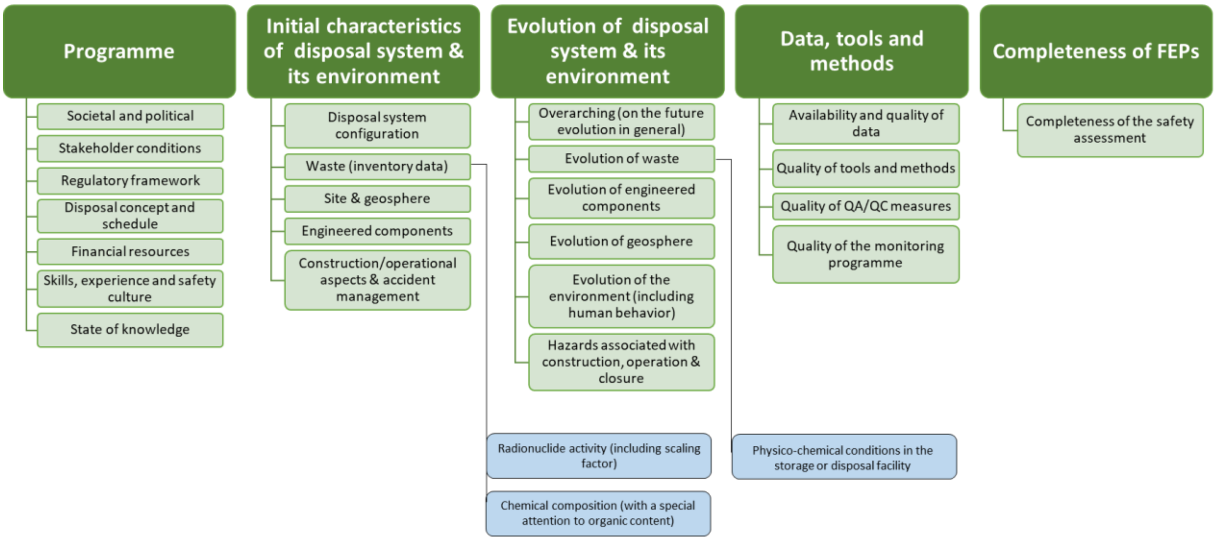

Figure 12 – Multi-level uncertainty classification scheme developed in WP UMAN for uncertainties related to waste inventory

6.2 Views of the actors´ groups

6.2.1 Uncertainties related to physico-chemical conditions in the storage or disposal facility

One of the questions addressed during the workshop was safety significance of the uncertainties related to physico-chemical conditions in storage or disposal facility. The WMOs considered that the safety significance of this uncertainty is between medium and high. Such rating was based on the lack of knowledge. However, it was also pointed out that the significance of the uncertainties is expected to decrease to low in the later phases of the disposal programme, i.e. once the facility would be constructed. During discussions it was mentioned by WMOs that after repository closure, remaining uncertainties cannot decrease, but if repository's design is robust, the consequences of the uncertainties would be low.

Slightly different view was expressed by REs. It was recognised that the physico-chemical conditions in storage or disposal facility are very important, as they influence the mobility of safety relevant radionuclides when interacting with engineered barrier materials, its alteration products and the repository rock. They are particularly important for safety after post-closure. During site selection, these conditions are important as they may allow to distinguish between a more and a less favourable site. However, the related uncertainties are of lower importance. REs also emphasised that the effect of the uncertainty is radionuclide specific. Similar to WMOs, REs indicated that significance of the uncertainties will probably decrease over time due to increase of knowledge and experience. However, it was pointed out that the opposite result also cannot be excluded, e.g. due to ageing of equipment and facilities, non-implementation of the programme, introduction of stronger legal and regulatory requirements, increasing of the civil society interest, etc.

In case of TSOs, there was no consensus about safety significance of this uncertainty and especially about its evolution over time. In one case it was considered that uncertainties linked to this topic are known, but further analysis still could be beneficial, while in the other cases its high safety significance was identified, especially in the later phases of the disposal programme, as physico-chemical conditions in storage or disposal facility can influence the waste package integrity and performance, and indirectly the engineered barrier system integrity, e.g. in the case of expansive reactions in waste.

In REs view, identification and characterisation of the uncertainties related to the physico-chemical conditions in a storage or disposal facility could be through FEPs analysis, research and safety assessment. Characterisation of the uncertainty should take into account internal conditions in the facilities as well as the external conditions around them.

A common agreement between WMOs, TSOs and REs was related to characterisation of physico-chemical conditions. It was pointed out that collection of data and appropriate characterisation of the conditions in the storage and disposal facilities can reduce the uncertainties. For this purpose, WMOs suggested to develop conceptual models and to perform necessary measurements and experiments. REs emphasised the role of detailed research for uncertainties reduction in case of disposal facilities. They pointed out that even in the case when the evaluated impact is acceptable and the remaining uncertainties are not safety-relevant, it is always possible to go further and reduce the uncertainties.

Safety assessment as an important tool for management of the uncertainties was identified by all the actors – WMOs, TSOs and REs. All actors agreed that analysis of a set of alternative scenarios could be an effective way to manage the uncertainties related to the physico-chemical conditions in a storage or disposal facility. In addition, TSOs and REs pointed out application of realism vs. conservatism approach with conservative hypotheses concerning conditions and/or waste behaviour and development of the worst case as well as uncertainty-oriented safety assessment with stochastic modelling and sensitivity analysis. TSOs paid attention to regular review of safety assessment and verification and validation of calculation tools adopted. WMOs mentioned the evaluation of several scenarios that take all uncertainties into account and cumulate their potential effect. REs identified the need to evaluate the evolution of prevailing conditions in time and analyse the influence of the repository on the geological parameters.

The preferences regarding the treatment of the uncertainty are effective actions to reduce, mitigate or even avoid the uncertainty. However, the TSOs pointed out that this uncertainty cannot or will not be reduced to a level that no other management options are needed, i.e. the need for mitigating actions must be anticipated. It was also mentioned by TSOs that uncertainties related to physico-chemical conditions should be lowered in the operational period of storage/disposal facility.

Regarding management of uncertainties related to physico-chemical conditions in storage or disposal facility, WMOs emphasised the importance of a close cooperation among waste producers and the WMO. Such cooperation ensures good knowledge transfer of all relevant data towards WMOs, which can reduce the conservatism.

Monitoring is also one of the uncertainties management options that was considered by WMOs, TSOs and REs, however, with focus on slightly different aspects. REs identified monitoring as a tool for mitigation of uncertainties in physico-chemical conditions in the storage facility, TSOs mentioned frequent inspections of the waste package conditions, while WMOs pointed out the role of pilot facilities – monitoring of such facilities allows to obtain more input data and the ability to compare the current results with new data.

WMOs and REs identified the important role of the facility design and site selection. It was pointed out by WMOs that during the operational period, the design aims to limit the risks by limiting human intervention, optimising ventilation, and setting up a reliable monitoring device for the facility. Concerning the post-closure period, appropriate design can help to minimise the post-closure uncertainties. As an example, here was mentioned the design strategy, which mainly consists in limiting the disturbance of the host clay rock, when the properties of the clay ensure the global performance of the repository. It was also emphasised that the operational safety objectives are not readily compatible with the post-closure safety objectives, and none of them must be given up, e.g. when the retrievability objective tends to make the global design more complex. REs pointed out that appropriate design could help even to avoid uncertainties, e.g. uncertainties on oxidation of spent fuel during storage could be avoided by quality assured storage containers.

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

WMOs and REs expressed a similar view on the significance of the radionuclide activity uncertainties. It was emphasised by WMOs and REs that uncertainties in the determination of activities can lead to underestimation or overestimation of the inventory, with consequences on environmental and human health impact and/or costs. WMOs pointed out that it is necessary to know the characteristics of each kind of waste packages and their radioactive content, because this is key information with regard to the dose rate, the exothermicity and the gas production, among others. On the other hand, the evaluation of inventories must be realistic. An example was given that consequences of the waste package fall accident are crucial for assessing the operational safety and this can have a serious impact on the repository volume and site capacity. In the case of the post-closure safety, the knowledge of the maximum radiological inventory is required, the inventory is also needed to prove the absence of criticality risk. Regarding high level waste, the radionuclide activity determines the exothermicity and its evolution with time what can have impact on the repository design (e.g. the spacing of the micro-tunnel cells). The inventory uncertainties are high for the new nuclear power plants. WMOs rated this uncertainty as of medium significance for all phases and REs considered radionuclide activity uncertainties of higher safety significance, because the process of determination of radioactivity contributes to the waste characterisation and defining an appropriate waste management route (when the uncertainties on the radiological inventory remain large, waste packages might need to be oriented towards another management route, minimising the risks associated with the uncertainties). However, both groups of actors recognised that these uncertainties gradually decrease as disposal programme progresses, waste characterisation improves and Waste Acceptance Criteria (WAC) become clearer. It was also pointed out that significance of activity uncertainty can be radionuclide specific.

There was no general agreement about the significance of the uncertainty on radionuclides activity among the TSOs participants. It was considered relevant, but in one case the uncertainties were rated as very predictable or not very significant (e.g. large uncertainty is identified concerning activation products, but given the low radiotoxicity and short half-life, significance is considered limited), while in the other cases medium or even high importance was indicated (e.g. scaling factor uncertainty may lead to an inventory underestimation or overestimation, with consequences on environmental impact and/or costs). The technical capability to quantify accurately this kind of uncertainties was not fully shared by all TSOs participants.

The methods for identification and characterisation of the uncertainties related to radionuclide activity, identified by REs, include radiological characterisation, application of statistical methods on data and consideration of the accuracy of the measurements. WMOs linked the radionuclide activity uncertainties to representativeness of samples, measurement accuracy and model uncertainty. They identified that the uncertainties relate mainly to parts of the overall radioactive waste inventory, being: (i) waste prognosis for the future decommissioning and dismantling, (ii) waste from past decades, for which the records are compiled according to the then-existing criteria (this includes the waste awaiting retrieval). It was also noted that higher uncertainties of daughter activities can be caused by how the computational code considers radioactive decay or what simplification was used.

WMOs indicated that representation of radionuclide activity uncertainties in a safety assessment depends on the particular disposal project and its current phase. Each type of waste and package must be taken into account for the safety assessment. Both, WMOs and REs pointed out the approach when conservative assumptions regarding radionuclide activity are introduced. According to WMOs, in such case the post-closure assessment makes the results more robust because of the increased inventory and appropriate margin. However, this approach could lead, for some poorly known waste types, to exaggeratedly increased radionuclide contents leading to inconsistencies. In this case, some specific scenarios, such as human intrusion, require a specific method to avoid focusing on results that would not have any physical meaning. WMOs also paid attention that the conservative values obtained from the reference activity value and added upper bound might be very conservative if these upper bounds are given by waste producers. Therefore, it is suggested to determine the upper bound values by expert judgment. WMOs also noticed that regular review of safety assessment can also reduce the uncertainties.

It was pointed out by REs that the uncertainty management strategy should be accompanied by effective actions to reduce, mitigate or avoid the uncertainty. All the actors agreed that these uncertainties can be reduced (if there is a need to) or, in view of WMOs, mitigated.

Regarding the radionuclide activity uncertainty management strategy, WMOs indicated that depending on the phase of the national disposal programme, it may involve various sets of means, from legal and regulatory requirements, through an ongoing iterative process on detailing the data as the waste arises and/or undergoes its characterisation through the predisposal management chain. All representatives of the WMOs agreed that uncertainties related to radionuclide activity can be reduced and mitigated during waste treatment and conditioning by characterisation process. The priority was given to non-destructive measures. It was suggested that focus should be given on more accurate evaluation of activities for specific key radionuclides with higher impact on environment and human health. Other radionuclide activity uncertainty management options include periodical redefine/update of the scaling factors. Important role in reducing the uncertainty also plays interaction between waste producer and WMO. A regular contact with waste producers ensures that the WMO is informed about anomalies or expected changes in the batches. Special attention was paid by WMOs to the spent nuclear fuel and heat generating waste: development of credit burnup evaluation methodology for criticality assessment, methodologies reducing conservatism for loading of disposal canisters, activation calculations (Monte Carlo based) and verification of the calculations by measurements allowing for well bound activation related uncertainty, development of models for the temperature evolution during the interim storage before disposal to reduce/remove temperature requirements for disposal. In addition, the issue of “historical” waste was also raised by WMOs. It was indicated that radionuclide activity uncertainties in this case can be reduced through the inspection and re-measuring, if required.

REs also emphasised the role of measurements in reducing the radionuclide activity uncertainties. It was pointed out that early identification, even if not very accurate, is very important. It can be later improved with the more detailed and accurate measurements. Regular update of information on waste amounts and radionuclide activity as well as review of scaling factors were indicated as primary options for reduction of the uncertainty on radionuclide activity. REs also indicated that, depending on the type of waste, there could be problematic radionuclides that would require special attention (e.g. I-129, Cl- 36 and C-14 in HLW glass, Cl-36 and the organic/gaseous C-14 source term in spent fuel, gaseous C-14 source term evolution over time for metallic waste).

It was mentioned earlier that not all TSOs considered radionuclide activity uncertainties of high importance. However, those who did so, indicated minimisation of waste inventory, scaling calculations in case of difficult to measure radionuclides, supplementary measurements, reliability and traceability of the radionuclide activity (also through the strict cooperation between waste producers and WMOs), waste tracking system and additional checks and characterisation as preferred uncertainty management strategy. This was in agreement with the point of view of WMOs and REs.

6.2.3 Uncertainties related to chemical composition of the waste (with a special attention to organic content)

The significance of the uncertainty on chemical composition depends on waste, chemicals and disposal system. Most WMOs considered this uncertainty as relevant (chemicals can have an impact on the stability of the waste and waste package, the presence of organics may lead to formation of complexing substances and mobilise even poorly mobile radionuclides and facilitate their migration; bacteria can consume the organic matter and thus influence the geochemical environment in some disposal cells) and noted that it should be studied deeply. However, it depends on the aspect considered: safety significance was assessed to be high for impurities, medium for chemical behaviour and low for others. In addition, it was indicated that the significance can be radionuclide specific.

TSOs considered uncertainty related to chemical composition relevant in the later phases of the RWM programme implementation (relevant in phases 2 – 3 and very relevant in phases 4 – 5) mainly due to the same reasons as WMOs, i.e. presence of complexing agents which can influence the mobility of the radionuclides and affect the integrity and stability of waste as well as barriers surrounding the waste. However, the significance of this uncertainty was assessed mainly as limited, because the chemical composition of waste is generally assumed to be known. This uncertainty could be more important only for the waste types with slow leaching from the waste matrix as the chemical composition of the waste is a factor in establishing the limitation of radionuclide solubility and mobility. It is expected that the safety significance does not change over long-term time scales.

REs pointed out that significance of the chemical composition uncertainty depends on the stage of the repository development programme. It is supposed that gained knowledge will reduce the uncertainties in course of time and mainly its significance was not considered as high. REs expressed a similar approach as TSOs and WMOs and identified formation of complexes as one of the factors that makes this uncertainty relevant. Other issues related to chemical composition uncertainties considered by REs included: C-14 release associated to organic and gaseous form, detrimental impact to engineered barriers (e.g. sulphate attack), release of organic materials from cementitious waste products and structures, salt content of bitumen and fire hazard.

As potential methods for identification and characterisation of the uncertainties related to chemical composition, WMOs noted knowledge of used non-radiological features of used materials (e.g. electronic waste, though knowledge is limited) and mass of overall materials and additives. REs mentioned waste characterisation (e.g. laboratory measurements on organic and inorganic C-14 content in spent ion exchange resins) as well as waste generation history.

The uncertainties related to chemical composition can be represented in the safety assessment by development of specific scenarios and appropriate parameter selection, performing organic content oriented uncertainty analysis (TSOs and REs) and using conservative assumptions (REs).

All the actors, WMOs, TSOs and REs, noticed that there is potential for reduction of the uncertainties related to chemical composition.

WMOs recognised that knowledge and characterisation are very important in management of the uncertainty related to chemical composition. It can be reduced by more accurate measurements, improved waste acceptance processes and increased knowledge of physico-chemical properties through research and development activities. It was pointed out that analysis of specific waste streams related to dose-contributing radionuclides could provide more detailed information about specific safety relevant materials. Appropriate waste package design is also an important factor. WMOs indicated that close cooperation between WMO and waste producers can help to reduce this uncertainty as well. It was emphasised that information about materials should be provided as soon as possible and before conditioning.

The preferred management strategies identified by TSOs are also focused on research (e.g., studies on leaching, chemical interactions between the components of the disposal system, harmonisation of the knowledge on colloid transport), characterisation/verification of chemical content and cooperation between waste producers and authorities in order to receive timely the available records. In addition, it was pointed out that the uncertainties in chemical composition could be reduced by appropriate waste conditioning and waste package design.

The priority of REs in managing the chemical composition uncertainties was given to the detailed identification of the chemical composition for each type of radioactive waste. It was pointed out that chemicals in the materials, which are used for conditioning of radioactive waste, are also important. Information about waste generation history can help to reduce this uncertainty as well. Other elements that need attention in the management of this topical uncertainty are storage and disposal conditions. It was suggested to consider influence of the conditions within the storage facility on the behaviour of the chemicals and on the status of the waste and their packages, and to study if waste containing chemical components could impact waste located in other part of the repository.

7. Summary and Conclusions

Within WP UMAN Subtask 4.3 five workshops have been held to identify 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 for safety of considered uncertainties as well as the evolution of their safety significance over the programme phases were discussed. Finally in each workshop, future joint activities and initiatives such as research and development, strategic studies and knowledge management were identified by all three actors´ groups.

These above-mentioned aspects were discussed for selected examples of uncertainties related to five uncertainties types considered in WP UMAN, i.e. uncertainties related to site and geosphere, human aspects, spent nuclear fuel, waste inventory and near-field. The management aspects of uncertainties associated with the near-field are however not under the scope of this report and are provided in Becker et al. (2024).

Different types of radioactive waste and their disposal solutions in different host rocks (rock salt, claystone and crystalline rock) were considered in the first four UMAN workshops, reflecting the specificities of the national programmes represented by the participating organisations.

This report summarises the commonalities and differences with respect to the management of the in WP UMAN Subtask 4.3 addressed uncertainties among the participating actors (i.e. for WMOs, TSOs and REs).

The following general outcomes of the 1st UMAN Workshop, dedicated to management options and preferences of different actors regarding **site and geosphere uncertainties**, can be identified:

- There is generally a good agreement between WMOs, TSOs and REs regarding importance of an uncertainty and the management strategy to be followed.
- For the uncertainties regarding hydraulic conductivity of the host rock, sorption capacity of the host rock, homogeneities of the host rock and fault locations, detection and reactivation, the importance of the uncertainty is generally high in the first phases 0 – 2 of the development of a disposal facility, and is decreasing afterwards, with some exceptions for some of the host rocks. There is an evolution in the safety significance of the uncertainty, and it is also depending on the type of the host rock. Worth mentioning is that some of the uncertainties can increase after construction, waste emplacement and/or facility closure due to the effects of e.g. temperature rise in the disposal galleries, EDZ, etc.
- For the above-mentioned uncertainties, the main management strategy is to reduce them by exploration of the features of the host rock and surrounding areas during the early stages of the development of the disposal facility.
- The significance of the uncertainty related to climate evolution is dependent on the climatic zone/latitude and altitude of the country/site as well as host rock depth. Its importance can be determined rather on a case by case basis.
- The representation of these uncertainties in the SA depends on the goal of the assessment/scenario. Often, the preferred representation was through probabilistic/stochastic modelling, or through using bounding parameters/hypothesis for the uncertainty. Scenarios such as altered evolution scenarios and what-if-scenarios can be used to assess some of the uncertainties and demonstrate the robustness/remaining safety margin.

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 C1 for each topical uncertainty considered in the 1st UMAN Workshop. Note that these identified activities and initiatives are presented as originally formulated and are not prioritised.

The 2nd UMAN Workshop, dedicated to the management options and preferences of the different actors with respect to the **uncertainties on human aspects**, was found to be of high interest by all three participating actors´ groups (i.e. WMOs, TSOs and REs). The actual constellation of the three actors groups corresponded very well to the intended list of the participating organisations. As planned, the number of WMOs representatives was slightly higher as compared to those of TSOs and REs; the latter actors´ groups were however equally balanced. Based on the material available after the workshop, an elaboration of a detailed description of the status of the national programmes (i.e. current programme phase, host rock, waste types, disposal type, etc.), constituting the framework of the workshop discussions, was not possible.

All actors provided their views on the safety significance of the considered four topical uncertainties as well as on the expected evolution of the safety relevance of these uncertainties over the programme phases. The management preferences were discussed by the three types of actors particularly for the specific actions for uncertainty reduction, mitigation and avoidance; the preferred options for the other elements of the uncertainty management scheme were also provided, however in a narrower extent and not always by all three actors´ groups. This could be most probably explained by the different roles/interest/concerns of these actors in RWM programme – the considered topical uncertainties on human aspects seems to be rather of a concern of WMOs and TSOs in comparison to the participating REs. Another factor influencing the actors´ responses might be the current implementation stage of the national programmes reflecting the available experience and information, for which uncertainty management strategy and/or SC/SA are currently under development. In the workshop, future joint activities and initiatives such as research and development, strategic studies and knowledge management were in addition presented by all three actors´ groups. These activities and initiatives are provided in a tabular form in Appendix C2 for each topical uncertainties considered in this workshop. Note that these identified activities and initiatives are presented in their original formulation and are not prioritised.

Some differences in the actors' view, particularly on the assessment of the uncertainties safety significance and its evolution over programme phases, were identified already within the single actors´ groups, particularly for WMOs. With this respect, comparison of the views among the actors´ groups was challenging and for this reason the broad spectrum of the views within the actors´ groups was presented in this report. These differences most probably result from the current implementation phase of the national programme, national regulations and safety concept (e.g. provision of waste retrievability, waste recoverability, monitoring), lessons learned and even some cultural aspects (e.g. in case of the uncertainty related to public acceptance). A deep analysis of the differences within the actors´ groups is however out of the scope of this report.

In general, very similar impacts of the topical uncertainties on safety were identified by the three actors´ groups. Different national regulatory frameworks and safety concepts (e.g. provision of waste retrievability, waste recoverability and monitoring), led to minor differences in the actors´ views on this aspect. Negative impacts for safety were identified by all three actors´ groups for the uncertainty related to the schedule for implementation of a disposal programme (here specifically for transport, interim storage, operational, post-closure safety) and the uncertainty related to the adequacy of safety-related activities in the construction phase (here specifically for construction, operational and long-term safety). For the uncertainty related to public acceptance and uncertainty on "new" knowledge both negative and positive implications for safety were identified by at least two actors´ groups.

The assessment of the safety significance (as low, medium and high) as well as its expected evolution over the programme phases differed among the actors´ groups (and as mentioned above, in case of WMOs also within this group). As compared to the other actors´ groups, this assessment was very detailed and phase-dependent for WMOs, under consideration of specific regulatory/safety requirements such as waste retrievability, waste recoverability and monitoring provision. This results from the fact that WMOs are responsible for implementation of the national programme as well as for uncertainties management over the phases of the national programme. On the other hand, the differences in the assessment were also due to the different aspects of the topical uncertainties considered by the different actors, depending on their roles/interest/concerns in RWM programme. This was very predominant particularly in case of the uncertainty related to “new” knowledge. The presented assessment of the safety significance and its evolution as well as the preferred management options varied accordingly and could not be compared directly. Further, there was an impression, when analysing the actors´ views on the uncertainties significance for safety, that there was different understanding of this term, related sometimes to significance of the uncertainty itself.

Generally, several common preferences with respect to the management of the topical uncertainties could be identified for all three actors´ groups, including general management strategy. Furthermore, there was a number of options provided by individual actors, reflecting predominantly their role/interest/concern in RWM programme as well as the current implementation phase of a national programme they represented. In some cases, these specific preferences of the actors complemented each other and as such were analysed and presented in this chapter. Further it should be noted that it was not always possible to assign the presented options to the specific categories for uncertainty reduction, mitigation and avoidance, based on the material available from the workshop. For this reasons, these options were presented in this chapter without this specific classification.

All actor´s groups identified several key elements of the general management strategy, which are in line with the strategy developed in WP UMAN (see Figure 7 on left hand side). Depending on the topical uncertainty, these key common elements are stepwise, flexible approach (important for the uncertainty on the schedule for implementation of a disposal programme), stakeholder interactions (relevant for the uncertainty on public acceptance, on the schedule for implementation of a disposal programme and on “new” knowledge) and safety culture (important for the uncertainty on the adequacy of safety-related activities in the construction phase). There were other key elements identified by (some of) the actors, not included in the general management strategy depicted in Figure 7. In case of the uncertainty on public acceptance all actors emphasised transparency, WMOs the scientific basis, both TSOs and REs trust building required in a decision-making process. Further, in case of the uncertainty related to “new” knowledge, appropriate knowledge management (strategy) was underlined by TSOs and REs.

The actual constellation of the three actors´ groups, participating in the 3rd UMAN Workshop (regarding **spent nuclear fuel related uncertainties**) corresponded very well to the intended list of the participating organisations. This means that the number and type of participants were balanced so that the weight of each point of view was also balanced. Further, all or almost all types of host rocks have been considered and also almost all programme phases have been represented in the evaluation, covering policy, framework and programme establishment, site evaluation and site selection, and also construction phase.

Uncertainties related to SNF have different importance - from low to high level. It is not really possible to develop one common view. There were provided different preferences and these depended on the type of the actors.

As far as uncertainties on fuel history/reactor operation/irradiation and nuclear data were concerned, the range of the importance varied from low to high, depending on the stage of the RWM programme, the particularities of the nuclear programme (different NPP and fuel types) and also the repository concept.

For the participants it was important to underline that only few radionuclides are considered relevant for post-closure safety. These radionuclides are: Cl-36, C-14, Se-79, I-129, Ni-59, tc-99 Ra-226.

More important is to know nuclide inventory, implying a good knowledge of fuel history data (reactor, operation, and irradiation conditions) and nuclear data. The most relevant uncertainties were the burnup and linear power uncertainties for Cl-36 and I-129 inventories and IRF values, however it is important to consider that long migration time (for example in clay rock) could decrease the relevance. Uncertainties in nuclear data, like fission yield and cross section, were considered as being of lower relevance than uncertainties related to transport time in geosphere. The dose assessment varies with safe implementation during storage, transport, conditioning, disposal as well as post-closure safety.

Uncertainties associated with fuel history, reactor operation, irradiation and nuclear data were considered rather of low relevance for safety because of robust design of disposal system, with large safety margins. Fuel history is important for decay heat production, but it is not relevant for long-term safety. Decay heat is controlled through a good barrier system, and it is more important for post-closure safety. Uncertainty related to nuclear data is important if they are estimated using burnup credits. It evolves. Nuclear data and the related uncertainties are important for estimating burnup credits. Burnup credit is a safety approach that accounts for the reduction in the reactivity of configurations with SNF due to the change in their composition after irradiation. There was a consensus that uncertainties on nuclear data have lower impact than fuel history data and reactor operation/irradiation conditions.

Assessment of safety relevance of uncertainties related to performance of SNF during (dry) interim storage varied from low to high; this aspect was considered relevant for prolonged storage (more than 50 years). Particularly important is cladding integrity, challenged by hydrogen embrittlement and hydride reorientations, which could result in deformation of cladding and also cladding creep. This uncertainty is particularly important for transport from an interim storage to potentially existing encapsulation plant and repackaging in a disposal container for a repository. It was considered to have low relevance for post-closure safety because no credit is taken from cladding in safety assessment.

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 C3 for each topical uncertainty considered in the 3rd UMAN Workshop. Note that these identified activities and initiatives are presented as originally formulated and are not prioritised. These activities were considered as means for increase of knowledge and reduction of the topical uncertainties.

Finally, the 4th UMAN Workshop, dedicated to management options and preferences of different actors regarding **waste inventory uncertainties**, gained solid attention from the UMAN participants. It provided a good opportunity to identify and compare the views and approaches of the different types of actors on management of the selected waste inventory related uncertainties.

A lot of commonalities in the approaches of the different actors have been identified. WMOs, TSOs and REs agreed that uncertainties related to physico-chemical conditions in storage or disposal facility can be reduced by a better characterisation of these conditions, monitoring and performing safety assessment. In case of uncertainties on radionuclide activity, all actors´ groups put their focus on measurements. Regarding uncertainties associated with chemical composition, all actors´ groups mentioned the importance of appropriate waste characterisation. In addition, WMOs and TSOs emphasised collaboration among waste producers and WMO.

However, some points of disagreement between the WMOs, TSOs and REs were identified as well. They mainly arise in rating the uncertainties by their significance. The workshop also revealed that the differences in the approaches can arise not only among the different types of actors, but also internally among the participants of the same group. The identified disagreements between the different actors' groups as well as between the participants of the same group can be related to the differences in the implementation stages of the national radioactive waste management programme and different types of facilities considered.

During the 4th UMAN Workshop, all three actors' groups suggested a number of potential future joint activities and initiatives, including research and development, strategic studies and knowledge management. Summary of proposals for each topical uncertainty considered in the 4th UMAN Workshop is provided in a table in Appendix C4. It should be noted that the list of activities and initiatives is presented as originally formulated, i.e. without prioritisation.

Finally it can be concluded that in WP UMAN Subtask 4.3 in general a lot of commonalities in the approaches of the different actors have been identified, also some rather different points of views among the actors´ groups were identified as well. The latter mainly arise in the assessment of the uncertainties significance for safety, which can be related to the differences in the implementation stages of the national radioactive waste management programme and different types of facilities/safety concepts considered.

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Appendix A. Workshops´ agendas

Appendix A1. Agenda of the 1st UMAN Workshop dedicated to management options and preferences of different actors regarding site and geosphere related uncertainties

UMAN Subtask 4.3

Workshop 1: Management options and preferences of different actors regarding site and geosphere related uncertainties

Agenda

The overall objectives of Task 4 of UMAN are 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,…),
- 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 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 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 discussed, analysed and described. Four workshops bringing together organisations contributing to Subtask 4.3, one of the expert groups of Subtasks 3.2 to 3.5 (depending on the addressed topic) as well as other interested EURAD partners, are planned. These workshops constitute 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 first workshop is to foster exchanges and uncover the views of WMOs, REs and TSOs with regard to the management of key uncertainties related to the site and the geosphere. In particular the following topics are focused on:

1. Management of uncertainties in the hydraulic conductivity of the host rock
2. Management of uncertainties in the sorption capacity of the host rock
3. Management of uncertainties of homogeneities of the host rock
4. Management of uncertainties in fault locations, detection and reactivation
5. Management of uncertainties in the climatic evolution (focused on glaciations and permafrost)

These uncertainties were identified as safety significant by the respondents to the questionnaire prepared by Task 3 of UMAN on the characterization, evolution and potential significance of site and geosphere related uncertainties. 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.

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
Workshop Day 2: Actor groups RE, WMO and TSO discuss possible management options and their preferences
Workshop Day 3: Presentation from each actor group, discussion on differences and commonalities between the different groups of actors

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 results will be presented by rapporteurs in three parallel sessions on the second day of the workshop. There is also room for the participants to present their own results, which of course is encouraged.
Due to the ongoing pandemic, it is decided to that the workshop will be held online. This will be done in Skype sessions for every day. Invites to these sessions will follow.

Workshop Day 1
Friday 19 February 2021
Introduction and goals of the workshop

9:00 **Welcome of participants** - Jacques Grupa (NRG)

9:10 **Introduction to the workshop and objectives** - Frank Lemy (Bel V) & Astrid Göbel (BGE)

9:30 **Organisation of the workshop** - Jacques Grupa (NRG)

9:40 **Outcome of UMAN Subtask 3.3** - Daniela Diaconu (RATEN)

10:00 **Discussion and questions** - All participants

10:15 *Break*

10:30 **Uncertainty management strategies and options (interim results of subtask 4.2)** - Thomas Kämpfer (Nagra), Bernd Grambow (Subatech), Nina Müller-Hoeppe (BGE)

> *10:30 **General overview of the interim results of subtask 4.2** - Thomas Kämpfer*
>
> *10:45 **Preferred management options and strategies - Hydraulic conductivity / flow properties** - Thomas Kämpfer (Nagra)*
>
> *10:55 **Preferred management options and strategies - Sorption capacity and radionuclide transport** - Bernd Grambow (Subatech)*
>
> *11:05 **Fault location, detection and reactivation** - Thomas Kämpfer (Nagra)*

11:15 ***Climatic evolution with focus on glaciations and permafrost*** *- Nina Müller-Hoeppe (BGE)*

11:25 ***Summary and outlook from the perspective of subtask 4.2*** *- Thomas Kämpfer (Nagra)*

11:30 **Discussion and questions** - All participants

11:45 *Break*

12:00 **Geosphere uncertainties: presentation from FUTURE on the management of uncertainties associated with radionuclide mobility** - Sergey Churakov (PSI) speaks for Eurad-FUTURE

12:20 **Discussion and questions -** All participants

12:35 **Expected input from workshop participants + explanation of the homework in preparation of Day 2 -** (Jacques Grupa)

12:45 *End of the first day*

Workshop day 2
Tuesday 2 March 2021
Presentations of participation input

9:00 **Welcome and introduction to workshop day 2 -** Jacques Grupa (NRG)

9:15 Three *parallel sessions for WMO's, RE's and TSO's*

9:25 **Presentation and discussion of the homework results** - Rapporteur & participants

10:10 *Break*

10:25 **Continuation of presentations and discussion of the homework results** - Rapporteur & participants

12:00 **Discussion and synthesis** – Rapporteur

12:30 *End of parallel sessions*

12:35 **Closing of workshop day 2**

12:45 *End of the second day*

Workshop day 3
Thursday 11 March 2021
Synthesis of participation input

9:00 **Introduction to workshop day 3 -** (Jacques Grupa)

9:15 **Presentation of the synthesis TSO** (including 15’ for discussions and questions) - rapporteur of TSO parallel session

10:00 **Presentation of the synthesis RE** (including 15’ for discussions and questions) - rapporteur of RE parallel session

10:45 *Break*

11:00 **Presentation of the synthesis WMO** (including 15’ for discussions and questions) - rapporteur of WMO parallel session

11:45 **Discussion on commonalities and differences between the different actors** - All participants

12:15 **Discussion on workshop model -** All participants

12:30 **Concluding remarks on the outcome of the workshop - (**Astrid Göbel & Frank Lemy)

12:45 **Closing of workshop day 3 -** (Jacques Grupa)

12:50 *End of day 3*

Appendix A2. Agenda of the 2nd UMAN Workshop dedicated to management options and preferences of different actors regarding human aspects related uncertainties

UMAN Subtask 4.3

Workshop 2: Management options and preferences of different actors regarding uncertainties related to human aspects

Agenda

The overall objectives of Task 4 of UMAN are 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,…),
- 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 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 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 discussed, analysed and described. Four workshops bringing together organisations contributing to Subtask 4.3, one of the expert groups of Subtasks 3.2 to 3.5 (depending on the addressed topic) as well as other interested EURAD partners, are planned. These workshops constitute 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 second workshop is to foster exchanges and uncover the views of WMOs, REs and TSOs with regard to the management of key uncertainties related to human aspects. In particular, uncertainties associated with the following topics are focused on:

6. **Public acceptance of the repository at potentially suitable or projected locations**
7. **Schedule to be considered for implementing the different phases of the disposal programme**
8. **Adequacy of safety-related activities during construction for the implementation of safety provisions**.
9. **“New” knowledge”** i.e. any new knowledge becoming available in the course of RWM programme generated through RD&D activities, technology development, etc. and does not refer solely to the monitoring aspects .“New” means here that the knowledge has emerged by research and monitoring, but also is new for certain actors and has been ignored by others.

These uncertainties were identified as safety significant by respondents to the questionnaire prepared by Task 3 of UMAN on the uncertainties related to human aspects and represent different categories of uncertainties identified in UMAN (i.e. programme 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
Workshop Day 2
Actor groups RE, WMO and TSO discuss possible management options and their preferences
Workshop Day 3
Presentation from each actor group, discussion on differences and commonalities between the different groups of actors

The participants will be asked to do some work on their views on the different topics between Day 1 and Day 2 of the workshop. These views will be presented by rapporteurs during one of the parallel sessions dedicated to the three actor groups on the second day of the workshop. There is also room for the participants to present their own results, which of course is encouraged.
Due to the ongoing pandemic, it is decided that the workshop will be held online. This will be done in Skype sessions for every day. Invitations to these sessions will follow.

Workshop Day 1
Friday 4 June 2021
Introduction and goals of the workshop

9:00 **Welcome of participants**

9:10 **General Introduction to UMAN & Types of Uncertainties - Frank Lemy (Bel V)**

9:25 **Selection of the key uncertainties related to Human Aspects - Jean-Noël Dumont (ANDRA)**

9:55 **Discussion and questions**

10:10 **UMAN Task 4 Objectives & Approach - Frank Lemy (Bel V)**

10:30 Break

10:45 **Options for managing uncertainties related to Human Aspects - Jitka Mikšová (SURO)**

I. Programme uncertainties:
Topic 1: Public acceptance of the repository at potentially suitable or projected locations
Topic 2: Schedule to be considered for implementing the different phases of the disposal programme - SURO (Jitka Mikšová, Hana Vojtěchová)

II. Uncertainties related to initial characteristics and uncertainties associated with data, tools & methods used in the safety case:
Topic 3: Adequacy of safety-related activities during construction for the implementation of safety provisions - BGE (Astrid Göbel, Nina Müller-Hoeppe and Agnieszka Strusińska-Correia)

III. Uncertainties in the evolution of the disposal system and its environment:
Topic 4: “New” knowledge - SURO (Jitka Mikšová, Hana Vojtěchová)

11:45 **Discussion and questions**

12:00 **Expected input from workshop participants + explanation of the homework in preparation of Day 2 - Jacques Grupa (NRG)**

12:10 **Discussion and questions**

12:15 *End of the first day*

Workshop day 2
Friday 11 June 2021
Presentations of the input provided by the participants

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

9:15 Three *parallel sessions for WMO's, RE's and TSO's*

9:25 **Presentation and discussion of the homework results**

10:10 *Break*

10:25 **Continuation of presentations and discussion of the homework results**

12:00 **Discussion and synthesis**

12:30 *End of parallel sessions*

12:35 **Closing of workshop day 2**

12:45 *End of the second day*

Workshop day 3
Wednesday 23 June 2021
Synthesis of the views of the different actor groups

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

9:15 **Presentation of the synthesis TSO** (including 15' for discussions and questions)

10:00 **Presentation of the synthesis RE** (including 15' for discussions and questions)

10:45 *Break*

11:00 **Presentation of the synthesis WMO** (including 15' for discussions and questions)

11:45 **Discussion on commonalities and differences between the different actors**

12:15 **Discussion on workshop model**

12:30 **Concluding remarks on the outcome of the workshop**

12:45 Closing of workshop day 3

12:50 *End of day 3*

Appendix A3. Agenda of the 3rd UMAN Workshop dedicated to management options and preferences of different actors regarding spent nuclear fuel related uncertainties

UMAN Subtask 4.3

Workshop 3: Management options and preferences of different actors regarding spent fuel related uncertainties

Agenda

The overall objectives of Task 4 of UMAN are 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,…),
- 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 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 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 discussed, analysed and described. Five workshops bringing together organisations 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 constitute 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 third workshop is to foster exchanges and uncover the views of WMOs, TSOs and REs with regard to the management of key uncertainties related to spent fuel. In particular, uncertainties associated with the following topics are focused on:

1. **Fuel history data** (e.g. composition of fresh fuel/cladding, especially on impurity level), **reactor operation and irradiation conditions** (e.g. burn-up history, cooling time).
2. **Nuclear data** (e.g. cross-sections, fission product yields, decay data, etc.).
3. **Performance of spent nuclear fuel (SNF) during (dry) interim storage** (e.g. degradation mechanisms and their impact on handling of SNF for conditioning of SNF for final disposal).

These uncertainties were identified as safety significant by respondents to the questionnaire prepared by Task 3 of UMAN on the uncertainties due to spent fuel and represent different categories of uncertainties identified in UMAN (i.e. programme 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
Workshop Day 2
Actor groups WMO, TSO and RE discuss possible management options and their preferences
Workshop Day 3
Presentation from each actor group, discussion on differences and commonalities between the different groups of actors

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 the second day of the workshop. Due to the ongoing pandemic, it is decided to that the workshop will be held online. This will be done in ZOOM sessions for every day. Invitations to these sessions will follow.

We would like to pay your attention to other material related to spent nuclear fuel, developed by EURAD WP11 State of Knowledge:

- State of Knowledge Report (SoK) - Spent Nuclear Fuel (Domain 3.1.1) by Kastriot Spahiu (formerly SKB)
- EURAD internal Wiki
  see Theme 3: Engineered Barrier System → 3.1 Wasteforms → 3.1.1 Spent nuclear fuel (SNF)

Workshop Day 1
Wednesday 9 February 2022
Introduction and goals of the workshop

9:00 **Welcome of participants**

9:10 **General introduction to UMAN & types of uncertainties – Daniela Diaconu (RATEN)**

9:30 **Selection of the key uncertainties related to spent fuel – Valéry Detilleux (Bel V)**

9:55 **Discussion and questions**

10:10 **UMAN Task 4 objectives & approach – Agnieszka Strusińska-Correia (BGE)**

10:30 Break

10:45 **Options for managing uncertainties related to spent fuel – Michel Herm (KIT INE)**

11:25 **Evolution of appreciation of uncertianties of spent fuel management and disposal from the MICADO project to EURAD – Bernd Grambow (Prof. emeritus, Subatech/IMT Atlantique)**

11:45 **Discussion and questions**

12:00 **Expected input from workshop participants + explanation of the homework in preparation of Day 2 – Marieke Schopman - van Gemert (NRG)**

12:15 **Discussion and questions**

12:30 *End of the first day*

Workshop day 2
Thursday 17 February 2022
Presentations of participation input

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

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

9:25 **Presentation and discussion of the homework results**

10:10 *Break*

10:25 **Continuation of presentations and discussion of the homework results**

11:40 **Discussion and synthesis**

12:10 *End of parallel sessions*

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

12:30 *End of the second day*

Workshop day 3
Monday 28 February 2022
Synthesis of participation input

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

9:05 **Objectives of the workshop – Daniela Diaconu (RATEN)**

Topic 1
Fuel history data, reactor operation and irradiation conditions
9:10 **Presentation of the synthesis TSO** of Topic 1
9:25 **Presentation of the synthesis RE** of Topic 1
9:40 **Presentation of the synthesis WMO** of Topic 1

9:55 **Discussion of the results** of Topic 1

10:15 *Break*

Topic 2
Nuclear data
10:30 **Presentation of the synthesis TSO** of Topic 2
10:45 **Presentation of the synthesis RE** of Topic 2
11:00 **Presentation of the synthesis WMO** of Topic 2

11:15 **Discussion of the results** of Topic 2

Topic 3
Performance of spent nuclear fuel (SNF) during (dry) interim storage
11:35 **Presentation of the synthesis TSO** of Topic 3
11:50 **Presentation of the synthesis RE** of Topic 3
12:05 **Presentation of the synthesis WMO** of 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*

Appendix A4. Agenda of the 4th UMAN Workshop dedicated to management options and preferences of different actors regarding waste inventory related uncertainties

UMAN Subtask 4.3

Workshop 4: Management options and preferences of different actors regarding waste inventory related uncertainties

Final Agenda

The overall objectives of Task 4 of UMAN are 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,…),
- 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 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 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 discussed, analysed and described. Five workshops bringing together organisations 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 constitute 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 third workshop is to foster exchanges and uncover the views of WMOs, TSOs and REs with regard to the management of key uncertainties related to waste inventory. In particular, uncertainties associated with the following topics are focused on:

1. **Physico-chemical conditions in the storage or disposal facility**
2. **Radionuclide activity (including the scaling factor)**
3. **Chemical composition (with a special attention to organic content).**

These uncertainties were identified as safety significant by respondents to the questionnaire prepared by Task 3 of UMAN on the uncertainties due to waste inventory and represent different categories of uncertainties identified in UMAN (i.e. programme 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
Workshop Day 2
Actor groups WMO, TSO and RE discuss possible uncertainty management options and their preferences
Workshop Day 3
Presentation from each actor group, discussion on differences and commonalities among the different groups of actors

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 the second day of the workshop. Due to the ongoing pandemic, it is decided that the workshop will be held online. This will be done in MS Teams/ZOOM sessions for every day. Invitations to these sessions will follow.

Workshop Day 1
6. April 2022
Introduction and goals of the workshop

9:00 **Welcome of participants**

9:20 **General introduction to UMAN & types of uncertainties – Daniela Diaconu (RATEN)**

9:45 **UMAN Task 4 objectives & approach – Agnieszka Strusińska-Correia (BGE)**

10:05 **IAEA activities in Radioactive Waste Characterization – Felicia Dragolici (IAEA)**

10:35 **Discussion and questions**

10:50 Break

11:05 **Selection of the key uncertainties related to waste inventory – An Bielen (Subtask 3.2)**

11:25 **Options for managing uncertainties related to waste inventory – Thomas Kämpfer (Subtask 4.2)**

11:45 **Discussion and questions**

12:00 **Expected input from workshop participants + explanation of the homework in preparation of Day 2 – Marieke Schopman - van Gemert (NRG)**

12:15 **Discussion and questions**

12:30 *End of the first day*

Workshop day 2
20. April 2022
Presentations of participation input

13:00 **Welcome and introduction to workshop day 2**

13:15 *Three parallel sessions for WMOs, TSOs and REs*

13:25 **Presentation and discussion of the homework results**

14:10 *Break*

14:25 **Continuation of presentations and discussion of the homework results**

15:40 **Discussion and synthesis**

16:10 *End of parallel sessions*

16:15 **Closing of workshop day 2**

16:30 *End of the second day*

Workshop day 3
9. May 2022
Synthesis of participation input

9:00 **Welcome and introduction to workshop day 3**

Topic 1
Physico-chemical conditions in the storage or disposal facility
9:10 **Presentation of the synthesis TSO** of Topic 1
9:25 **Presentation of the synthesis RE** of Topic 1
9:40 **Presentation of the synthesis WMO** of Topic 1

9:55 **Discussion of the results** of Topic 1

10:15 *Break*

Topic 2
Radionuclide activity (including the scaling factor)
10:30 **Presentation of the synthesis TSO** of Topic 2
10:45 **Presentation of the synthesis RE** of Topic 2
11:00 **Presentation of the synthesis WMO** of Topic 2

11:15 **Discussion of the results** of Topic 2

Topic 3
Chemical composition (with a special attention to organic content)
11:35 **Presentation of the synthesis TSO** of Topic 3
11:50 **Presentation of the synthesis RE** of Topic 3
12:05 **Presentation of the synthesis WMO** of 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*

Appendix B. Exemplary homework template

TOPIC 1: MANAGEMENT UNCERTAINTIES IN THE HYDRAULIC CONDUCTIVITY OF THE HOST ROCK

- **Our view on the safety significance of this uncertainty**
  - 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.

TOPIC 1: MANAGEMENT UNCERTAINTIES IN THE HYDRAULIC CONDUCTIVITY OF THE HOST ROCK

- **Preferred management strategy**
  - What is your preference regarding the treatment of the uncertainty in the context of the different elements of the strategy? Please substantiate your answer with references and examples. Of particular interest would be examples of pitfalls encountered and lessons learned.

TOPIC 1: MANAGEMENT UNCERTAINTIES IN THE HYDRAULIC CONDUCTIVITY OF THE HOST ROCK

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

TOPIC 1: MANAGEMENT UNCERTAINTIES IN THE HYDRAULIC CONDUCTIVITY OF THE HOST ROCK

- **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

Appendix C. Future joint activities and initiatives identified in UMAN workshops

Appendix C1. List of future joint activities and initiatives (research and development R&D, strategic studies StSt, knowledge management KM, guidance G, not specified NS) identified in the 1st UMAN Workshop dedicated to management options and preferences of different actors regarding site and geosphere related uncertainties

Uncertainty related to	No.	Ideas for future joint activities and initiatives	Actor	Activity type
Hydraulic conductivity of the host rock (and other geological units)	1.1	Guidance/strategic study on upscaling and the management of associated uncertainties (see recommendation associated with the management of uncertainties related to heterogeneities)	TSO	G/StSt
	1.2	A linked key uncertainty in clay to be assessed experimentally is the time it takes for a void volume to become filled by pore water from the host rock after closure of emplacement locations, considering simultaneously the • Diffusion/advection in host rock, plugs and seals • Hydraulic conductivity of host rock including the EDZ • Hydrogen production by corrosion of containers or of cement enforcements, H_2 transport and build up of counter pressure	RE	R&D
	1.3	Knowledge sharing: Methods used in hydraulic conductivity measurement and uncertainty characterization.	RE	KM
Sorption capacity of the host rock (and other geological units)	1.4	Reactive transport modelling approaches	WMO	NS
	1.5	Activity already ongoing in the framework of FUTURE	WMO	R&D
	1.6	Guidance/strategic study on upscaling and transposition from lab to in situ conditions and the management of associated uncertainties, (RE): Upscaling from batch systems on pure phases to the real host rock in confined conditions, and corresponding availability of sorption sites.	TSO	G/StSt
	1.7	Justification of a Kd approach in the SA considering associated uncertainties	TSO	NS
	1.8	Highest safety relevant uncertainties in sorption capacity (SC) in clay rock are for anions. Often zero retention is assumed while even a small retention would block these anions from moving to the biosphere. As this concerns all repository projects in clay rock, and as large statistics is required, a joint experiment (R&D) of large scale diffusion shall be conducted to assess very weak but non-zero Kds, maybe as a first step a conclusive SoK or SOTA shall be produced, focused on ^{129}I and ^{36}Cl.	RE	R&D/KM
	1.9	Identification of relevant sorption processes / mechanism, mechanistic sorption models - bottom up approach for Kd understanding.	RE	NS
	1.10	Activities related to improvement of the sorption models and changes of the transport parameters over time.	RE	NS
Homogeneities of the host rock (and other geological units)	1.11	Identification of what is really understood by "homogeneity", within what degree of variation of what safety relevant property (retention, hydraulic or thermal conductivity, fracture mechanics,….) a host rock volume is considered homogeneous.	RE	NS
	1.12	Knowledge sharing: Assumptions for "homogeneous medium approach" with worse and best case parameters in PA yield very likely too conservative approximations of "heterogeneity". Investigation on which "homogenisation" includes which uncertainties might be worthwhile.	RE	KM
	1.13	R&D regarding upscaling aspects	WMO	R&D
	1.14	Guidance/strategic study/SoK on upscaling and transposition of available data (e.g. from lab, areas surrounding the repository or geophysical investigations) to in situ conditions and the management of associated uncertainties. Upscaling and characterization of heterogeneities (including faults) before the construction of the repository (and in absence of borehole data from the disposal area) are of particular interest.	TSO	G/StSt/KM
	1.15	R&D upscaling aspects	WMO	R&D

Fault locations, detection and reactivation	1.16	As faults are highly safety-relevant, it would be very interesting to investigate uncertainties of methods for their characterization, e. g. the identification of active faults. In general, a strategy seems important how exactly and to what extent uncertainties associated with faults could be reduced to the lowest possible level.	WMO	R&D
	1.17	Guidance/SoK on the treatment of faults and associated uncertainties in a geological disposal program (see also recommendation regarding the management of uncertainties related to heterogeneities)	TSO	G/KM
	1.18	Elucidating reactivation potential of dormant faults if they cannot be avoided through siting.	RE	R&D
	1.19	Knowledge sharing: New fault detection and characterization methods.	RE	KM
Climatic evolution (focus on glaciations and permafrost)	1.20	Knowledge sharing: Development of a common approach how to handle glaciation periods because glaciation periods are not restricted to national borders.	WMO	KM
	1.21	Further research on the climate history and the effects of glaciations will lead to a reduction of uncertainties but some uncertainty will of course remain, especially considering the timescale of one million years. To suggest a way of communication that the system is safe despite this remaining uncertainty.	WMO	R&D
	1.22	Validation of permafrost depth models	RE	R&D
	1.23	Development of coupled climate-permafrost-flow models	RE	R&D
	1.24	Influence of decompaction on host rock properties from analogues and modelling	RE	R&D

Appendix C2. List of future joint activities and initiatives (research and development R&D, strategic studies StSt, knowledge management KM, guidance G, not specified NS) identified in the 2nd UMAN Workshop dedicated to management options and preferences of different actors regarding human aspects related uncertainties

Uncertainty related to	No.	Ideas for future joint activities and initiatives	Actor	Activity type
Public acceptance of the repository at potentially suitable or projected locations	2.1	Transversality of tasks related to "human aspects" within EURAD is very appropriate. UMAN Task 5 in particular could be even enlarged and strengthened in the future.	WMO	NS
	2.2	How to work on safety? Mutual understanding achievable?	WMO	NS
	2.3	International civil society exchange on different national RWM programmes and approaches adopted in different Member States.	WMO	NS
	2.4	Evolution of civil society in the context of/ during the temporality of GDF.	WMO	NS
	2.5	Academic research on ethics and public decisions, with feedback from case studies.	WMO	R&D
	2.6	Human intrusion scenario (which human aspects related ?) – check with IAEA, HIDRA.	WMO	NS
	2.7	Management of programme uncertainties in disposal programmes & safety cases.	TSO	R&D or StSt
	2.8	How to determine/define a level of sufficient public acceptance?	TSO	NS
	2.9	International cooperation in the development of tools/methods and activities related to the demonstration of long-term safety of the planned disposal facility (models, natural analogues, visits to similar existing facilities, etc.) towards the public.	TSO	NS
	2.10	Public acceptance of international repositories?	TSO	NS
	2.11	Analysing possible consequences of changes over time in: (i) social and political conditions and acceptance, (ii) actor groups and-actor opinions.	TSO	NS
	2.12	Exchange of experience on public engagement: There have been different stakeholder engagement processes, but they have not been compared. For instance, in the SITEX projects, actors had a national view. Some comparisons were made in the past as part of the COWAM projects, but	RE	StSt

		these need to go deeper and understand the changes in the public attitude. This initiative could compare the previous experience in public engagement looking across all over Europe and investigate what the best methodologies and tools are in the social science and humanities (SSH) to study public perceptions and attitudes.		
	2.13	A research SSH agenda using advanced methodologies could help answering questions such as: How to measure the perception changes over generations? What triggers compartmental and psychological changes? What determines public perception and is it possible to predict its evolution? What is the trend in public acceptability regarding nuclear energy in general and RWM in particular? Is there a general "law" that can give consistency between public acceptance and local community behaviour?	RE	NS
	2.14	Historical study (similar to the one conducted by the US NWTRB, "Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel: A Report to Congress and the Secretary of Energy" (United States Nuclear Waste Technical Review Board, Arlington, VA, 2009), (available at http://www.nwtrb.gov/reports/nwtrb%20sept%2009.pdf)), analysing for all national programmes how schedule has changed over time, how in some cases planning has been completely abandoned, etc.	RE	NS
Schedule to be considered for implementing the different phases of the disposal programme	2.15	Most of the international projects focus on the long term safety perspective. Comparison between construction plans and different strategies to operate an underground facility.	WMO	
	2.16	Influence of a prolonged interim storage on radioactive waste properties and its effects on a final repository design.	WMO	R&D
	2.17	Connection between interim storage and predisposal to disposal.	WMO	NS
	2.18	Discussion of the aspect that in a GDF mining safety and radiological safety are strongly linked, in particular in the operational phase (phases 3 and 4).	WMO	NS
	2.19	Knowledge management at the level of the nuclear ecosystem, namely the WMO itself, its subcontractors, the waste producers and the TSO, between WMOs / national programmes.	WMO	KM
	2.20	Management of programme uncertainties in disposal programmes & safety cases.	TSO	R&D or StSt
	2.21	Human factors: investigation of the possible ways to maintain knowledge and competence despite big changes in disposal programme implementation.	TSO	NS
	2.22	Monitoring: development on sensors to make sure that parameters influenced by ageing could still be monitored in case of prolonged delays as well as to support the decisions (e.g. by politics) and by this lessen the possibility that a decision at a main step is unduly postponed.	TSO	R&D
Adequacy of safety-related activities during construction for the implementation of safety provisions	2.23	Apart from a few exceptions (GEOSAF, EGOS), construction and operation phases are often underestimated in international projects, the focus being on long-term safety. Engineering issues – not only science – can lead to strategic issues.	WMO	NS
	2.24	Review of available construction technologies/materials.	WMO	KM
	2.25	Integration of knowledge management and safety culture.	WMO	NS
	2.26	An important and extremely valuable activity to the EURAD community would be to create a common understanding of the operational and long-term safety implications of repository construction as an industrial megaproject over 50-100 years or more.	RE	NS
	2.27	Development of Engineered Barrier Systems (EBS).	TSO	R&D
	2.28	Geotechnical properties of host rock in relation to the mining technologies for the construction of underground spaces.	TSO	R&D
	2.29	Development of data and information systems.	TSO	R&D
	2.30	Development of new monitoring systems/technologies capable of detecting unexpected component behaviours.	TSO	R&D
"New" knowledge	2.31	The implementation of an experience feedback programme at the European level.	TSO	R&D or StSt
	2.32	The development and maintenance of a strong safety culture within the organisations involved in disposal programmes (including their (sub)contractors).	TSO	R&D or StSt

	2.33	Development of what-if scenarios.	TSO	R&D or StSt
	2.34	We need a stronger inclusion of research entities in the assessment of the methodology of the safety case. An EURAD strategic action could be organised around this question of safety margins and how to design a process of incorporating new knowledge as it comes available.	RE	StSt
	2.35	An example for new knowledge is the handling of big data and related analysis tools, which should be used to investigate uncertainties at all stages. With respect to future generations, new developments in information technology and knowledge transfer should be taken into account. In addition to reports, scientific papers and huge data bases, which are very important for the scientific community, animated scientific videos or repository digital twins should be used to better address the younger/future generations being continuously in a dialog with all stakeholders, using the up-to-date means. Besides, this strategic action could work on regularly and exhaustively review new knowledge in the different relevant fields. Then, it could discuss the safety significance of this new knowledge for disposal programmes in the context of the periodic revisions of the safety case and safety assessment.	RE	StSt

Appendix C3. List of future joint activities and initiatives (research and development R&D, strategic studies StSt, knowledge management KM, guidance G, not specified NS) identified in the 3rd UMAN Workshop dedicated to management options and preferences of different actors regarding spent nuclear fuel related uncertainties

Uncertainty related to	No.	Ideas for future joint activities and initiatives	Actor	Activity type
Fuel history data, reactor operation and irradiation conditions	3.1	Development and operation of fuel data management tools (e.g., develop own solutions or share experience with existing tools)	WMO	NS
	3.2	For validation cases, we see a need for wider coverage of higher burnups and fuel types (especially MOX)	WMO	NS
	3.3	Continuation of RD&D on best estimate and maximum impurity levels of relevant elements in UOX, MOX and different types of zircalloys	WMO	R&D
	3.4	To establish a common protocol for the collection of relevant data	TSO	NS
	3.5	A ranking list of relevant information quantifying their relative impact on the disposal process chain	TSO	NS
	3.6	Uncertainties in inventories can be about 2% for U and Pu contents, 7% for fission products and 11% for minor actinides (SKB, 2010a). The EURAD WP8 SFC tries to reduce these. Results of WP8 SFC needs to be awaited before identifying future needs.	RE	NS
	3.7	Uncertainties in IRF are probably sufficiently known, and difficult to reduce by more research, considering that in clay even an IRF value of 100% does not constitute an unbearable risk. A research strategy to reduce Cl-36 and Se-79 inventory uncertainties is still important. For Cl-36 this concerns the statistics of stable Cl trace inventories of unirradiated fuel and cladding; for Se this is a question of better nuclear data.	RE	NS
	3.8	Further experimental and numerical investigations that contribute in decreasing the uncertainties via better understanding of long-term processes and behaviour of SNF (including MOX and other novel types of fuel).	RE	R&D
Nuclear data	3.9	Knowledge transfer, networking, training	WMO	KM and StSt
	3.10	Identification of most reliable nuclear data	TSO	NS
	3.11	Programs addressing improving cross-section and fission yields data accuracy	TSO	NS
	3.12	Assessment of the impact of uncertainties in nuclear data	TSO	NS
	3.13	Depends on the outcome of WP8 SFC on the evaluation of the actual uncertainties	RE	NS
	3.14	We would welcome programs which try to assess the parameter space coverage achieved by the current programs, as well as try to evaluate the	WMO	NS

Performance of spent nuclear fuel (SNF) during (dry) interim storage		necessary further steps to expand this coverage (to further material types, temperature ranges, burnups, etc.).		
	3.15	The present activities on this topic (including EURAD SFC WP8) tend to focus on the technical and scientific understanding of the subject. It would be beneficial to have *activities focusing on the practical recommendations*.	WMO	G
	3.16	Benchmarks to test reliability of data and codes	TSO	NS
	3.17	Study and testing SNF in interim storage conditions	TSO	R&D
	3.18	Testing handling of degraded SNF	TSO	R&D
	3.19	Defining strategies for handling degraded SNF	TSO	G
	3.20	R&D on adoption, validation and verification of fuel-performance codes for SNF dry storage conditions, transportation.	RE	R&D
	3.21	Investigation of aging effects during long term storage – combined effect of delayed-hydride cracking (DHC), creep, stress-corrosion-cracking (SCC).	RE	R&D
Performance of spent nuclear fuel (SNF) in repository conditions - additional remarks by WMOs	3.22	We would welcome programs which would establish a link between the (generally microscopic level) science and the actual macroscopic effects, which could then be used to define *more realistic scenarios for criticality assessment*.	WMO	NS
	3.23	Most spent fuel leaching experiments have been done at neutral pH. For higher pH environments, the scientific database needs some enlargement to further underpin conclusions drawn so far. The fast/instant release of nuclides such as Cl-36 and Se-79 should also be further assessed. Additionally, several parameters that have an impact on matrix dissolution could be explored further (e.g. hydrogen pressure, “intermediate” pH (next to neutral and highly alkaline), MOX.	WMO	R&D

Appendix C4. List of future joint activities and initiatives (research and development R&D, strategic studies StSt, knowledge management KM, guidance G, not specified NS) identified in the 4th UMAN Workshop dedicated to management options and preferences of different actors regarding waste inventory related uncertainties

Uncertainty related to	No.	Ideas for future joint activities and initiatives	Actor	Activity type
Physico-chemical conditions in the storage or disposal facility	4.1	Organize a seminar to explain and summarize the management of uncertainties	WMO	KM
	4.2	Prepare a printed summary of the approach to uncertainties	WMO	KM
	4.3	Simplification and the ability to explain the uncertainty approach	WMO	NS
	4.4	R&D on techniques to measure radionuclides with very low concentration in the spent fuel	WMO	R&D
	4.5	Integrated research into waste, waste matrix and container	TSO	R&D
	4.6	Methods of facility closure using different types of protection from infiltrated water, with respect to the repository type (surface, subsurface)	TSO	R&D
	4.7	Study of redox kinetics for Se	RE	R&D
Radionuclide activity (including the scaling factor)	4.8	R&D on best estimate and maximum impurity levels of relevant elements in UO_X, MO_X and different type of Zircalloys (also relevant for reprocessing waste)	WMO	R&D
	4.9	Discussion with SFC WP, determination of uncertainties for long-term safety assessment	WMO	NS
	4.10	R&D regarding BWR fuel isotopic composition	WMO	R&D
	4.11	Benchmarking of burnup credit methodologies for disposal	WMO	NS
	4.12	To perform a comparison between countries about the list of more relevant nuclides, how they are determined together with respective uncertainties, including doses to personnel, radiotoxicity, peak dose to the public in an evolution scenario, etc.	TSO	NS
	4.13	Review of scaling factors used by participants	TSO	NS

	4.14	Measurement techniques for DTM nuclides in HLW and spent fuel for C-14, Cl-36 and I-129	RE	R&D
Chemical composition (with a special attention to organic content)	4.15	R&D on techniques to measure radionuclides with very low concentration in the spent fuel	WMO	R&D
	4.16	Development of databases for the impurities in the SNF materials (analogous to the main radionuclides databases) as most of the EURAD countries share similar waste inventory (zirconium alloys for the cladding, UO_2 for the pellets)	WMO	R&D or StSt
	4.17	Continuation of EURAD-GAS	WMO	R&D
	4.18	R&D on best estimate and maximum impurity levels of relevant elements in UO_X, MO_X and different type of Zircalloys	WMO	R&D
	4.19	Research about complexing agents that appear in LLW and their role (list of potential chemicals and their presence in the waste) and the identification of common strategies to identify and handle them to minimize their impact	TSO	R&D
	4.20	Project on bitumen including ionic strength plume, microbial growth, fire risks, tomography, statistics of variability of existing packages	RE	R&D