EPJ Nuclear Sci. Technol. **9**, 2 (2023)

https://doi.org/10.1051/epjn/2022049

EPJ Nuclear Sciences & Technologies

Euratom Research and Training in 2022: challenges, achievements and future perspectives, Roger Garbil, Seif Ben Hadj Hassine, Patrick Blaise and Cécile Ferry (Guest editors)

Available online at: https://www.epj-n.org

Review Article

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UMAN – a pluralistic view of uncertainty management

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Received: 11 August 2022 / Received in final form: 17 October 2022 / Accepted: 4 November 2022

Abstract. Decisions associated with Radioactive Waste (RW) Management programmes are made in the presence of irreducible and reducible uncertainties. Responsibilities and roles of each actor, the nature of the RW disposal programme and the stage in its implementation influence the preferences of each category of actors in approaching uncertainty management. UMAN (UMAN – Uncertainties Management Multi-Actor Network is a Work Package of the European Radioactive Waste Management Programme – EURAD) carries out a strategic study about the management of uncertainties based on extended exchanges among actors representing Waste Management Organisations, Technical Support Organisations, Research Entities and Civil Society, a review of knowledge generated by past and ongoing R&D projects, and findings of international organisations. UMAN discusses the classification schemes and approaches applied in uncertainty management, and identifies possible actions to be considered in the uncertainty treatment. The relevance for the safety of the uncertainties associated with waste inventory, including spent fuel, near-field, site and geosphere and human aspects, as perceived by each type of actors, and approaches used in their management are explored with the aim to reach either a common understanding on how uncertainties relate to risk and safety and how to deal with them along the programme implementation, or at least arrive at a mutual understanding of each individual view. Finally, uncertainties assessed as highly significant and the associated R&D issues that can be further investigated are being identified.

1 Introduction

Decisions associated with radioactive waste management (RWM) programmes are made in the presence of irreducible and reducible uncertainties. In the early phase of a programme, several choices must be made on the basis of limited information and need to be confirmed before or during the construction and operation of the disposal facility. At the end of the process, some uncertainties will inevitably remain and it should be demonstrated that these uncertainties do not undermine safety arguments. Hence, the management of uncertainties is a key issue when developing and reviewing the safety case of waste management facilities and, in particular, of waste disposal facilities due to the long-time scales during which the radiotoxicity of the waste remains significant.

In the European Joint Programme EURAD, it was agreed that a clear strategy and commitment to actors' involvement are essential to the decision-making process at all stages of a waste management programme [1]. Furthermore, scientific activities associated with an RWM programme (on-site characterisation, process modelling, safety assessment, etc.) are evolving over time, sometimes leading to new viewpoints and new uncertainties that may require additional efforts to resolve. Accounting for such uncertainty has thus become a key part of successful programme planning, which can benefit from the continued sharing of methodologies and experience.

Uncertainty is a cross-cutting issue of the different themes and stages identified in the EURAD Roadmap [2], and is associated with several topics of common European interest considered as having a medium or a high priority, such as inventory uncertainty, geological uncertainties, or uncertainty treatment.

R&D activities aim at improving the state of knowledge and thus are expected to reduce uncertainties. Understanding the contribution of these activities to the overall uncertainty management is important for the different actors involved in the decision-making process as well as for the identification of future EURAD priorities and activities.

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An extensive experience in uncertainty management has been already acquired by each category of actors. The Work Package *"Uncertainty Management Multi-Actors Network"* (WP UMAN) is therefore a strategic study intended to provide an opportunity for organisations and different actors of the Member States to share their experiences and views on uncertainty management and to identify emerging needs associated with this topic. Its specific objectives are:

- to develop a common understanding among the different categories of actors in uncertainty management and how it relates to risk & safety. In cases where a common understanding is beyond reach, the objective is to achieve a mutual understanding of why views on uncertainties and their management are different;
- to share knowledge/know-how and discuss common methodological and strategical challenging issues on uncertainty management;
- to identify the contribution of past and ongoing R&D projects to the overall management of uncertainties;
- to identify remaining and emerging issues and needs associated with uncertainty management.

In order to capture a pluralistic view on uncertainty management, WP UMAN brings together the main categories of players involved in the RWM programme, namely Waste Management Organisations (WMOs), Technical Support Organisations (TSOs), Research Entities (REs) and Civil Society (CS).

2 General approach

To reach its objectives, WP UMAN dedicates activities, organized into five tasks (Fig. 1):

- compiling, reviewing, comparing and refining uncertainty management strategies, approaches and tools that could be used in a radioactive waste disposal programme to assess and demonstrate repository safety (Task 2);
- identification & characterization of potentially safety-relevant uncertainties that need to be taken into consideration when implementing a disposal programme and in the safety case (Task 3);
- identifying possible options for the management of specific safety-relevant uncertainties in a safety case at different programme phases (Task 4);
- identifying methods to discuss and exchange uncertainties and uncertainty management during the development and review of the safety case (Task 5), therefore contributing to building mutual trust and understanding between various actors.

Besides the interactions between different types of actors, including Civil Society, UMAN collaborates and seeks synergies with other EURAD WPs, and international initiatives and organizations (i.e. IAEA, NEA, NUGENIA).

The UMAN scope covers any waste type for which there are uncertainties requiring adequate management in order to assess or ensure safety. A particular focus is

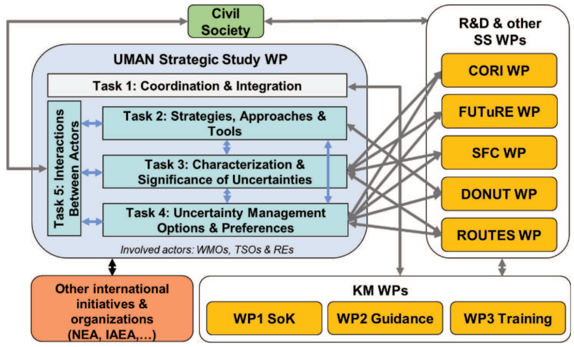

Fig. 1. UMAN structure, activities and interactions inside and outside EURAD.

put on uncertainties in direct link with the EURAD R&D WPs and with high (and where relevant medium) priority subdomains of the EURAD Strategic Research Agenda (SRA) [1]: waste inventory and spent nuclear fuel, near field, site and geosphere, and human aspects.

Expert groups consisting of specialists from REs, TSOs and WMOs from Member States with different disposal programmes, at different stages of implementation, have been established to identify the uncertainties with high significance for safety as well as discuss options and strategies to be used for their management. Their findings are discussed with a broader range of participants from the technical actors during dedicated UMAN Workshops, and further on, complemented/validated by a wider range of actors including the Civil Society, during Seminars.

3 A mutual understanding of uncertainty management

Radioactive waste management programmes and related safety cases are very complex topics reaching into several fields of science and involving several categories of actors. This leads for instance to multiple understandings and definitions for certain terms associated with uncertainty management. Reaching a mutual understanding of uncertainty management first requires:

- the identification of the categories of actors involved in the different phases of a radioactive waste disposal programme;
- the definition, the classification and the management of uncertainty along the phases of a radioactive waste disposal programme.

As illustrated in Section 4, this mutual understanding was used as a basis to identify and analyze the preferences of the different categories of actors involved in UMAN for the management of uncertainties associated with several topics.

3.1 Categories of actors involved in a radioactive waste disposal programme

To succeed in the decision-making process in RWM, the involvement of all actors is particularly important [3].

Identification and characterisation of the actors with respect to their roles/engagement in all phases of an RWM programme were possible on the basis of the answers received to the 1st UMAN questionnaire from 10 *WMOs*, 7 *TSOs*, 6 *REs* and 1 *TCC (Technical Consulting Company)* participating in EURAD strategic studies (WPs UMAN and ROUTES). The survey covered 17 countries in different phases of their disposal programme, including the Member States with Small Inventory [4] and allowed for the classification into 18 actors' categories and definition of their role, mission and responsibility in each phase of the RWM programme with a focus on safety case-related activities [4]. The 18 categories of actors are WMOs, TSOs, REs, Waste Generators, Waste Owners, Regulators, Governments/ Legislators, Ministries, Municipalities, State Authorities, Civil Society, Environmental Actors, NGOs, Geological Surveys, Technical Surveys, Operating Companies, Technical Consulting Companies and Miscellaneous Actors.

The results show the complexity of the actors' system, characterised by very strong interactions and dependencies [4]. This system is multidisciplinary and includes organisations and individuals with different technical, political, scientific and societal backgrounds. The types and number of actors vary among countries, reflecting the diversity of approaches employed in the national RWM programmes, as well as the different national frameworks and thus political, administrative, and regulatory systems. Particularly in the early implementation phases, it is likely that the overall RWM framework, including the system of allocation of competencies and the decision-making process, will evolve, and therefore the functions of all actors are not yet fully clarified.

The categories of the actors identified in UMAN represent an important input in planning the assessment of the preferred options used in uncertainty management by each of them.

3.2 Definition: uncertainty vs. risk

A prerequisite in reaching a mutual or even common understanding of uncertainty management is to have a clear and common definition of uncertainty and risk, as these two terms are very often mixed in (not only public) discussions.

Here, *uncertainty* is understood as a total or partial lack of objective information (evidence) or subjective information (knowledge) [5] and is used to express ambiguity about a result. This includes also ambiguities about the validity of concepts, methods, measurements and values.

Risk is "a quantity expressing hazard, danger, or chance of harmful or injurious consequences associated with exposures or potential exposures, and relates to quantities such as the probability that specific deleterious consequences may arise, and to the magnitude and character of such consequences" [6]. A risk thus relates to a scenario or sequence of events and can be interpreted as the measure of the significance of uncertainty.

Uncertainties can be epistemic or aleatory. *Epistemic uncertainty* addresses the uncertainty about a used model due to limited knowledge of conditions and processes. In principle, it can be reduced by performing adequate research and acquiring more information about the systems [7]. *Aleatory uncertainty* addresses the uncertainty that is stochastic for the parameter in a model. This type of uncertainty is an intrinsic property of the system and cannot be reduced [5]. Therefore, considering the nature of uncertainties (i.e. aleatory, epistemic or a mixture of both), it is important to address the aspect of uncertainty reducibility if more knowledge is gained.

3.3 Classification of uncertainties

Besides the general classification of uncertainties mentioned above, the views of a large number of actors representing WMOs, TSOs and REs on the uncertainties associated with radioactive waste disposal safety, collected via the 1st UMAN questionnaire, led to a three-level classification scheme, illustrated in Figures 2 and 3.

This complex scheme which integrates all points of view and covers all stages of the RWM programme distinguishes five main types of uncertainties:

1. Programme uncertainties, associated with the RWM programme and other prevailing circumstances (societal, resources, etc.);
2. Uncertainties associated with the initial characteristics of the disposal system and its environment;
3. Uncertainties associated with the evolution of the disposal system and its environment, which include effects of events and processes that may affect the initial characteristics (e.g. uncertainties associated with the radiotoxic and chemotoxic elements) as well as human influence or intrusion;
4. Uncertainties related to concepts (models) and parameters (data) used in the safety assessment;
5. Uncertainties associated with the completeness of the safety assessment (uncertainty in overlooking certain aspects relevant to safety).

Each type of uncertainty is grouped in topical groups of uncertainties, which represent the second level of this classification, listed in Figure 2.

The third level of the classification scheme includes the uncertainties potentially significant for the disposal safety of each topical group. Figure 3 illustrates the third level for the uncertainties associated with the site and geosphere, as identified in UMAN.

On another side, from the point of view of the availability of knowledge, uncertainties can belong to one of the three categories illustrated in Figure 4: we know what we don't know (known unknowns), we don't know that knowledge exists or we ignore existing knowledge (unknown/ignored knowns), and we don't know what we don't know (unknown unknowns). The last two circumstances represent the uncertainties associated with the completeness of the safety assessment, which corresponds to the 5th type of uncertainty in Figure 2.

The two approaches can be merged in an Uncertainty matrix (Fig. 4) which has been used by the actors involved in UMAN as a tool to classify uncertainties associated

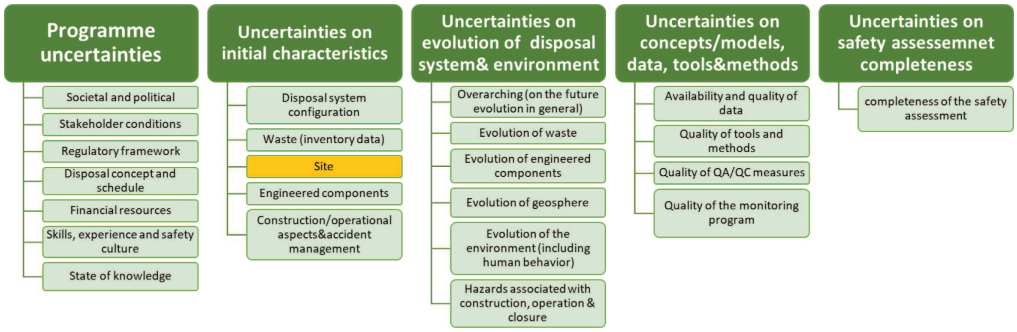

Fig. 2. Multi-level classification of uncertainties into different types of uncertainty and each type into different topical groups that various actors consider potentially relevant for the safety case. The third level (see Fig. 3) represents uncertainties specific to each topical group.

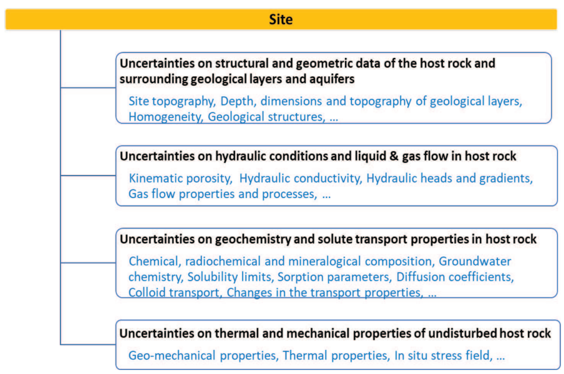

Fig. 3. Site specific uncertainties representing the third level of the classification scheme.

with several topics, as further illustrated in Section 4 for site and geosphere. The uncertainty matrix can provide a comprehensive picture of the stage reached in the treatment of uncertainties at a given moment and could guide the actors in the management of uncertainties.

3.4 Uncertainty management strategy

Safety strategies are based on: (1) a stepwise, iterative approach, (2) a regular dialogue with actors and (3) a safety-oriented management process. These include approaches for uncertainty management, currently at different stages of development in EU Member States, depending on the phase of the national disposal programme.

Managing uncertainties also requires an iterative approach, correlated with the progress of the disposal programme. This includes an iterative approach to research and data acquisition activities aimed at reducing or avoiding uncertainties or mitigating their impact. At each stage of such a process, safety assessment results can be used to understand the processes to which performance measures are most sensitive and therefore guide subsequent investigation activities to reduce the importance of the associated uncertainties in a meaningful way.

The safety case is typically expected to include a programme for uncertainty management, which generally involves the following steps, discussed in WP UMAN by integrating the views of all actors involved in this work:

- identification of uncertainties and their characterisation,
- analysis of the safety relevance of uncertainties,
- representation of safety-relevant uncertainties in the safety assessment,
- evaluation of uncertainties impact on safety assessment results,
- identification of uncertainties that need to be reduced, avoided or whose impact could be mitigated,
- actions to reduce, avoid or mitigate the uncertainties impact.

All these steps are framed and depend on a number of factors, such as state of knowledge, size of the RWM programme, national policies, regulations, actors, and resources, which altogether represent the prevailing circumstances in the uncertainty management strategy.

Figure 5 represents the common view reached in UMAN about the key elements of the uncertainty management process and strategy.

As illustrated in Figure 5, each step of the uncertainty management strategy is updated progressively and iteratively as the disposal programme and its prevailing circumstances progress. For example, the identification, characterisation and analysis of uncertainties is an ongoing process that needs to consider the newly identified and emerging uncertainties. The assessment of uncertainties' impact on disposal safety is iterated as new information on safety-relevant uncertainties is acquired through appropriate activities for uncertainty avoidance, mitigation and reduction. Such activities may include R&D, further data acquisition (e.g. waste characterisation), site selection and site characterisation, adapting the disposal concept (either at the high level or in the detailed design), adopting particular construction methods, adapting the limits, controls (e.g. reduction of uncertainties on as-built properties by additional Quality Assurance/Quality Control [QA/QC] measures) and conditions for the construction and operation of the repository, as well as interacting with the actors. The choice of particular measures depends, in part, on the stage of the programme and the prevailing circumstances.

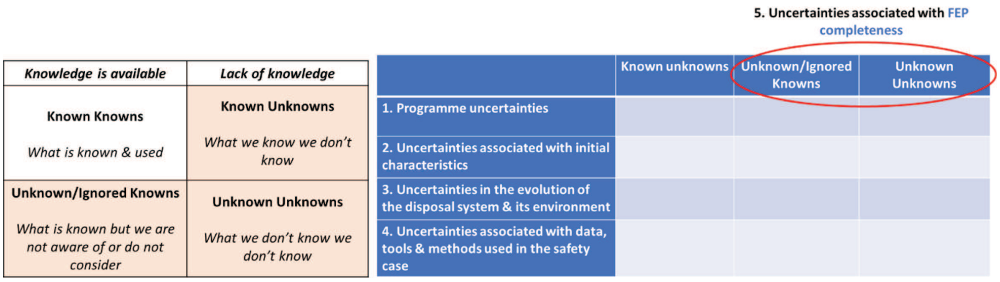

Fig. 4. Classification of uncertainties according to the availability and use of associated knowledge (left) and the uncertainty matrix combining specific uncertainties types with availability of knowledge (right).

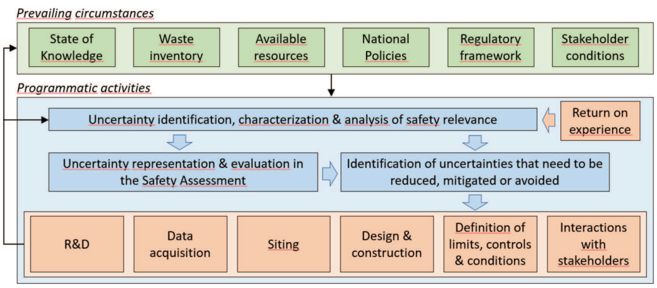

Fig. 5. Key elements of an uncertainty management strategy, and its associated stepwise and iterative process.

The possible measures to reduce, mitigate or avoid uncertainties associated with several topics, as well as the preferences of the various actors involved in UMAN for these measures, have been investigated by the multi-actors network and are illustrated in the following section for the case of site and geosphere related uncertainties.

4 Application of UMAN strategy to uncertainties associated with site and geosphere

To test and validate the uncertainty management strategy and the actions proposed by UMAN for uncertainties reduction, mitigation or avoidance, the following sequence of activities has been implemented for all five topics approached in UMAN (waste inventory, spent nuclear fuel, near-field, site and geosphere and human aspects):

- uncertainties identification and assessment of their significance for safety;
- identification of appropriate options for uncertainties reduction, avoidance or impact mitigation;
- interaction with actors in order to confirm/amend/complete the uncertainty management strategy via workshops and seminars.

Up to now, this sequence has been fully implemented only for the uncertainties associated with site and geosphere, and human aspects. This paper focuses on the process and results related to site and geosphere; findings for the other topical uncertainties are/will be publicly available on the EURAD website (`https://www.ejp-eurad.eu/`).

4.1 Identification and assessment of significance for safety

Based on the expert group experience acquired in the national disposal programmes in France, Switzerland, Czech Republic and Romania as WMO, TSO or RE, on the IAEA guidance [8] and the review of other safety assessments reports publicly available [9–11] a comprehensive list of uncertainties associated to site and geosphere, potentially significant for safety, has been developed. Sixty four uncertainties associated with 15 thematic groups were structured in three broad uncertainty categories, as shown in Figures 6 and 7.

The significance for safety of each uncertainty has been assessed based on the evaluation provided by actors representing WMOs, TSOs and REs collected via the 2nd UMAN questionnaire addressed to all EURAD participants, thus covering the diversity of national disposal programmes in terms of repository types and implementation phase, as well as the diversity of actors.

The 22 answers (received from 7 WMOs, 4 TSOs and 11 REs) on the significance of safety as perceived by each actor *at the current phase* of his geological disposal programmes generally show comparable levels of the potential impacts of uncertainty on safety, for of each group of uncertainties (Fig. 7). In particular, there is a consensus among the three categories of actors on the low significance for the safety of the uncertainties associated with volcanism. The low number of answers from TSOs explains the large, dominated groups of uncertainties by *not known/ not considered yet* answers, *which* is the reason for large discrepancies in the level of significance for safety.

In justifying the impact on disposal safety and the level of impact (high, medium or low) the arguments provided by the actors complement each other, providing a more comprehensive picture.

The site and geosphere uncertainties of the greatest significance for the geological disposal safety, scored as medium or high *by all actors*, are those associated with:

- conditions and hydraulic properties of the host rock;
- geochemistry and transport properties, with particular emphasis on groundwater chemistry and host rock-specific sorption properties;
- thermal and mechanical properties of the host rock in its natural state.

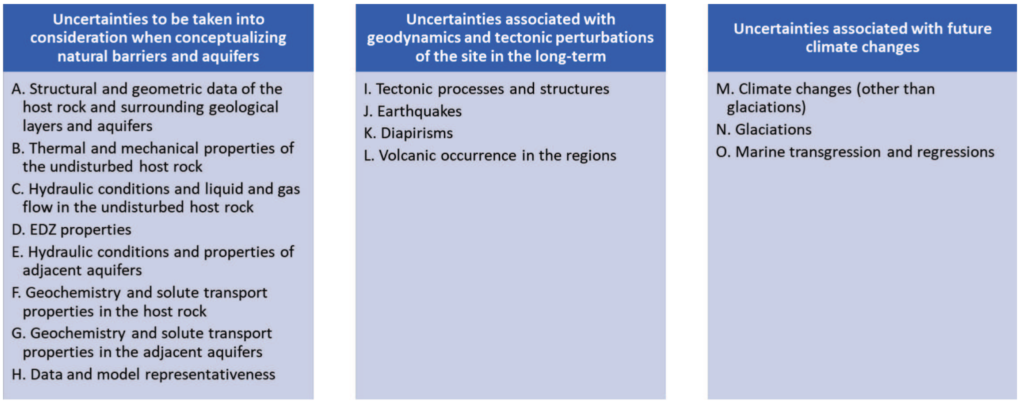

Fig. 6. The thematic groups of site and geosphere uncertainties addressed for safety relevance assessment.

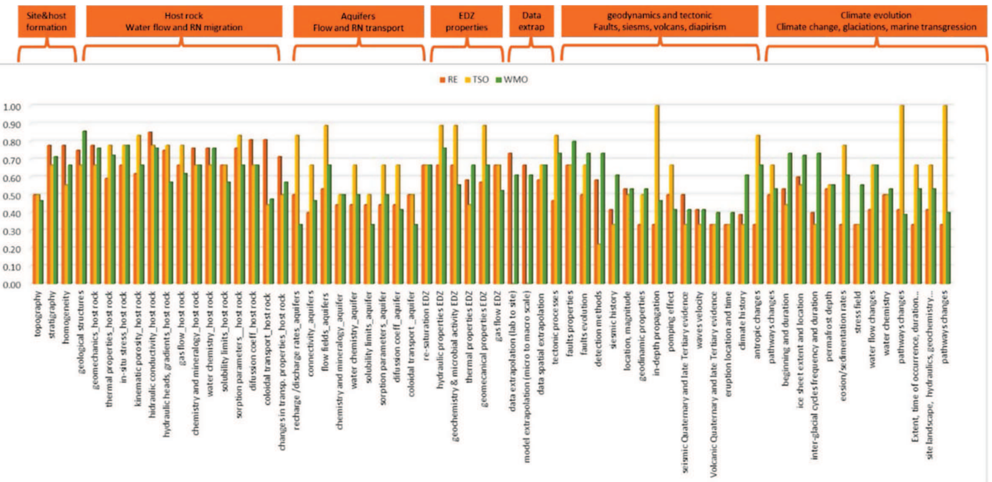

Fig. 7. Distribution of "significance for safety" level for geological disposal (low: <0.33; medium: 0.33-0.66; high: >0.66).

As illustrated in Figure 7, *REs* are mainly concerned with the uncertainties related to natural barriers characterisation (in particular host rock homogeneity, flow and transport parameters) and data extrapolation, while *TSOs and WMOs* tend to give a higher significance to uncertainties related to the long term evolution of the geosphere (future climate changes and glaciations effects, and geodynamics and tectonic perturbations of site).

4.2 Consolidation of available information on uncertainty management options

The different available approaches and options for uncertainty management were identified for a few uncertainties selected with respect to their relevance for the safety case. In order to cover as wide as possible range of uncertainty management options, these uncertainties were selected to cover all types of uncertainty in the uncertainty matrix, except for programme uncertainties, which address mainly human aspects.

These are (Fig. 8):

- *Hydraulic conductivity* of the host rock (and other geological units) – as an example of uncertainty related to the *initial state* of a disposal system. The uncertainty on hydraulic conductivity is primarily linked with the measurement errors on the very low permeable rocks and with the upscaling of permeability (or conductivity) value at the disposal site. Even more uncertain is the resaturation process of the host rock in the presence of the hydrogen build-up pressure generated in the repository. Over-pressure measured in the clay rocks adds new uncertainty related to its potential impact on the radionuclide transport in this host environment.
- *Sorption capacity* of the host rock (and other geological units) – as an example of uncertainty related to the *initial state* of a disposal system as well as to *conceptual models, data, tools and methods.* A particular concern is raised by the anionic species, which could have a large range of distribution coefficient values (K_d) depending on the chemical conditions in the host rock, the presence of organic matter, etc. Sorption reversibility introduces additional uncertainties on the migration kinetics with a direct impact on long-term safety.
- *Heterogeneities* of the host rock (and other geological units) – as an example of uncertainty related to the *initial state* of a disposal system as well as to *data, tools and methods*. This uncertainty is mainly linked to the degree of variability of site parameters up to which a geologic unit/layer can be considered homogenous.

		Known unknowns	Unknown/Ignored Knowns	Unknown Unknowns
1. Programme uncertainties				
2. Uncertainties associated with initial characteristics	Hydraulic conductivity	Upscaling errors, saturation recovering		
	Sorption	Speciation, anionic species, reversibility, Organic Matter		Other processes speeding up migration
	Faults	Locations, detection Undetected faults		
	Heterogeneities of host rock	Discontinuities; anisotropy, gradients		
3. Uncertainties in the evolution of the disposal system & its environment	Faults	Reactivation	new faults formation	
	Climatic evolution (glaciations)	Start &duration Isostatic adjustment Ice thickness Erosion Permafrost layer and temperatures	Depth and location of glacial erosion (mapping quaternary sediments)	Unexpected evolution of the next glaciations
4. Uncertainties associated with data, tools & methods used in the safety case	Sorption	Kd - measurement and models accuracy	Changes in geochemistry	
	Heterogeneities of host rock	Transport properties		

Fig. 8. Uncertainty matrix filled in for safety-relevant site and geosphere uncertainties.

- *Fault location, detection and reactivation* – as an example that addresses the uncertainties related to the *initial state* and the *evolution* of a disposal system. Uncertainties on the tectonic and seismic activity of the site are in particular linked to the detection accuracy of active and passive faults location considered in the safety assessment. An additional concern is raised by the uncertainty on the reactivation of passive faults (which ones, when), or in the creation of new ones in the future (where, when, in what direction and what properties).
- *Climate evolution* with a focus on glaciations and *permafrost* – as an example of *evolution*-related uncertainty and allowing to address *completeness* (FEP's, scenarios) arguments. The high concern about the uncertainty of glaciations and permafrost is justified by the long-term period considered for safety assessment. This uncertainty sums up the uncertainties on a series of factors such as the beginning of the next glaciations, duration of intra- and inter-glacial cycles, ice sheet extent/thickness, erosion depth, and permafrost depth, all these parameters being important in defining changes in the radionuclide transport pathways and preservation of safety functions of the disposal system.

The identification of the different management options was done primarily through compilation, review and synthesis of existing documentation such as regulations, guidelines, handbooks, national reports, lists of options, cross-mappings and analysis of pitfalls.

Figure 9 synthesizes the options appropriate for the uncertainties considered, and applicable at different stages of the disposal programme implementation. In this paper, however, uncertainty management options are discussed only for an example of the climatic evolution with a focus on glaciations and permafrost.

The uncertainty related to climate evolution (specifically to glaciations and permafrost) includes further uncertainties such as (i) occurrence and duration of the next glaciations, (ii) magnitude of the isostatic adjustment associated with glaciation/de-glaciation, (iii) extent and thickness of the ice sheet, (iv) depth and location of glacial erosion, (v) depth of the permafrost layer or temperatures at repository depth, (vi) induced loading/unloading and related changes in hydraulic conductivity or seismicity, (vii) induced changes in groundwater flow regimes and chemistry, (viii) induced changes in the biosphere. Relevance of these uncertainties for safety is however dependent on several aspects such as assessment period, waste inventory, considered site, developed safety concept and repository system design.

The uncertainty associated with climate evolution can be identified through a FEPs list analysis, being part of an overall FEPs management process. The assessment period, within which the evolution of a disposal system shall be evaluated, may be defined by national guidelines (e.g. [12]), law and ordinances (e.g. [13–16]) or regulatory requirements (e.g. in [17]).

Framework for handling climate events in safety assessment is specified by safety-related principles with respect to siting and repository design (e.g. as defined by NAGRA [18]), requiring predictability, avoidance of and insensitivity to detrimental phenomena, as well as stability and longevity of a barrier system (e.g. as in [14–16]). Possible options to manage the uncertainties associated with climatic evolution can be identified in compliance with the abovementioned framework:

- Definition of specific site selection criteria and/or minimum requirements with respect to the depth of a repository (i.e. the depth of the repository ensures that all or a sufficient portion of the host rock is below the maximum anticipated erosion thickness or permafrost depth [13,19]). It is also possible to include safety margins in these criteria/requirements.
- Definition of specific design requirements or "design-basis glacier scenarios" [20] in order to account for those significant, glaciation-induced perturbations that cannot be excluded. The induced conditions and

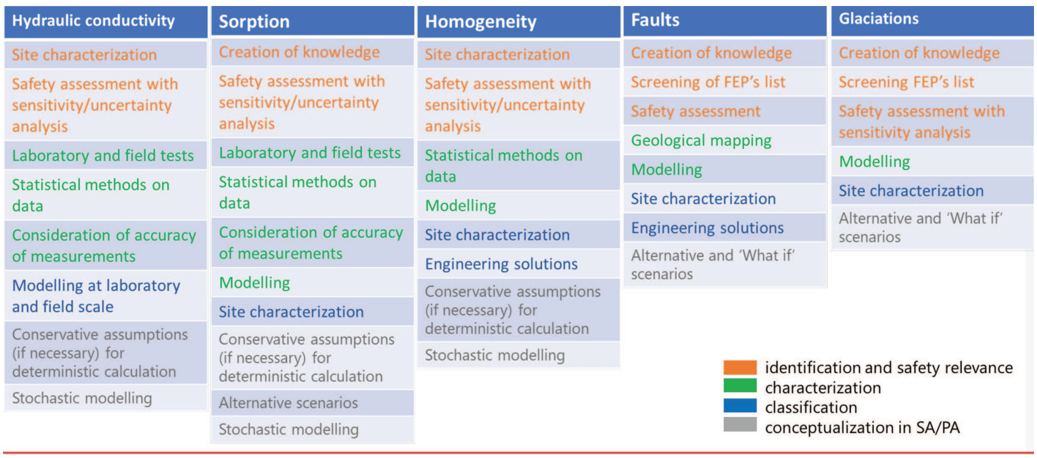

Fig. 9. Steps and options for uncertainties management at different stages of disposal programme implementation.

the corresponding uncertainties can be considered in numerical modelling by using conservative or bounding assumptions. Optionally, safety margins can be included in the repository design to address these uncertainties.

– Performing R&D to reduce the uncertainties related to climate evolution/climatic events (e.g. improving climate evolution models to predict future glaciations, dating of quaternary sediments, analysis of erodability of the overburden, investigation of the influence of decompaction on host rock properties (e.g. as in [21]).

4.3 Exchange in a workshop

Workshops organized in the framework of WP UMAN contribute to the development of a common understanding among "technical" actors representing WMOs, TSOs, and REs with a focus on (i) discussing views and preferences of these actors on different options for uncertainty management and (ii) identification and understanding the differences among these views/preferences (if any). Further, the workshops allow for the identification of remaining and emerging future R&D, Knowledge Management or strategic study activities in EURAD.

The exchange and discussion during the workshops dedicated to site and geosphere uncertainties indicated rather homogeneous views of the different actors in their management [7]. Generally, the uncertainty management strategy was perceived by all actors as an iterative approach, accompanied by a communication/regular dialogue with all involved actors, particularly with the public it was underlined that the preferred uncertainty management strategy might differ among EU member states, depending on the considered host rock and the associated safety concept. Some other minor discrepancies result from the different roles the actors play in the RWM programme. While WMOs and TSOs are sinterested in developing management strategies for safety-relevant uncertainties in compliance with current regulatory requirements/international guidelines, REs are interested in performing much broader investigations towards the provision of a sound scientific basis for assessing the significance for safety, including also processes that are not safety-relevant but contribute to a deeper and more confident understanding.

4.4 A seminar for a larger exchange

Several results emerged from the UMAN seminar dedicated to site and geosphere uncertainties, notably the fact that a stepwise, transparent and flexible decision-making "process" is important to manage the site and geosphere-related uncertainties. This process involves decisions regarding the selection and use of complementary measures at different programme phases to avoid/reduce safety-significant uncertainties and mitigate the impact of residual uncertainties and manage "surprises" that could occur, for instance, during construction and through monitoring (even if very unlikely). Civil Society should have the possibility and the means (i.e. access to independent expertise, legal provisions, etc.) to be involved early in this process and to monitor the situation now and in the future (several generations involved). In order to do so, could the concept of rolling stewardship be addressed?

As a typical example, regarding climate evolution, the exchanges underlined that the management of this type of uncertainty would strongly benefit from a very transparent process with a detailed protocol to make clear how the decisions were made, modified by new knowledge, and even changed. The citizens should be informed about the refinement of climate models and related uncertainties. The climate scenarios should be regularly and pluralistically assessed to ensure it remains in the safety envelope. Climate is evolving and deviation from the previous assumptions should be a trigger for a dialogue.

The governance to manage such uncertainties could be applied during different stages of the programme on two levels: the first level of discussion between technical experts exchanging scientific and technical knowledge in order to establish a rational programme and relevant roadmaps for the uncertainty management activities. This should also include non-institutional experts (coming from civil society). The second level of discussion should consist of interactions between technical and non-technical actors such as NGOs, representatives from society, mayors, local public, and should address the programme and the roadmaps, but also decisions. Discussion on climate models rises societal challenges and should stay open for dialogue between actors along the programme phases but should also foresee a longer-term interaction between government, experts, and society.

5 Outlook

The same methodology was applied for the uncertainties on human aspects. Preferred options applied in the management of waste inventory and spent nuclear fuel were investigated as well, while those related to the near-field uncertainties will follow in 2023. These exchanges allowed the identification of the needs for future activities to be addressed by EURAD partnership as R&D or strategic studies on site and geosphere topical area.

Therefore, there may be benefits from *theoretical studies* addressing the uncertainties associated with the long-term effects, in particular future climate changes and their effects on host rock and biosphere, as well as the structural geology in combination with geochemistry and geostatistics. *Experimental studies on hydraulic conductivity* are still found useful for the investigation of clay re-saturation kinetics taking into account diffusion/advection in host rock, plugs & seals, hydraulic conductivity of host rock and EDZ, hydrogen production and transport, and counter-pressure build-up. *Large-scale and laboratory experiments on sorption of anionic species*, targeting large-scale diffusion in clay for low but non-zero K_d, and identification of relevant sorption processes/ mechanisms for the development of mechanistic sorption models based on a bottom-up approach for improved sorption models. Upscaling from batch systems on pure phases to the real host rock in confined conditions could bring an in-depth understanding and supplementary knowledge of the radionuclide transport mechanisms.

Further work should be done to *develop geochemical codes* allowing to combine of uncertainty components in a non-additive model (additive ones leading to unrealistic results due to the propagation of uncertainty), *improve glaciations codes* coupling the climate evolution, permafrost and groundwater flow models, *validate* permafrost depth models and decompaction influence on host rock properties.

A *strategic study on climate change* could provide additional insight into how to deal with glacial periods in safety cases and safety assessment, while a *strategic study of on-site homogeneity* could clarify the conditions under which a host rock volume can be considered homogeneous.

6 Conclusions

The approaches to uncertainty management developed in WP UMAN capitalize on the experience of a wide variety of disposal programs, the results of past and ongoing research, as well as the exchanges of views both at the scientific-technical level and with Civil Society, that have allowed to develop a mutual understanding of uncertainty management issues.

The uncertainty management strategy, its classification scheme and the management options proposed by WP UMAN represent the result of the integration of the points of view of all the actors involved in unitary and comprehensive concepts, which can be used in the planning and implementation of uncertainty management in any geological disposal programme and at any stage of its realization.

Uncertainties associated with the site and the geosphere with a potentially significant impact on the safety of geological disposal for all categories of actors are related to hydraulic conductivity in low permeable rocks and resaturation process, sorption of anionic radionuclides, homogeneity of host geological units, and long-term climate evolution, with focus on glaciations and permafrost.

Conflict of interests

The authors declare that they have no competing interests to report.

Acknowledgements

The authors thank all the WP UMAN partners who contributed to this work, as well as all the EURAD members who responded to the questionnaire and provided valuable input during the UMAN workshops and seminars. Special thanks are also addressed to Frank Lemy who coordinated the WP UMAN activity presented in this paper.

Funding

The work reported in this paper has been done under the WP UMAN of the EURAD project and has been financed by the European Commission under the Horizon 2020 EURATOM Programme, GA 847593.

Data availability statement

This article has no associated data generated to be disclosed.

Author contribution statement

All authors contributed equally to this publication. Daniela Diaconu prepared the introductory sections and the section on the uncertainty significance for disposal safety, Valéry Detilleux prepared the sections on mutual understanding of uncertainty management, Dirk-Alexander Becker prepared the section on identification and classification of uncertainty, Agnieszka Strusińska-Correia and Astrid Göbel prepared the sections about the options of the uncertainty management and actors' preferences, while Julien Dewoghelaere provided the aspects of civil society views on uncertainty management.

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Cite this article as: Daniela Diaconu, Valéry Detilleux, Agnieszka Strusińska-Correia, Astrid Göbel, Julien Dewoghelaere, and Dirk-Alexander Becker. UMAN – a pluralistic view of uncertainty management, EPJ Nuclear Sci. Technol. **9**, 2 (2023)