Deliverable 10.6: Views of the different actors on the identification, characterization and potential significance of uncertainties on waste inventory and on the impact of predisposal steps

Work Package 10

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

Document information

Project Acronym	**EURAD**
Project Title	**European Joint Programme on Radioactive Waste Management**
Project Type	**European Joint Programme (EJP)**
EC grant agreement No.	**847593**
Project starting / end date	**1st June 2019 – 30 May 2024**
Work Package No.	**10**
Work Package Title	**Uncertainties Management multi-Actor Network**
Work Package Acronym	**UMAN**
Deliverable No.	**10.6**
Deliverable Title	**Views of the different actors on the identification, characterization and potential significance of uncertainties on waste inventory and on the impact of predisposal steps**
Lead Beneficiary	**SCK CEN**
Contractual Delivery Date	**November 2022**
Actual Delivery Date	**07-08-2023**
Type	**Report**
Dissemination level	**Public**
Authors	**An Bielen (SCK CEN), Attila Baksay (TS ENERCOM), Sylvia De Gregorio y Robledo (ENRESA), Arturas Plukis (FTMC)**

To be cited as:

Bielen A., Baksay A., De Gregorio y Robledo S., Plukis A., (2023): UMAN -Views of the different actors on the identification, characterization and potential significance of uncertainties on waste inventory and on the impact of predisposal steps - Final version as of 07.08.2023 of deliverable D10.6 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

Disclaimer

All information in this document is provided "as is" and no guarantee or warranty is given that the information is fit for any particular purpose. The user, therefore, uses the information at its sole risk and liability. For the avoidance of all doubts, the European Commission has no liability in respect of this document, which is merely representing the authors' view.

Acknowledgement

This document is a deliverable of the European Joint Programme on Radioactive Waste Management (EURAD). EURAD has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 847593.

Status of Deliverable		
	By	Date
Draft version (Lead Beneficiary)	An Bielen (SCK CEN)	30-12-2022
Verified (WP Leader)	Daniela Diaconu (RATEN)	20-02-2023
Final draft version (Lead Beneficiary)	An Bielen (SCK.CEN) Attila Baksay (TS ENERCON)	25-04-2023
Verified (WP Leader)	Daniela Diaconu (RATEN)	25-04-2023
Final draft version submitted to review (Lead Beneficiary)	Daniela Diaconu (RATEN)	25-04-2023
Final version (Lead Beneficiary)	An Bielen (SCK CEN)	26-06-2023
Reviewed (Reviewers)	Crina Bucur (RATEN)	12-06-2023
Approved (PMO)	Elisabeth SALAT (IRSN)	04-08-2023
Submitted to EC (Coordinator)	Andra	08/08/2023

Executive Summary

This UMAN WP deliverable D 10.6 presents the views of the different actors on the identification, characterization and potential significance of uncertainties related to waste inventory. Information contained in this deliverable provides input to the work performed in Subtask 4.2 on possible uncertainty management options, as well as to Task 5 dedicated to interactions within a broader group of actors including civil society.

Characterization of uncertainties related to the waste inventory was built up on a preliminary list presented in the EURAD milestone 92*, "UMAN Preliminary list of uncertainties from Subtask 3.2 as input to Subtask 4.2*". This list of uncertainties was elaborated by the expert group composed of representatives of REs, WMOs and TSOs, based on their own experiences and literature review. Subsequently, EURAD-1 participants, who completed the 2nd UMAN Questionnaire (section waste inventory), were also sources of the identification and description of waste inventory related uncertainties. In addition, the results of the questionnaire of the CHANCE project have also been considered in the analysis of the uncertainties related to waste inventory.

This report provides a description of the 5 groups of uncertainties related to waste inventory, the view of the different actors, its significance for safety, how to characterize these uncertainties and their evolution in time. The 5 main groups are:

- uncertainties related to radiological properties
- uncertainties related to physico-chemical properties
- uncertainties related to waste stream identification and management route
- uncertainties related to pre-treatment, treatment and conditioning processes
- uncertainties related to long-term behaviour of radioactive waste

Table of content

List of figures

List of Tables

Glossary

ASR	Alkali silica reaction
DEF	Delayed ettringite formation
DTM	Difficult to measure (radionuclides)
ETM	Easy to measure (radionuclides)
EBS	Engineering barrier systems
KN	Key nuclide
NPP	Nuclear Power Plant
RE	Research entities (Universities, national research centres)
RN	Radionuclide
RW	Radioactive waste
SF	Scaling factor
TSO	Technical safety organisation (typically working for regulators)
WAC	Waste acceptance criteria
WMO	Waste management organisations

1. Introduction

This report presents the final version of UMAN WP deliverable 10.6. The report is based on the views of the different actors on the identification, characterization and potential significance of uncertainties related to waste inventory. The main goal of the current document was to provide input to the work performed in Subtask 4.2 on possible uncertainty management options, as well as to Task 5 dedicated to interactions within a broader group of actors including civil society.

For the identification of key waste inventory uncertainties, a preliminary list was built up based on the own UMAN experts' experience and information from national programs represented in the Subtask 3.2 as well as from the available information from other national programs and international initiatives [1]. This preliminary list was supplemented with information received from other EURAD-1 participants via the 2nd UMAN Questionnaire (section waste inventory) which focussed on three major properties: Amount (volume), radiological content and physico-chemical properties. The answers to the questionnaire allowed the identification of the main factors contributing to the uncertainty associated with these properties during the life cycle of radioactive waste (RW) (generation, pre-treatment, treatment, conditioning, storage and disposal), and the potential impact these uncertainties could have on the disposal safety (near-surface and/or (deep) geological).The questionnaire addressed a limited number of waste types, which is based notably on the outcomes of the workshop of ROUTES (ROUTES Workshop 1, 2-6 March 2020, Athens, Greece), in which challenging waste types and related difficult issues to management and disposal were defined for each participating country:

1. standard cementitious waste forms,
2. organic waste containing PVC, cellulose etc.,
3. graphite,
4. bituminized waste and
5. waste containing reactive metals.

Furthermore, the results of the questionnaire of the CHANCE project have also been considered in the analysis of the uncertainties related to waste inventory [2, 3].

Twenty uncertainties associated with waste inventory have been considered, which can be divided into five main groups:

- uncertainties related to radiological properties,
- uncertainties related to physico-chemical properties,
- uncertainties related to waste stream identification and management route,
- uncertainties related to pre-treatment, treatment and conditioning processes, and
- uncertainties related to long-term behaviour of radioactive waste.

Information about the views of the different actors on the significance for safety of each type of uncertainty, on their characterization and expected evolution in time was obtained from the 2nd UMAN Questionnaire and is discussed in this report for the above mentioned 5 main groups of uncertainties.

To get more information about which uncertainties are of most concern/interest to the different organizations, task 4.2 has sent out a small survey to UMAN Subtasks 4.2 and 3.2 members, who have been requested to assess the importance/priority for safety of the 20 uncertainties, by rating them as 'high', 'medium' or 'low'.

This report ends with a chapter about recommendations and general conclusions.

2. Methodology

A list of uncertainties related to waste inventory was created based on existing knowledge, as well as on the input from the different actors who answered the 2nd UMAN Questionnaire. The actors considered in this investigation were:

- TSOs: Technical safety organizations (typically working for regulators)
- WMOs: Waste management organizations
- REs: Research entities (Universities, national research centres)

A total of 21 responses were received from representatives of REs (6x), TSOs (6x) and WMOs (9x). More information of the participating organizations can be found in Table 1.

For the potential safety implications of uncertainties associated with waste inventory, the following possible impacts have been considered:

- Impact on the radiological composition and dose rate
- Impact on the physico-chemical properties of the waste
- Impact on the volume
- Impact on the waste form stability and release processes during operations or after disposal facility closure
- Impact on safety functions fulfilled by other disposal system components

A well performed characterization of the RW package is important to know what waste we are dealing with and to eventually minimize uncertainties related to waste inventory.

In the 2nd UMAN Questionnaire, for each uncertainty addressed as medium/high safety significant, the question about "What specific actions can be taken to characterize the associated uncertainty?", was asked to each actor. Additionally, answers were gathered on the question "How will evolve the general uncertainty over time?".

Table 1 – List of actors answering the questionnaire, with details on the disposal programmes and status in implementation

			Current phase			Type of host rock		
Affiliation	**Country**	**Type of actor**	**Near surface disposal**	**Sub-surface disposal**	**Deep geological disposal**	**Near surface disposal**	**Sub-surface disposal**	**Deep geological disposal**
ENRESA	Spain	WMO	Operation and closure	Operation and closure		Sedimentary rock	Sedimentary rock	
NAGRA	Switzerland	WMO			Site evaluation and site selection			Sedimentary rock
NES	Austria	WMO						
ONDRAF/NIRAS	Belgium	WMO	Facility construction			Sedimentary rock		
SURAO	CZ	WMO	Facility operation and closure	Facility operation and closure	Site evaluation and site selection	Crystalline rock	Sedimentary rock	Crystalline rock
Denmark	Denmark	WMO			Policy, framework and programme establishment			-
ANDRA	France	WMO	Post-closure	Site evaluation and site selection	Facility construction	Sedimentary rock	Sedimentary rock	Sedimentary rock
BGE	Germany	WMO			Facility construction			Sedimentary rock
COVRA	The Netherlands	WMO			Policy, framework and programme establishment			Salt rock
SCK CEN	Belgium	RE	Facility construction		Policy, framework and programme establishment	Sedimentary rock		Sedimentary rock
TUS	Bulgaria	RE	Policy, framework and programme establishment		Policy, framework and programme establishment	-		-
LEI	Lithuania	RE	Facility construction			Sedimentary rock		
CVR	Czech Republic	RE	Facility operation and closure	Facility operation and closure	Site evaluation and site selection	Sedimentary rock	Sedimentary rock	Crystalline rock
FTMC	Lithuania	RE						
BGR	Germany	RE			Site evaluation and site selection			Sedimentary, crystalline and salt rock
TS Enercon	Hungary	TSO	Facility operation and closure	Facility operation and closure	Site evaluation and site selection	Sedimentary rock	Crystalline rock	Sedimentary rock
FTMC	Lithuania	TSO	Facility construction	Facility construction	Policy, framework and programme establishment	Sedimentary rock	Sedimentary rock	Crystalline rock
SURO	Czech Republic	TSO	Facility operation and closure	Facility operation and closure	Site evaluation and site selection	Crystalline rock	RICHARD repository: Sedimentary rock; Bratrstvi repository: crystalline rock	Crystalline rock
EIMV	Slovenia	TSO	Site characterisation	Site characterisation	Policy, framework and programme establishment	Sedimentary rock	Sedimentary rock	Crystalline rock
Bel V & FANC	Belgium	TSO	Site characterisation		Policy, framework and programme establishment	Sedimentary rock		Sedimentary rock
SSTC	Ukraine	TSO	Facility operation and closure		Policy, framework and programme establishment	Sedimentary rock		Crystalline rock

2.1 Radiological properties

The main radiological properties of the RW package that should be taken into consideration are:

- radionuclide (RN) content,
- specific activities of RNs and the total activity of the RW package,
- ionizing radiation type,
- dose rate, and
- distribution of RNs within the waste (volume activity or surface contamination).

The identified uncertainties related to radiological properties are shown in Table 2.

The uncertainty regarding RN activity is commonly the most significant one and has an impact to all waste management scenarios including treatment, conditioning and disposal. Many nuclear programs are using the scaling factor (SF) method which allows to determine the activity of difficult-to-measure (DTM) radionuclides from the activity of easy-to-measure (ETM) gamma emitters obtained by gamma spectrometry, which are called key nuclides (KNs).

One should distinguish the uncertainties of major gamma emitters such as Cs-137 and Co-60, which could be directly measured by non-destructive analysis and which can serve as KNs for the calculation of DTM nuclides.

The correlation factor between ETM and DTM nuclides used in the SF method is based on radio-chemical measurements based on destructive analysis, resulting in more significant uncertainties associated to the beta and alpha emitters compared to the ETM nuclides. Since the KNs can be measured by non-destructive analysis such as gamma spectrometry, the total uncertainty of their activities is lower than the uncertainty of the DTM nuclides. Due to the high energy and their abundance, which make them able to penetrate deeper into materials, KNs (and other gamma emitters) have a higher impact to the ionizing radiation dose, especially for personnel involved in waste processing, while DTM nuclides have an impact on the long-term safety.

Table 2 – Uncertainties related to radiological properties

Associated uncertainties	Description	Safety relevance of the uncertainty
List of critical radionuclides	A reliable and up to date source of information on the critical radionuclides to be considered in safety assessments needs to be available in the inventories of radioactive waste generated by commercial and institutional activities in the nuclear sector. For this reason an identification approach has to be adopted, which intends to provide an approximate but comprehensive assessment of the inventory of radioactive waste to be disposed of. This uncertainty relates to the reliability of the adopted approach and the comprehensiveness of the resulting list.	The importance of reporting the presence of certain radionuclides may vary between operational safety and long-term safety, and there may be significant differences between various disposal facilities (surface, geological). The safety assessment of each facility relies on a proper identification of radionuclides critical for their safety.
Radionuclide activity	A variety of measurement and calculation methods can be applied to estimate the activity levels of radionuclides enclosed in a waste package. Uncertainties are associated with each of these methods.	The process of determination of radioactivity contributes to the characterisation of radioactive waste for defining an appropriate waste management route (safe processing, storage and disposal). When the uncertainties on the radiological inventory remain large, waste packages might need to be oriented towards another management route, minimizing the risks associated with the uncertainties.
	Radiological waste characterisation is often based on the determination of the key nuclides gamma-ray emitting radionuclides by a measurement and the estimation of the DTM alpha and beta emitter radionuclides via SF method.	Uncertainties in the activity may lead to an underestimation of the inventory, which may eventually lead to an underestimation of the potential release to the environment.
Scaling factor (SF)	Another important source of uncertainty is related to the confidence in a SF, which is used to determine the activity of DTM radionuclides. Possible sources of uncertainty on the determination of the SF are: • radiological parameters (such as flux, cooling time, irradiation time …), • the chemical behaviour of the radionuclides and • the chemical composition of materials. One must also take into account the uncertainties related to the numerical modelling for nuclide production and poor correlation with key nuclides considering SF. The uncertainties on the SF will mostly contribute to the total uncertainty in terms of representativeness of the SF for the drum and basic assumptions of the calculation of the radionuclides. The correlation factors used in the SF method has to be updated and whenever it is possible, they have to be waste stream specific. This way the uncertainties might be handled.	Uncertainties in its determination (underestimation), could result in underestimated doses for involved workers or the public, or in case of excessive conservativeness, limits the choice to a suboptimal waste management scenario in terms of associated costs.

Weak gamma emitters (I-129, Am-241), and beta/alpha emitting nuclides (Ni-63, C-14, Cl-36, H-3, actinides, etc.)can be determined using destructive analysis or indirectly using a SF approach. This results in three types of uncertainties for DTM nuclides:

- Uncertainties related to the KNs activity measurement in the sample
- Uncertainties associated with the radiochemical analysis technique
- Uncertainties associated with modelling or radiochemical analysis technique

The uncertainties related to activities of long-lived radionuclides could have an impact on the long-term safety of a waste package, and on the radiological safety of waste disposal. For instance, radioactivity of graphite waste is mainly deriving from DTM nuclides(such as C-14, Cl-36) which have a weak correlation with gamma emitters, such as Co-60. If the SF approach is used, it may result in large uncertainties for the total activity of graphite.

The uncertainty due to surface activity of the RW package (removable or fixed) has an impact on the solid waste treatment process. This is due to the requirement of additional surface treatment and cleaning, and radiation safety of the conditioned waste.

2.1.1 Views of different actors on uncertainty significance

All actors who responded to the questionnaire stressed the importance of the uncertainties associated with the radioactivity of KNs (Co-60, Cs-137) in radioactive waste, and the possible impact of uncertainties related to the use of SFs for the determination of the activity of DTM radionuclides.

The WMOs mainly consider uncertainties related to the critical RNs such as Co-60, Cs-137, and C-14 and Cl-36 as high or medium significant for safety for graphite waste disposal. TSOs have selected Cs-137, Cs-134, Co-58, Co-60, Mn-54, Ag-110m, Ag-108m, Ni-59, Ni-63, Nb-94, Tc-99, I-129, Cs-135, Am-241 and Pu-239 as main RNs, regarding uncertainties related to radiological properties and their significance for safety. Due to practical considerations mostly, the SF method will be used for large scale RW measurements, which implies a large degree of uncertainty. REs underlined the high importance to safety of low energy RNs (in addition to the KNs as Co-60 and Cs-137), alpha emitters (which are DTM) and the use of scaling factors.

Long-lived RNs could be released after repository closure, a process which has large uncertainties, but the activity dispersion can nowadays be predicted with sufficient accuracy if all parameters are known with adequate accuracy.

The chemical form of C-14 – bearing compounds (organic/inorganic) in the waste affects its release rate.

The views of the three categories of actors on the safety significance of uncertainties associated with radiological properties are shown in Figure 1. Concerning WMOs, no major differences were found between the different waste streams. For REs, more significance for safety was designated to standard and graphite waste types, while standard waste types were indicated by TSOs as having the highest level of significance for safety, followed by bituminized, organic and graphite waste types.

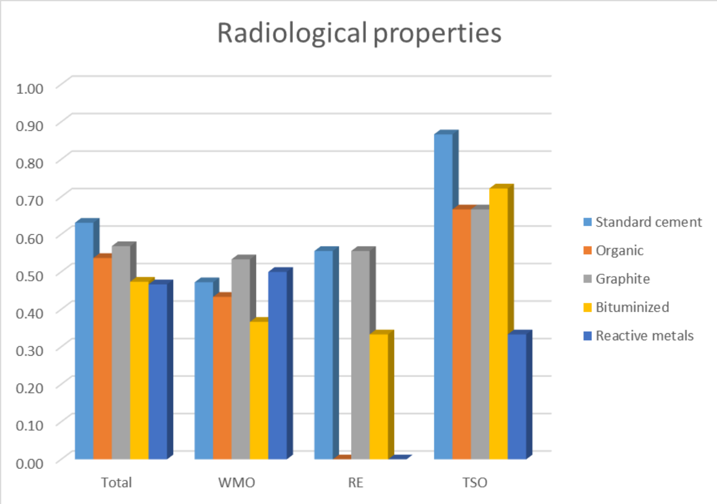

Figure 1 – Relative safety significance of uncertainties associated with radiological properties of different waste types from the perspective of different actors.

In general, concerning all waste types together (Figure 2), TSOs give a higher significance for safety to the uncertainties associated with radiological properties of the RW compared to REs and WMOs.

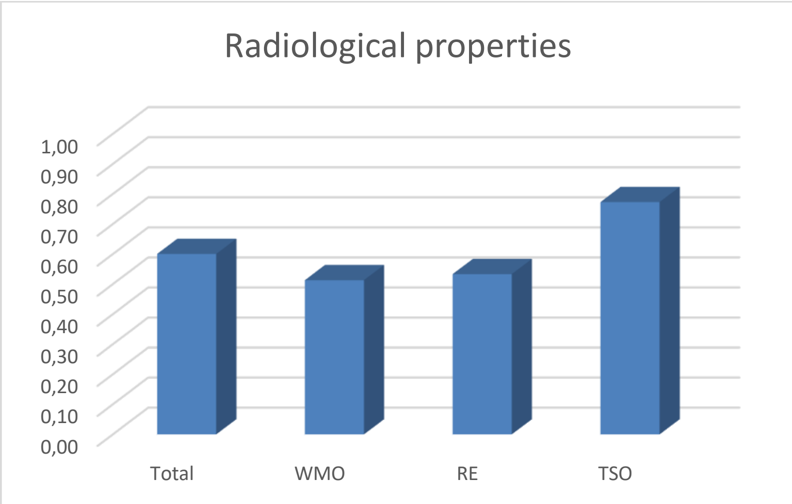

Figure 2 – Overall view of the safety significance of uncertainties associated with radiological properties for each category of actors.

As a final conclusion, uncertainties on radionuclide activity are considered as highly significant for safety by all types of actors.

2.1.2 Potential impact of uncertainties

The radiological inventory of RW packages eventually determines the dimensions of the engineering barrier systems (EBS), because radiological properties are affecting all the design properties of the waste packages, the disposal operations, and the required robustness of the EBS.

Some historical RW packages have been cemented without proper radiological characterization, meaning without applying radiological characterization methods which are currently implemented, resulting in high uncertainties of the RN content. Consequently, some specific approaches (testing, SF method, etc.) must be used to determine the RN inventory and activity.

2.1.3 Characterization of uncertainties

Uncertainties related to proper radiological characterization of RW are the most important uncertainties to be identified. Therefore, radiological characterization should be implemented at each stage of RW management. Technical improvements in the detection capacity of beta-gamma and alpha emitters or progress in techniques for detecting the hard to measure radionuclides, together with the development of improved quality control are processes that lead to a much better characterization. In addition, more research and analyses are needed for a more accurate characterization of RW packages. Subsequently, a method dealing with characterization of uncertainties, such as a list of probability distribution functions for each RN for each available waste stream could give a better idea on this uncertainty.

Measurements performed using gamma spectrometry, and sampling and analysis of beta and alpha content, allow narrowing the uncertainty associated to the SFs. For actinides such as Pu-239 and Pu-240,radiochemical analyses in specialized laboratory allowed to work with radioactive samples and alpha spectroscopy measurements, are required. The development of an adequate methodology and procedures for waste characterization and the use of a high-quality and certified characterization equipment could improve characterization of the RW package.

2.1.4 Evolution of uncertainties

Improving characterization generally results in reduced uncertainties. Given that more information about the RW package will be available in the future, uncertainties will reduce in time. Before RW disposal, it will be verified whether the performed characterization is sufficient. It may happen that re-characterization will take place in order to obtain (more) information and/or to reduce the uncertainty. For these reasons, one expects that the uncertainty will decrease with time due to:

1. Operational experience, which will give more insight and more specific knowledge on the behaviour of waste and its activities.
2. Improvement of characterization quality.

2.2 Physico-chemical properties

Physico-chemical properties of RW packages play a role in the conformity with the storage and/or the disposal facility. The uncertainties associated with the physico-chemical properties identified are presented in Table 3. The impacts of these uncertainties can be divided into three main groups, as follows:

A. Properties related to the RN release from the waste form
   - content of corrosive materials
   - biodegradation
   - gas production
   - free liquid content
   - leachability
   - homogeneity

B. Behaviour of the waste in relation to its conditioning matrix
   - effects of heat and radiation
   - flammability
   - physical form
   - mechanical strength
   - content of corrosive materials
   - biodegradation
   - gas production

C. Behaviour of surrounding disposal components
   - effects of heat and radiation
   - physical form
   - mechanical strength

Table 3 – Uncertainties related to physico-chemical properties of radioactive waste

Associated uncertainties	Description	Safety relevance of the uncertainty
Cellulose content in the organics-bearing waste	Uncertainty in the cellulose content in organics-bearing waste.	Degradation products of organic material due e.g. to radiolysis and hydrolysis can lead to a potential bypass of barriers due to radionuclide complexation on organic degradation products resulting in higher radionuclide release rate.
Behaviour of cementitious waste forms	*Uncertainty in the occurrence of ASR & DEF in cementitious waste forms:* chemical reactions within the waste matrix can cause the hardened concrete to expand, the production of gel and induce tensile cracking.	ASR & DEF could have an impact on the stability of the waste package and surrounding barriers and may result in a higher dissolution rate and release of radionuclides.
Chemical composition	*Uncertainty in the content of chlorides, sulphates, nitrates and hazardous materials such as asbestos, etc*. These chemicals could have an impact on the stability of waste and waste package.	Limits on these elements are needed to avoid radionuclide complexation, or processes like steel corrosion or sulphate attack of cementitious materials, thereby avoiding an attack of concrete barriers. This may affect the integrity of the engineered barrier system components or radionuclide migration.
Thermal reactivity	*Uncertainty in thermal reactivity in bituminised waste:* Radiolysis affects rheological properties; some bituminised wastes contain both oxidisers (e.g. nitrate) and reductors (bitumen), which if heated to a threshold temperature will auto-ignite and, if conditions are 'optimal' lead to continued burning of the waste that is difficult to stop.	During operation, thermal reactivity in close link with a fire accident, could have an impact on the safety of operations and post-closure safety functions of the host rock around the disposal cell of bituminised waste.
Swelling	Uncertainties on processes leading to the swelling of the waste matrix (e.g. as a result of DEF or gas generation).	Swelling induces mechanical perturbations of the surrounding barriers which may result in higher radionuclide release rates.
Volume, mass	Uncertainty in its generation/destination route might affect the final volume to be disposed of. Release of the waste, choices for decontamination, segregation, incineration, etc. could have huge effects on the volume of the waste which will be disposed of. Uncertainties on the volume of the waste that will be accepted in the facility due to the absence of WAC, the use of generic WAC or changes in WAC. These uncertainties may also be caused by changes in national energy policies.	Final waste volume has an impact on the footprint of the repository and may use up the valuable area that fits with the disposal criteria. The uncertainty in waste volume could in principle result in larger amount of treatment required for radioactive waste, and insufficient amount of space in existing or designed disposal facilities, meaning that the waste will stay longer in less safe form compared to final disposal. This field can be a part of the optimisation.
Voids	Uncertainty regarding the presence of voids: Avoiding voids provides integrity and meets stability requirements.	When voids are present, the integrity and stability of the waste form can be affected. Radionuclide release through advective processes could also be enhanced.

2.2.1 Views of different actors on uncertainty significance

Analysing the answers received from the 2nd UMAN Questionnaire, it is clear that the concerns and viewpoints differ among the different type of actors: While the TSOs are mostly assessing the physico-chemical properties from the safety case point of view, the WMOs mainly focus on the practical approaches, that affect the operation of the predisposal management of radioactive waste, the storage and the disposal. The REs are in between the two approaches.

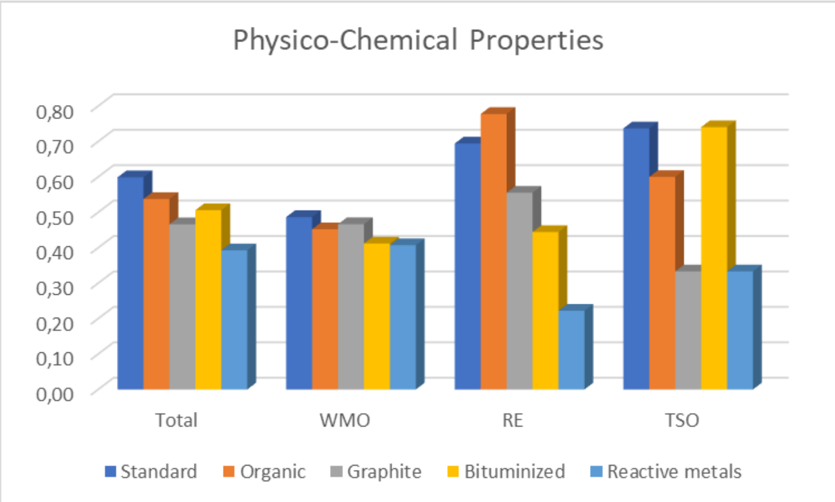

Figure 3 – Relative safety significance of uncertainties associated with physico-chemical properties of different waste types from the perspective of different actors.

The significance for safety of uncertainties related to the physico-chemical properties of the waste forms regarding the five different waste types is summarized and presented in Figure 3. Additionally, an overall view on the uncertainty significance for safety of the different actors is presented in Figure 4.

In case of WMOs (Figure 3), the significance for safety regarding the different waste types is relatively similar, only a minor deviation can be observed from the average. The answers received from REs show much more variance: uncertainties on physico-chemical properties of organic waste are seen as having the highest significance, while those of the waste containing reactive metals are perceived as having the least importance for safety. Regarding TSOs, a relatively high significance for safety is shown for both standard and bituminized waste types concerning uncertainties associated with physico-chemical properties, in case of graphite waste and waste containing reactive metals, significance for safety of these uncertainties is quite low.

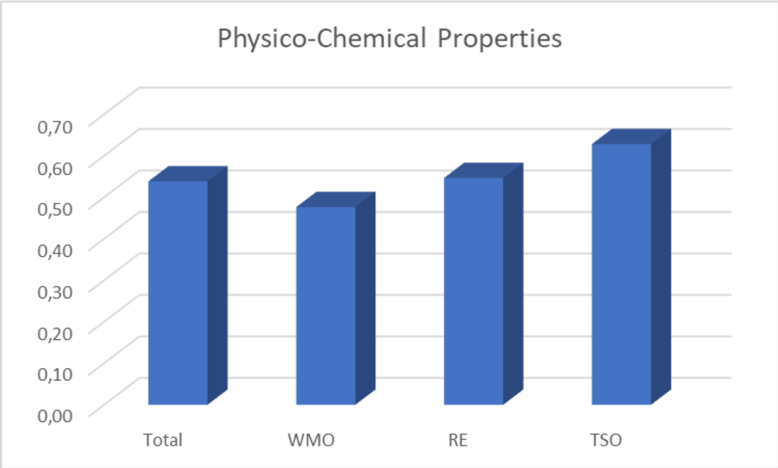

Figure 4 – Overall view of the safety significance of uncertainties associated with physico-chemical properties for each category of actors.

Answers received from WMOs are reflecting actual problems which these actors are facing with. This is the reason why references to practical issues such as the PVC content of the waste or selecting other waste management routes for problematic waste types (i.e. choosing reprocessing instead of disposing of the waste) were provided.

In case of TSOs and REs, changes in the RNs transport parameters induced by the waste properties are highlighted. Physico-chemical properties may indeed induce changes in the long-term behaviour of the disposal system: leachability of the waste forms and migration properties of radioactive contaminants, etc. This is due to degradation processes resulting from ageing and long-term behaviour processes of waste forms and waste packages, and the coupled processes between waste packages and disposal site, due to chemical reactions between them.

In general, TSOs have addressed the most concerns about uncertainties related to physico-chemical properties, followed by REs and then WMOs, which is shown in Figure 4.

2.2.2 Potential impact of uncertainties

The purpose of the RW management is to guarantee a safe storage and final disposal with the lowest risk of exposing RW in order to protect people and environment. Besides the radiological properties, the physio-chemical properties of waste forms dictate the management of RW packages as disposal units.

First goal is to prevent release of radioactive components from the waste form. Therefore, one key element is to avoid the presence of corrosive materials in the waste. Waste containing reactive metals may influence the pH and H_2 release, and may change the chemical composition of the waste forms.

Other important aspects are the integrity of the waste matrix and factors affecting the behaviour of the waste matrix in a disposal environment. An issue regarding the presence of organic content in waste is that, due to radiolysis and hydrolysis, degradation products derived from organic material can form complexing agents with RNs. For instance, the content of cellulose plays an important role in the RN migration because it may affect the rate of transport through certain barriers.

Waste from dismantling projects, such as concrete, concentrates or resins may contain water-soluble chlorides/sulphates, or ASR/DEF processes may occur. These chemical components or phenomena can harm the integrity of the waste form. Additionally, chlorides can form complexes/chelates with RNs. The performance of all concrete barriers around the waste form may be adversely impacted by these processes in the same way as the waste form.

In many cases the repository sealing is planned to be carried out using bentonite. The interaction between concrete and bentonite is important, since the high pH environment caused by, for example, the cementitious waste form may cause the clayish material to lose its integrity.

Bituminized waste, due to the variability of thermal reactivity has an impact, not only on the long-term, but also on the operational safety of the repository. This property has a close link with fire accident. Due to its swelling property, bituminized waste also has an impact on its surrounding barrier in the disposal.

2.2.3 Characterization of uncertainties

Characterization of uncertainties related to the physico-chemical properties are in close relation with the development of the characterization techniques/methods. The parameters connected to the physico-chemical properties (such as chemical composition, amount of complexing agents, mechanical strength, content of restricted components: flammable, explosive material, etc.) are detected or quantified by non-radiological characterization techniques. The administrative issues of waste collection and treatment can also help in the determination of uncertainties of physico-chemical parameters.

Chemical composition can be determined during the waste management; the chemical characterization of the raw waste and additives can help in the identification of possible chemical reactions that can occur in the waste matrix.

In some cases, it is difficult to quantify some specific compounds in the waste forms, such as toxic and flammable components. In these cases, only expert assessment is the tool that can help in the quantification of the uncertainty.

2.2.4 Evolution of uncertainties

To handle uncertainties associated with the physico-chemical properties, there are different approaches as they are related to different waste streams. Additionally, the actors have a different view on the evolution of these uncertainties in time.

The WMOs have a positive view on the evolution of the uncertainties, indicating that they will be reduced in time. The main reason of their optimistic view is based on the technical improvements in the detection capacity and the better and better performance of the laboratories. Also the development of quality control improves the uncertainty management over time.

A more conservative view can be observed in the answers of the TSOs. This group of actors put emphasis on the reduction of uncertainties as a result of the newest outcomes from research and their implementation in safety assessment. Projects involved in decommissioning of fuel cycle facilities provide a reduction of uncertainties, since in this case the assessments are not going to rely only on speculations but on actual measurements and experiences.

Answers from REs are generally of the opinion that uncertainties will most probably decrease over time. However, their rate of decrease may depend on the improvement of the equipment and facilities and the consequent execution of the radioactive waste management programs.

2.3 Waste stream identification & management route

To dispose of RW, the waste will be classified according to physical, chemical and radiological properties. Therefore, the characterization process is of great importance and contributes to the classification of RW. A correct classification of the waste is necessary, because the waste will be classified in a particular waste class meeting different criteria for a long-term safe disposal, and thus determining a waste management route, which includes the safe processing and storage of RW packages.

A waste stream identification intends to provide an approximate but comprehensive assessment of the inventory of RW to be disposed of. Knowledge about the produced waste streams is essential for defining and designing an appropriate disposal facility. For this, waste acceptance criteria (WAC) will be put in line with conformity criteria for the planned disposal facility. Subsequently, knowledge about the properties of the RW, including radiological and physico-chemical properties, is necessary to understand their uncertainties and the use of tools doing dose estimations related to the waste management process. Besides, it is an important input for the safety case. Waste characterization processes are mainly involved in the following phases of the life cycle of RW: generation, pre-treatment and treatment. Uncertainties related to waste identification and management routes are presented in Table 4.

2.3.1 Views of different actors on uncertainty significance

Each actor focuses on different aspects in the characterization process. Therefore, the weight given to each uncertainty is different. This is also the case for the WAC. The distribution of significance for safety according to the views of the different actors regarding uncertainties associated with waste stream identification and management route of different radioactive waste types is presented in Figure 5.

All actors agree that the type of waste is important for safety but the significance they have specified for each type of waste is different. As shown in Figure 5, TSOs give the highest significance to standard waste types, while the lowest significance was reported for graphite wastes and wastes containing reactive metals.

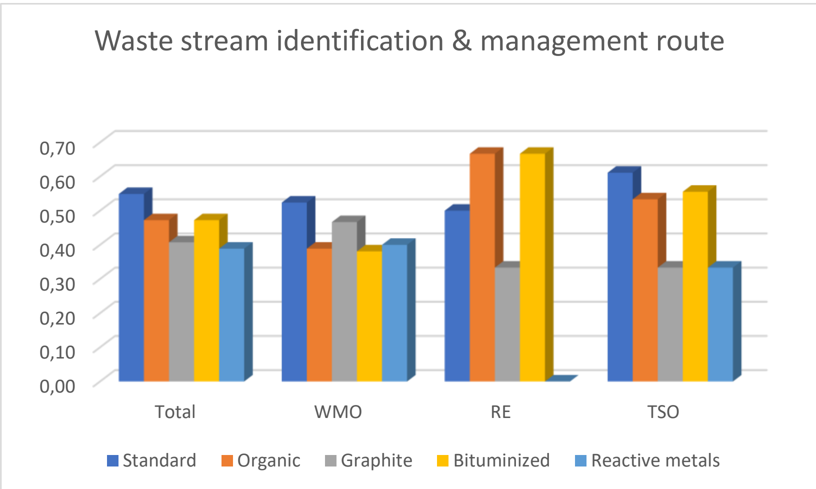

Figure 5 – Relative safety significance of uncertainties associated with waste stream identification and the management route of different waste types from the perspective of different actors.

For organizations included in the WMO group (Figure 5), no big differences were found regarding the significance for safety of different waste types, although, the highest significance is addressed to standard waste types. Furthermore, the small differences observed within the WMOs regarding the waste types seems to be caused by their maximum inventory and/or waste streams they have or produce. For instance, ENRESA has given a high significance for safety to standard and graphite waste types. On the other hand, COVRA has selected medium significance for standard waste, while ANDRA and NIRAS have selected medium significance for bituminized waste. In contrast, other organizations don't assess it, because they don't have these waste types. What is important to WMO for deciding the importance of a waste type, is how the waste will evolve in their installations, and also the requirements each type of waste need to comply with.

Lastly, REs have selected a high significance for safety to bituminized and organic waste types, followed by standard waste types.

The views of the different actors are influenced by their type of job/business. For REs, all uncertainties are critical because of their ongoing investigations and research projects. What TSOs consider important is determined by the kind of waste produced. The uncertainties important for WMO are defined by the waste they have to work with. Knowledge of the RW is important to each organization, because the uncertainty associated with limited knowledge can be large concerning the radiological characteristics of the RW package. In addition, WAC are very important to each actor, because they contain the criteria the waste must comply with. The WAC need input from characterization and radiological inventory and will evolve according to the needs and new knowledge.

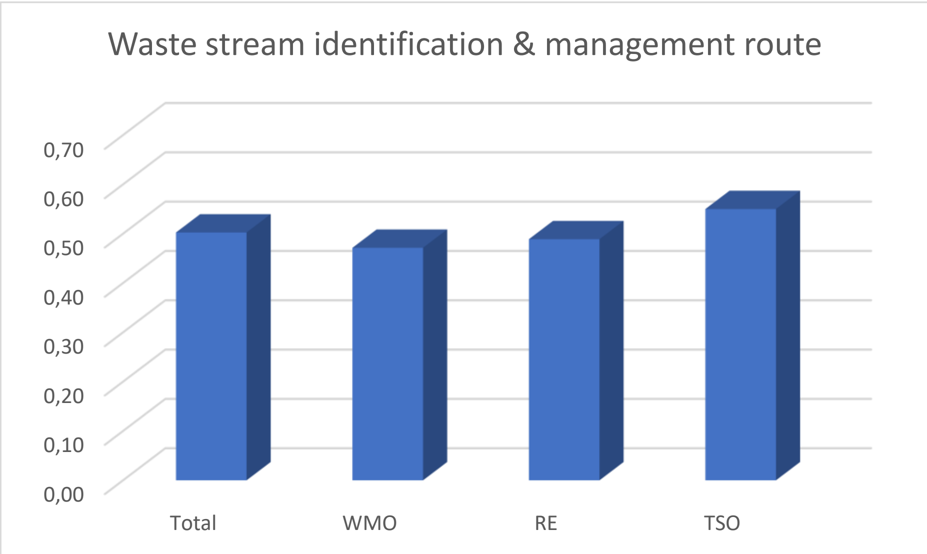

Figure 6 – Overall view of the safety significance of uncertainties associated with waste stream identification and management route for each category of actors.

The general view of the different actors on uncertainties related to waste stream identification and management route of the RW regarding safety is presented in Figure 6. Generally, these uncertainties are of medium importance for each type of actor. As shown in Figure 6, the TSOs reported the highest significance for safety regarding these uncertainties, followed by REs and WMOs, where the latter reported the lowest significance for safety.

Table 4 – Uncertainties related to waste stream identification and management routes.

Associated uncertainties	Description	Safety relevance of the uncertainty
Waste streams & associated waste forms	Streams where the waste always comes from a consistent process will be stable. And stable streams will tend to have a lower uncertainty in the SF. Wastes coming from varying or multiple processes are likely to be variable. Variable streams will tend to be difficult to manage, as the uncertainty in the SF will vary and could be quite large. If the degree of variation is unacceptable, then it may be necessary (if possible) to revisit the stream and partition it into more stable streams. Origin? What kind of waste is it? Location? History? It involves evaluation of information from the operating history.	All waste streams have to be treated appropriately. It is essential for the safety. The most safety relevant issue is underestimation of long-lived nuclides in the waste form and the incorrect qualification of long-lived waste as short-lived waste.
WAC's	WAC comprise a key component of the assemblage of limits, controls and conditions to be applied by the operator. Consequently, WAC are usually used to ensure that the wastes are compatible with all stages of waste management through the imposition of a series of technical and management controls. The role of WAC is to ensure the safety of all management steps of radioactive waste including disposal. Because WAC are a safety component of the facility design, it can change as a result of internal safety reviews and regulatory scrutiny. Revision of legislation: technical changes and new knowledge can cause a modification in the existing criteria. The final WAC's for the different waste management steps will be put in line with conformity criteria for the planned disposal facility. More stringent limits could be implemented.	Impact on the waste management route and volume of the waste stored or disposed of in a facility. This may have implications for the safety of facilities where the waste is stored or being disposed of. Where to focus on when no disposal facility is available?
Limited knowledge	Uncertainty includes the lack of information from the early days of the nuclear industry. It includes waste generated for which no or little information is available or poor traceability of the originating process/location. The uncertainty associated with limited knowledge can be large concerning the radiological characteristics of the waste package.	The inventory of radionuclides could be underestimated, leading to the incorrect qualification of the waste and underestimation of potential releases to the environment.
Not defined routes	When no disposal route can be selected, long-term storage is required and the waste package integrity has to be monitored regularly. There has to be action plans to treat with potential failed packages.	There is a risk that the final disposal package may not be the same as the stored package. In case of overpacking: further risk of irradiation.

2.3.2 Potential impact of uncertainties

Some RNs, such as Co-60, Cs-137, C-14 and Cl-36, are more important regarding safety assessment compared to others. Each organization has their own RNs of interest, due to their maximum RN inventory providing the maximum volume of RNs which is allowed to be stored/disposed of in the facility. For instance, the concentration of C-14 present in irradiated graphite does not comply with modern WAC for the near-surface repository. WAC related to a facility are more stringent on the maximum allowed RN concentrations and the total inventory of RNs. This might cause issues with historically accepted RW, such as bituminized waste, which will lead to changes in the waste management route.

Another issue, is that WAC can still change in view of uncertainties related to the hydrogeological situation of the surface disposal facility. Other uncertainties that are significant for safety are leaching rate, release rate, stress resistance, waste integrity, filling ratio and release rate after closure.

Another important aspect is the processing/conditioning of the waste. For WMOs this aspect is essential, especially when these processes are not performed by the WMO itself. In this case, the waste might not be of the same quality expected by the WMO, yet it will be delivered in that quality status to the disposal facility. Some processes have a negative effect on the matrix, for instance swelling, gas generation, etc., which in turn have an impact on safety.

In addition, it is important for safety host rock to limit RN migration.

2.3.3 Characterization of uncertainties

Waste characterization is important to know what we are dealing with, and a correct characterization will minimize the uncertainties. Subsequently, a correct characterization will give the effective dose rate of the RW, to which one can be exposed. This is important for REs, because as a result of a wrong characterization and improper use of the storage, incompatible wastes can be formed, affecting the physico-mechanical stability of the RW. Furthermore, the volume of the waste can be affected by incorrectly classified waste due to lack of WAC, while the stability of the waste is affected by incorrect application of the WAC on the contents of mixed waste types.

WMOs believe that knowledge and compliance of WAC are essential to guarantee non-release of RNs from the waste, which is in turn important for safety. Additionally, which type of waste will be allowed or not in the disposal facility is of great importance. For instance, when bituminized waste would not be accepted in the disposal facility, it may need to be processed, which may change completely its physical and chemical form, and a new characterization process should be considered.

Uncertainty on its generation/destination route might affect the volume of the waste, which could be reduced by releasing some parts of the waste for decontamination, segregation, incineration, etc.

Characterization of uncertainties related to waste identification and WAC, could be done by carrying out more studies and tests on waste matrices, using better activity measurement techniques, and improving quality control with an appropriate monitoring in facilities. The more detailed the dismantling studies are, the better the uncertainty can be characterized for dismantling waste. For bituminized waste, bounding hypothesis about the origin of the waste and the SF may help in characterizing the uncertainty. Moreover, a proper development and implementation of decommissioning plan/program and a proper identification of waste origin will help to reduce the uncertainty.

Furthermore, a sophisticated safety assessment to derive the WAC is necessary for near-surface repository with irradiated graphite considering better retention of RNs in a graphite matrix than in other waste matrices.

Characterizing uncertainties is essential to develop specific WAC for the disposal facility as soon as practically achievable. It is difficult to characterize it, as it depends on known as well as on unknown factors. For example, the concentration limits of particular compounds may not be complied with the WAC as a result of human intrusion. Additionally, new scientific insights, scenario hypothesis, etc. may enlarge or limit the allowed maximum concentration of the particular compound.

2.3.4 Evolution of uncertainties

There is a mutual agreement between all organizations on the evolution of uncertainties related to waste identification and WAC, this uncertainty will decrease or disappear in time. In order to minimize this uncertainty, it is necessary to conduct an upgrade and thorough evaluation of the current WAC. This process should encompass the incorporation of all the knowledge gained thus far, as it is crucial to establish a comprehensive WAC prior to the disposal of the waste.

Once the dismantling activities start and evolve, the uncertainty will be reduced. The experience obtained and a proper characterization will allow to identify better the characteristics of the waste. Therefore, re-characterization of waste will reduce the uncertainty for historical waste, such as additional characterization will have the same effect for bituminized waste.

Acceptability of bituminized waste must be discussed in due time with the safety authority. In this way, the decision on reprocessing the waste or not can be taken with sufficient time to take their characterization into account in WAC. This will result in a decrease in uncertainty.

The evolution of the uncertainty related to the waste stream identification & management route plays in our favour (decrease or disappear), since with time increased knowledge is continuously being implemented and eventually diminishes the uncertainty.

2.4 Pre-treatment, treatment and conditioning techniques

Pre-treatment, treatment and conditioning activities are dedicated to transform raw RW to a waste form that is capable to withstand the conditions of long-term storage and/or final disposal. These activities are connected to each other, and every step determines its following method of treatment, making the different steps of waste treatment dependent on each other.

Pre-treatment prepares the waste for further processing and may include sorting and separating different waste materials or waste types, as well as size/volume reduction or shredding to optimize treatment and disposal.

Table 5 – Uncertainties related to pre-treatment, treatment and conditioning processes.

Associated uncertainties	Description	Safety relevance of the uncertainty
Pre-treatment techniques	Uncertainties associated with collection, segregation, decontamination processes, yield of the process (efficiency of the process, how good is the set-up of the process at producing a good overall output): • Sorting and separating different types of waste to optimise treatment and disposal. • Decontamination techniques reduce the volume of the waste requiring treatment thereby minimising the disposal costs. The use of chemicals may cause new problems in processing of such waste (e.g. chemical complexing agents or an organic solvent). Yield of the process: Efficiency of the process: how good is the set-up of the process at producing a good overall output.	Waste which is not properly sorted, could have in the end an impact on the physico-chemical properties and volume of the waste. Uncertainties related to other pre-treatment processes could have a direct effect on the radionuclide content and physico-chemical form of the waste, as well as an influence on the eventual volume of the waste that shall be produced.
Treatment techniques	The waste treatment may reduce the volume with the activity remaining. • Incineration: Production of secondary waste? • Stabilisation • Compaction • Decontamination → Decontamination techniques reduce the volume of the waste minimizing the disposal costs. The use of chemicals may cause new problems in processing of such waste (e.g. chemical complexing agents or an organic solvent). Yield of the process: Efficiency of the process: how good is the set-up of the process at producing a good overall output.	Uncertainties related to treatment processes could result in more hazardous waste forms from radiation protection point of view.
Conditioning techniques	Conditioning techniques: • Appropriate waste packaging has to be chosen, • Super compaction and grouting, • Or waste immobilisation directly into disposal packages by a grout. Yield of the process: Efficiency of the process: how good is the set-up of the process at producing a good overall output.	Uncertainties associated with conditioning processes could have an impact on the content of radionuclides and dose rate, due to the type of shielding the package offers. Conditioning also has a direct effect on physico-chemical properties and can, in some cases, lead to new uncertainties regarding these properties (e.g. bituminized waste or cementitious waste with ASR). The way the conditioning will be done will have an influence on the release processes that could take place afterwards.

The aim of waste treatment processes is to transform the waste into a stable and solid physico-chemical form, and to reduce the volume of the waste. These activities focus on the reduction of the volume of the waste, and in removing, if possible, radioactivity from the waste, and are often involved in changing the physical and chemical composition of the waste.

Conditioning puts the waste in a safe, stable, and manageable form for transport, storage and disposal. Common forms of conditioned waste for disposal are encapsulated or solidified waste in cement, bitumen or glass. Conditioning techniques are designed to slow down the release of RNs from the disposed RW package into the environment.

Uncertainties associated with the performance of these techniques may have an impact on the volume of the waste, registered RN inventory and physico-chemical properties, and are described in Table 5.

2.4.1 Views of different actors on uncertainty significance

Pre-treatment, treatment and conditioning activities are really important for the different steps that have to be done to achieve the aim, such as creating waste packages that can withstand the long-term storage and disposal conditions. Although each actor has the same aim, they have different points of view. The distribution of significance for safety according to the views of the different actors regarding uncertainties associated to pre-treatment, treatment and conditioning processes related to the different radioactive waste types is respectively presented in Figure 7, Figure 9 and Figure 11. An overall view of the different actors on the significance for safety of uncertainties associated to pre-treatment, treatment and conditioning processes of radioactive waste packages is respectively presented in Figure 8, Figure 10 and Figure 12.

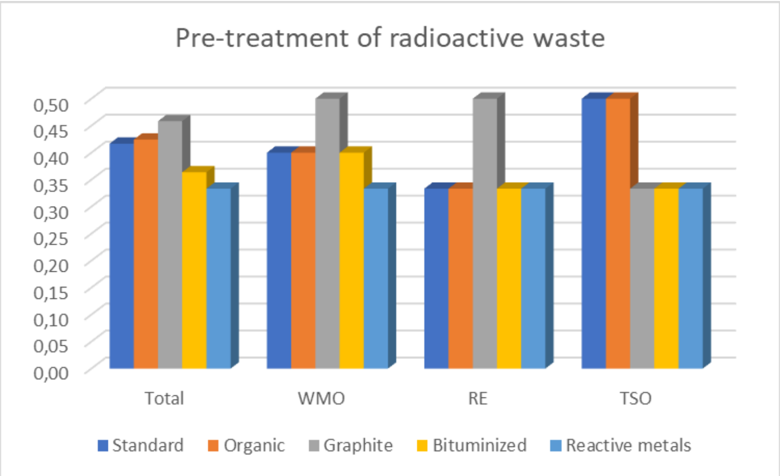

Figure 7 – Relative safety significance of uncertainties associated with pre-treatment processes of different waste types from the perspective of different actors.

For the first step, pre- treatment, TSOs believe that generation of the waste has an important impact on the design of the shielding parts of the disposal system. Insufficient knowledge on RN distribution between bulk and surface of irradiated graphite waste will prevent the development of an optimized strategy for the waste decontamination and segregation. When pre-treatment routes are not well defined, they may have a direct effect on RN content, the physico-chemical form and volume of the waste, resulting in high uncertainties. Reporting their concern, TSOs consider standard and organic waste types more important compared to the other waste types (Figure 7). On the other hand, WMOs express their concerns more to graphite waste, regarding safety. The issues concerning graphite waste are especially about the presence of C-14 and H-3, because their radiological characteristics change over time, due to uncertainties in the final physical form of graphite and its behaviour. Moreover, it is important to consider that graphite waste of NPP decommissioning involves huge volumes. REs consider uncertainties appearing due to not properly sorting of the RW, since correct sorting of RW is very important in terms of uncertainties. An inappropriate pre-treatment (sorting and combining RW) will have a significant impact on the physico-chemical stability, additionally a good or inappropriate pre-treatment can decrease or increase the amount of RW. From the point of view of REs, graphite waste is the most important which was also the case for WMOs (Figure 7).

In general, as showed in Figure 8, no differences between the different actors regarding uncertainties related to pre-treatment processes are observed.

According to TSOs, waste treatment, which is the next step, reduces the volume of waste containing the radioactivity, which may result in more hazardous wastes from radiation protection point of view. For WMOs it is important to choose the correct treatment process, because an inappropriate one may lead to degradation of the packaging and dispersion of the waste and to leaching out of toxic and/or radioactive components after disposal. A wrong determination of the physico-chemical properties will drive to an inappropriate treatment. REs agree with the other actors in a way that treatment of the waste has a high significant impact on radiological composition and physico-chemical properties, affecting the stability and safety of waste forms.

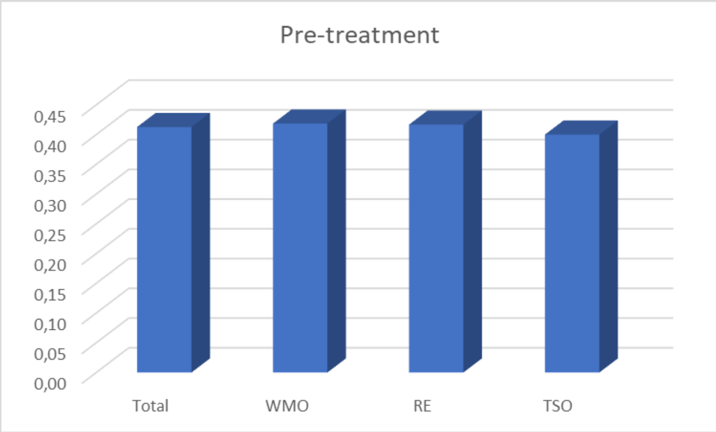

Figure 8 – Overall view of the safety significance of uncertainties associated with pre-treatment processes for each category of actors.

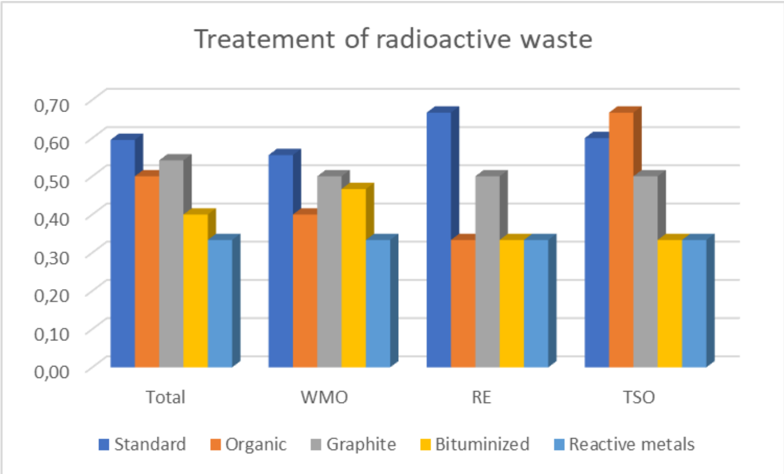

Figure 9 – Relative safety significance of uncertainties associated with treatment processes of different waste types from the perspective of different actors.

All three actors consider the uncertainty significance for safety regarding treatment of standard waste types as important (Figure 9), followed by graphite wastes. TSOs indicate organic waste types as highest significance for safety, besides standard and graphite waste types.

As shown in Figure 10, the overall view of the different actors on uncertainty significance for safety regarding treatment processes indicates more importance compared to the uncertainties related to pre-treatment processes. Interestingly, WMOs are showing less significance compared to REs and TSOs, which may be due to the operational experiences.

TSOs are pointing out that in the last step, conditioning techniques may impact the radiation protection properties. Depending on the techniques, different uncertainties arise, for instance, super compacting, grouting, etc. have a large impact on RN content and the associated dose rate. The different techniques according to conditioning have an impact on the physico-chemical properties of the RW packages, cementitious materials are mainly used, which limits the potential variation in the physico-chemical properties of the waste form. According to WMOs, an inappropriate conditioning may result in an increased volume of the final waste form, causing problems with the disposal capacity, leading to an inability to dispose of all stored waste.

Another uncertainty is the amount of aluminium present in the RW. The exact quantity of aluminium in the waste is not always known, which makes it difficult to select an appropriate conditioning technique. When aluminium gets in contact with concrete, it may lead to gas generation, making it very important to know the exact amount of it.

RE actors are worried about the uncertainty of gel formation due to ASR, foam formation and swelling, because it may have an impact on the waste form stability which could result in release processes.

On the other hand, degradation of the waste could also be a result of contact of organic waste with cement and degradation products of polymers with waste matrix.

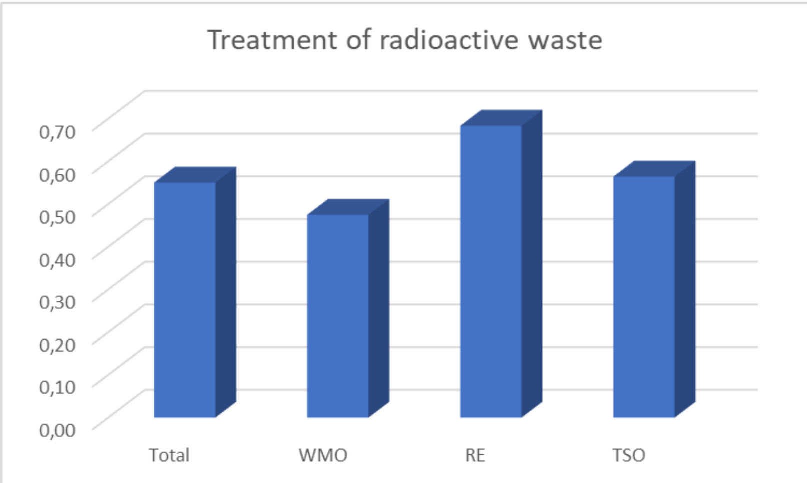

Figure 10 – Overall view of the safety significance of uncertainties associated with treatment processes for each category of actors.

Regarding the uncertainties associated with conditioning processes, TSOs consider standard waste types as most significant for safety, followed by organic and bituminized waste types (Figure 11). The distinction between the different waste types regarding the uncertainties related to conditioning processes is less pronounced for WMOs. In contrast, REs indicate the uncertainties related to organic waste types as most important for safety, followed by graphite and standard waste types.

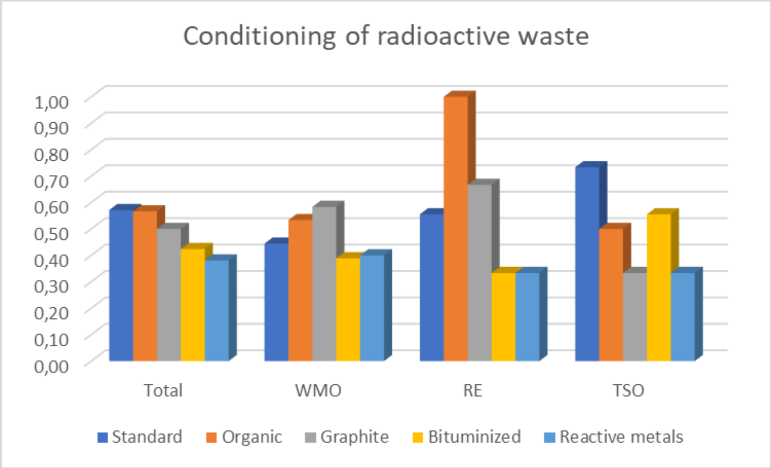

Figure 11 – Relative safety significance of uncertainties associated with conditioning processes of different waste types from the perspective of different actors.

Figure 12 shows that the uncertainties related to conditioning processes are considered as most important by REs, followed by TSOs. WMOs indicated less importance compared to the other actors.

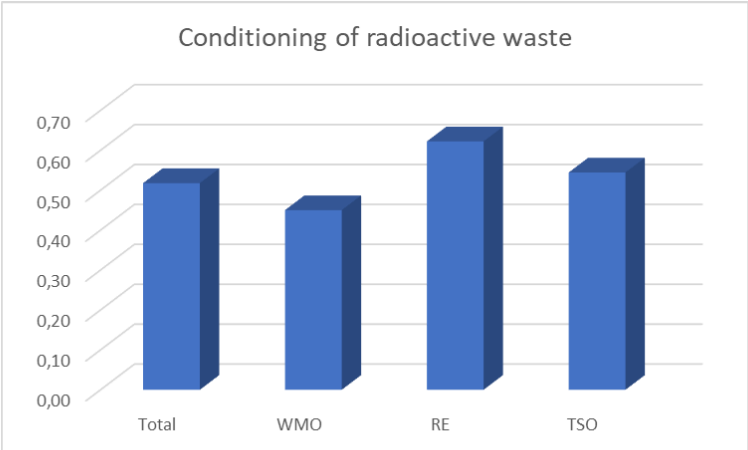

Figure 12 – Overall view of the safety significance of uncertainties associated with conditioning processes for each category of actors.

2.4.2 Potential impact of uncertainties

Steps of the RW management such as pre-treatment, treatment and conditioning have to guarantee the integrity of the waste forms for a long period of time, either it is carried out for the long-term storage or for the final disposal. Uncertainties related to these processes may affect the safe treatment and the long-term integrity of the waste package. Variability in radiological characterization may cause improper categorization of the waste package. Wrong characterization of the physico-chemical properties may also result in problems, it may cause premature failure of the waste package.

2.4.3 Characterization of uncertainties

Improvement of the methods and procedures related to the different steps and estimation of the potential waste management routes for different waste types is ongoing in several programs. For example additional investigation on RN distribution between bulk and surface of the irradiated graphite waste should be performed. The decontamination strategy used for surface contamination should be updated taking into account this extra information. Improvement of technical and quality control techniques will lead to a better characterization, which is essential for making the correct choice in waste management route, decreasing the uncertainties that could happen during (pre-)treatment and conditioning. Uncertainties related to radiological characterization may result in reducing the uncertainties associated with these processes.

Changing the management route, for example adding an extra treatment process, can reduce the uncertainty. For example for organic material, incineration seems a feasible solution, which will significantly decrease the volume of the waste for disposal. Furthermore, development of specific WAC for incineration of irradiated graphite is an important issue.

2.4.4 Evolution of uncertainties

All organizations agrees that improvement, knowledge and experience acquired in characterization and conditioning, will result in improvement in the impact of all previous aspects. The more advanced the strategies are for dismantling and associated operations, the less uncertainties related to conditioning will last. They also come to an understanding that the associated uncertainties decrease in significance for safety in later stages of the programme implementation due to updated information on generated waste. All these uncertainties will be reduced thanks to development of new techniques or to new findings in international research projects.

2.5 Long-term behaviour of radioactive waste

Uncertainty in the long-term behaviour of the RW in the storage or disposal facility depends on three groups of associated uncertainties:

- the environment characteristics present in the facility,
- the degradation rate of the waste, and
- storage time.

A description of the uncertainties and their relevance for safety is shown in Table 6.

Table 6 – Uncertainties related to long-term behaviour of radioactive waste.

Associated uncertainties	Description	Safety relevance of the uncertainty
Physico-chemical conditions in the storage or disposal facility	The long-term behaviour of the waste package and waste matrix in the surface facility or underground conditions due to uncertainties in the facility, such as pH, presence of aggressive species (chlorides, sulphates,…), mechanical stresses, etc. • Influence on the properties of the waste form: Uncertainty in disposal behaviour could produce reactions with the waste form, or result in corrosion, swelling, etc. of the matrix. Influence on the properties of the waste form – degradation rate.	Uncertainties in the storage or disposal facility conditions will impact all parameters related to the long-term waste package behaviour and can result in leaching out radionuclides, chemicals, by-products, etc. into the environment.
Waste form behaviour and ageing in storage or disposal conditions	There are uncertainties in the knowledge about corrosion, gas generation, swelling of the matrix, etc. All these processes are going to reduce the stability of the waste form. • Uncertainty in changes in matrix, degradation rate and integrity of the waste form/package → Due to poor characterisation of cellulose, ASR, DEF, chemical form of C-14, etc. degradation products could be generated. • Uncertainty on release rates of radionuclides and aggressive species in the waste form. • Uncertainty on waste-induced disturbances of other disposal system components.	Uncertainty persists on the way the waste will degrade in the storage or disposal facility. Reduction of the stability of the waste form will in turn affect those parameters that are responsible for the migration rate of the contaminants, evolving in uncertainty in which way, rate and extent the radionuclides will be released from the facility.
Storage time	Storage facilities are designed for specific classes of waste packages and therefore their design and implementation must take into account all the operational risks related to these classes of waste including those associated with extended storage times. The storage may be short term to allow for radioactive decay or long-term until the waste can be safely transferred to a suitable disposal site. Therefore, uncertainties in storage time are typically associated with uncertainties regarding the schedule of disposal programmes (as discussed e.g. in Subtasks 3.4 and 4.2 of UMAN). • The radioactive decay process for each radionuclide is unique and is calculated with a time period called half-life. Production of daughter products. • Uncertainty in the integrity of the waste package. • Storing in atmospheric condition is more challenging, because of no chemical buffer around the waste.	Uncertainties associated with storage time might arise and may affect the uncertainties on the waste form characteristics due to ageing processes or the occurrence of events like incidents or accidents. This could have an impact on the dose of key nuclides and long-lived nuclides to workers and population.

2.5.1 Physico-chemical conditions in the storage or disposal facility

The long-term behaviour of the RW package and RW matrix in the surface or underground facility depends on the environment conditions, such as pH, presence of aggressive species (chlorides, sulphates,…), mechanical stresses, etc. Uncertainties related to characteristics of the facility environment may influence the stability of the waste, by influencing the properties of the waste form, degradation rate and the rate of leaching out. In addition, the life time and condition of EBSs play an important role in the release rate.

2.5.1.1 Views of different actors on uncertainty significance

In general, for the TSOs, medium or high significance for safety was found mainly for standard and bituminized waste packages (Figure 13). TSO focus on the impact of the conditions in the facility on the physico-chemical properties of the waste. This can lead to a decrease of the waste form stability, which eventually can affect the degradation rate. Besides, the physico-chemical conditions in the facility and the degradation of the RW packages can have an impact on the life time of EBS components. All these processes could affect the rate of leaching out of RNs into the environment.

This also applies to the WMOs, where medium significance for safety was mainly found for bituminized waste and waste containing reactive metals (Figure 13). These organizations focus more on details. The evolution of pH will impact the corrosion rate of the reactive metals, which in turn affects the H2 release and thus swelling. In addition, bituminized hygroscopic salts will osmotically swell in contact with water. Subsequently, potential fracturing of host rock could occur due to water intake, swelling of bituminized waste and H2 release by waste containing reactive metals. Furthermore, the conditions of the facility do not only have an impact on the evolution of physico-chemical properties of the RW, but there is also a possible change in radiological composition because of the release of RNs.

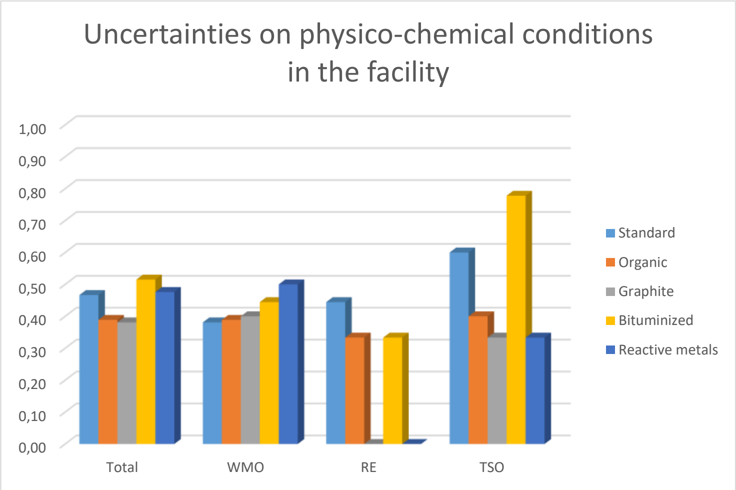

Figure 13 – Relative safety significance of uncertainties associated with physico-chemical conditions in the facility related to different waste types from the perspective of different actors.

Low significance for safety was designated by the REs, except one organization which gave a medium significance for standard waste (Figure 13). The facility conditions could have an impact on the radiological composition, especially for C-14. The impact on physico-chemical properties could lead to less mechanical stability, causing degradation of the waste form and release of RNs.

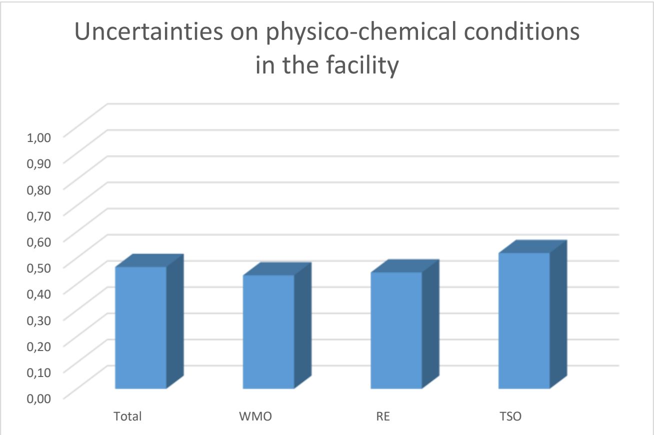

Figure 14 – Overall view of the safety significance of uncertainties associated with physico-chemical conditions in the facility for each category of actors.

Degradation of EBS results in loss of isolation and containment functions. Uncertainties in pH translates in uncertainties on waste form dissolution and RN mobility, but the overall impact is expected to be small. The high salt concentrations will decrease the rate of osmosis-induced water uptake – swelling, leading to the release of salts and RNs. Aggressive species present in the facility may increase the corrosion rate of reactive metals.

A general view, see Figure 14, shows that the TSOs have assigned the highest significance for safety regarding all waste types, followed by REs and WMOs, presenting a similar significance.

2.5.1.2 Potential impact of uncertainties

Uncertainties in the storage or disposal facility conditions will have an impact on properties related to long-term waste package behaviour. It could produce reactions with the waste form, or result in corrosion, swelling, etc. of the matrix, which in turn could result in degradation of the waste form. Because uncertainties have an impact on all parameters related to long-term waste package behaviour, it could eventually result in leaching out RNs, chemicals, by-products, etc. into the environment.

2.5.1.3 Characterization of uncertainties

Specific actions that can be taken to improve the characterization of this uncertainty:

- Further RD&D research is needed on the evolution of a disposal system and on the physical and chemical interactions of disposal conditions with the disposed waste forms. Collection of data can provide more insight into the parameters involved in the long-term behaviour of waste forms under particular facility conditions.
- More accuracy in the choice of site selection followed by a detailed characterization.
- Improve the quality of the safety assessment of the storage or disposal facility. Subsequently, consider a set of scenarios in the safety assessment including an evaluation of consequences when a faster degradation of the waste form occurs.
- A conservative approach is considered for host rock characteristics around disposal cell of bituminized waste. To develop a program on water intake and swelling pressure characterization of bituminized inventory particularly on variability.

2.5.1.4 Evolution of uncertainties

Uncertainties related to physico-chemical conditions in the facility are expected to decrease over time, as a result of the continuation of RD&D programs. New information about the characteristics of the disposal site together with the development and implementation of the disposal program may be responsible for the reduction of this uncertainty. The progress insiting processes, decisions on possible type(s) of host rock and the implementation of the uncertainty management in the safety assessment will decrease the uncertainty over time. On the other hand, uncertainties may increase with time, because prediction of long-term behaviour of RW packages entails significant uncertainties.

2.5.2 Waste form behaviour, ageing and time in storage or disposal conditions

Uncertainty persists on the way the RW will degrade in the disposal facility. There are uncertainties in the knowledge about corrosion, gas generation, swelling of the matrix, micro-organisms effects, etc. All these processes are going to reduce the stability of the waste form. In turn, this will affect those parameters that are responsible for the migration rate of the contaminants. This will evolve in uncertainty in which way the RNs will be released from the facility.

Storage facilities are designed for specific classes of RW packages and therefore their design and implementation must take into account all the operational risks related to these classes of waste including those associated with extended storage times. A storage facility is designed and licensed for a certain period which might have to be prolonged if the disposal facility is not operational in due time. Time spent by the RW package in the storage may affect the uncertainties on the waste form characteristics due to ageing processes or the occurrence of events like incidents or accidents.

2.5.2.1 Views of different actors on uncertainty significance

Figure 15 shows that the TSOs have chosen medium and high significance for safety for the following waste streams: standard, organic, bitumen (and graphite – one TSO organization). During the disposal a lot of interacting processes have to be taken into account. Storage time may impact the physico-chemical properties of the waste. For instance, long-term effects of corrosion are going to reduce the stability of the waste form, as well as hydrogen generation and subsequent swelling of the matrix is an issue. It is going to affect those parameters that are responsible for the rate of the migration of the contaminants, and thus have an impact on the release of RNs into the environment. This release could be prevented by WAC limiting for example the content of cellulose in the waste. Corrosion and gas generation of the RW packages may also affect the degradation rate of other parts of the EBS, such as closure plugs of the disposal chamber, integrity of the disposal vaults.

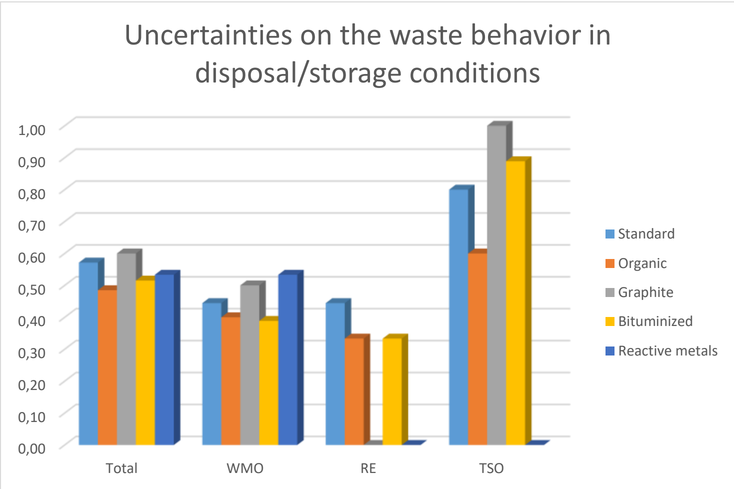

Figure 15 – Relative safety significance of uncertainties associated with waste form behaviour in storage/disposal facility related to different waste types from the perspective of different actors.

After disposal of RW, uptake of pore water by the dehydrated and hygroscopic salts will lead to a swelling of the waste and to a release of the salts. A possible consequence of the salt release is the oxidation of the host rock by nitrate, and possibly nitrite, resulting in a lower reducing capacity of the host rock towards redox sensitive RNs. This in turn could have an impact on the migration behaviour of these RNs. Additionally, underestimation of the capability of a graphite matrix to prevent the spread of RNs will increase the volume of the waste to be disposed of in the deep geological repository.

For the WMOs, there was no consensus about the significance for safety for the different waste types (Figure 15). Medium or high significance was sometimes given for standard waste, organic waste, bituminized waste and graphite, as well as low significance. Uncertainties on storage conditions may affect the population dose due to KNs and long-lived RNs. Corrosion activities from outside may occur, partly due to insufficient storage conditions. Additionally, as mentioned before, leaching processes in relation with the incoming water into the facility may arise. Due to the corrosion and leaching processes, reconditioning actions could be necessary, as well as waste which will be affected by gas generation or swelling, need to undergo additional treatment and conditioning. In case of reconditioning, the volume of the RW packages could increase. Also, the retrievability from the storage facility may be impacted by prolonged storage time.

The waste type with the most selected "high significance" is waste containing reactive metals. Corrosion and oxidation of metals could affect radiological composition and the physico-chemical properties. A change in the physico-chemical properties of the waste could lead to a chance in the matrix and mechanical strength and stability, resulting in leaching out of RNs. The long-term corrosion rate of reactive metals, and the stability of LiNO3 which has been added to inhibit the corrosion reaction, is not yet well known. Besides, in a geological disposal in poorly indurated clays, the performance of the EBS and host rock may be adversely impacted by gas build-up from corrosion of (reactive) metals. Organic waste was selected as medium significance for safety, because PVC is unpredictable in degradation and produces acids.

Low significance for safety or 'not known or assessed yet' was mainly chosen by the REs for all waste types (Figure 15). However, a few organizations have described the impact of this uncertainty. For existing standard cementitious waste forms, gas generation is not expected to be a problem. Fissuring and increasing the contact surface because of swelling due to DEF (high sulphate concentrations can lead to DEF) and maybe other deleterious reactions may occur, such as ASR (high dissolved salt concentration can lead to ASR). In organic waste forms, there is the uncertainty on the amount and type of organic degradation products. Radiation and the presence of water are the main factors of polymer ageing, resulting in degradation products which eventually have an impact on RN complexation and release. In addition, radiolysis affects rheological properties; some bituminized wastes contain both oxidizers (e.g. nitrate) and reductors (bitumen), which if heated to a threshold temperature will auto-ignite and, if conditions are 'optimal' lead to continued burning of the waste that is difficult to stop. Production of corrosion products in RW packages can result in faster degradation of EBSs, leading to loss of isolation and containment functions.

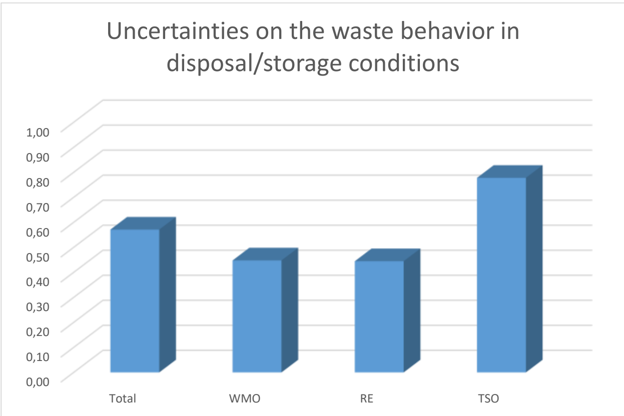

Figure 16 – Overall view of the safety significance of uncertainties associated with waste form behaviour in storage/disposal facility for each category of actors.

Furthermore, the volume of RW is influenced by the uncertainty of storage time, because due to ageing processes, it may be necessary to place the affected drums in a larger container. Waste form behaviour following different processes (radio-oxidation, swelling by water uptake and maybe by gas generation, leaching of embedded salts and RNs) is qualitatively and to some extent also quantitatively understood.

Figure 16 shows that again TSOs assigned the highest significance for safety regarding all waste types, compared to the WMOs and REs who are presenting a similar view. Here, the difference between TSOs and WMO/RE regarding uncertainties on waste behaviour in disposal conditions is more pronounced than the difference obtained regarding the uncertainties on the physico-chemical conditions.

2.5.2.2 Potential impact of uncertainties

Uncertainty persists on the way the waste will degrade and the time the waste will be in the storage or disposal facility. Due to ageing processes, reduction of the stability of the waste form will occur and in turn affect those parameters that are responsible for the migration rate of the contaminants and RNs. This could have an impact on the dose of KNs and long-lived RNs to workers and population.

2.5.2.3 Characterization of uncertainties

Knowledge about the waste form is essential to understand its behaviour in storage or disposal conditions. Therefore, laboratory testing and essays over real RW forms and matrices with all range of densifications are needed. Additional efforts should be taken to assess the retention capabilities of different matrices, as well as to optimize the WAC. Constant monitoring of the properties of the waste at the disposal facility could help in this process.

Like mentioned before, a conservative approach is considered for host rock characteristics around disposal cell of bituminized waste. Besides, the development of a program on water intake and swelling pressure characterization of bituminized inventory, particularly on variability, is considered and can estimate the uncertainty surrounding the problem and optimize the waste characterization concept. The quality of a safety assessment of a disposal facility includes time, whereby an estimation about the effect of rate of decay on radiological properties is given. Moreover, a set of scenarios could be considered, including evaluation of the consequences when a faster degradation of the waste form occurs. Justification of storage conditions in the safety case ensures proper control of conditions of RW packages during storage. Development of a safety case for storage of graphite is necessary.

2.5.2.4 Evolution of uncertainties

Significant uncertainties are expected to decrease and have less impact over time, depending on research results and their implementation in safety assessment. Additional RD&D on gas migration and corrosion behaviour of reactive metals in disposal conditions, as well as in-depth characterization of chemical compounds are expected to reduce the uncertainties and building more confidence. Furthermore, RD&D program has demonstrated compatibility of bituminized waste with geological disposal in poorly indurated clays. With time, more will be known about the waste matrices and its behaviour, especially, when the uncertainty is known, because it will be addressed before disposal.

One organization thinks that there will be little evolution with time on this uncertainty, because the uncertainty will remain on the very long-term evolution of the degradation of the RW packages. Another organization said uncertainties may increase with time, because prediction of long-term behaviour of RW packages entails significant uncertainties. On the other hand, new information about the characteristics of the disposal site with development of the disposal program may help to reduce this uncertainty.

Uncertainty regarding storage conditions is only applicable until waste emplacement. Uncertainties may increase in time due to increasing storage periods. To avoid or reduce uncertainties due to the ageing processes, the stored waste could be constantly monitored or the period of storage could be kept short where possible. More regular and more detailed inspections will help investigate the cause of the abnormalities and assess the necessity to take preventive actions to ensure retrievability. In contrast, studies are further advanced, and the disposal concept more developed, so the uncertainties will be reduced on the evolution of waste packages.

3. Uncertainties of interest

In the frame of the work to be performed on the uncertainties regarding waste inventory in UMAN Subtask 4.2, uncertainties that are of most concern to the different organizations need to be selected. Therefore, Subtask 4.2 has sent out a small survey, which includes the list of 20 uncertainties, to UMAN 4.2 and 3.2 members, where the organizations could judge the uncertainty as being of 'high', 'medium' or 'low' importance/priority.

The survey was completed by 10 organizations (TUS, TS Enercon, SURO, SCK CEN, FTMC, NAGRA, LEI, ENRESA, BelV and VTT). Three uncertainties with the highest importance were selected by UMAN Subtask 4.2 (Figure 17):

- Radionuclide activity (including the SF)
- Chemical composition (with a special attention to organic content)
- Physico-chemical conditions in the storage or disposal facilities

Some fields in the survey were not marked by some participants, and for one uncertainty, two answers were given depending on the specific issue. That explains why the total is not always equal to 10 answers.

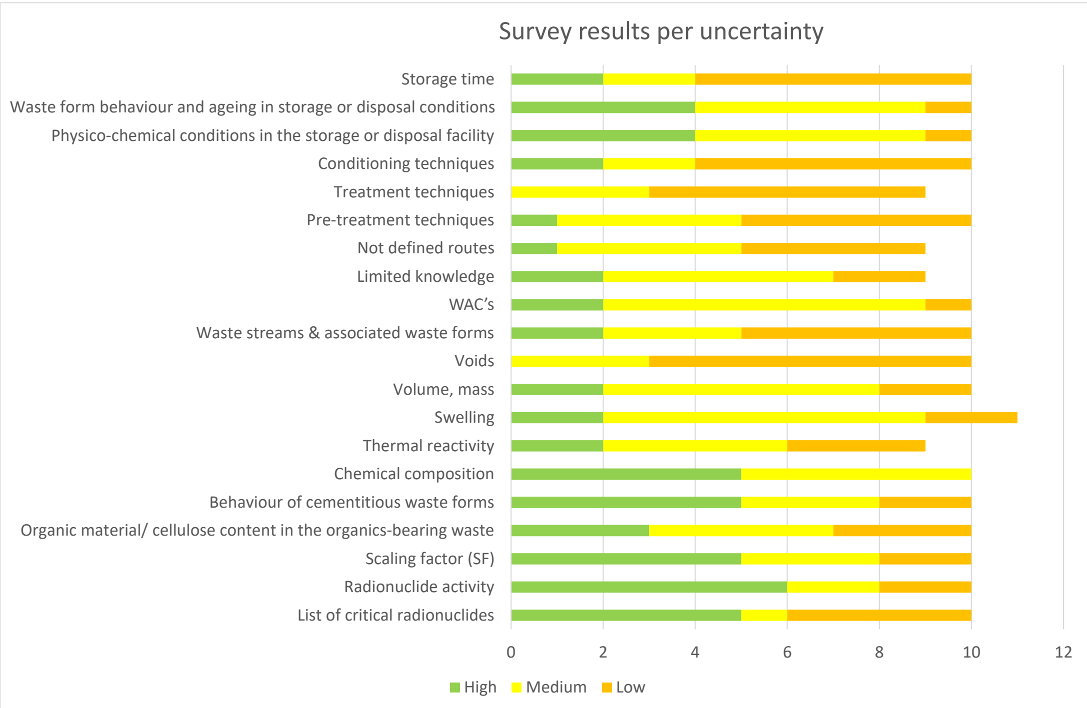

Figure 17 – Results of the survey performed by UMAN Subtask 4.2.

For the following sections, recommendations and conclusions, we will focus mainly on these three uncertainties of high priority for safety.

4. Recommendations

The most important uncertainties associated with waste inventory are the ones related to radiological characterization. Uncertainty about the declared radioactivity of a RW package has a direct impact on the safety of personnel, environment and general population. The gamma emitting radionuclides can be identified and confirmed with additional quality control measurements. With regard to historical waste, the impact of the uncertainties is much larger, due to the lack of knowledge about the specific materials within the waste package which makes it challenging to accurately measure the impact of shielding. To identify materials and other physical properties, measurements can be performed by innovative X-ray technologies, which need to be explored more in detail in the future. On the other hand, concerning the DTM radionuclides, emitting only beta and/or alpha radiation, development of the scaling factor approach has the highest potential to reduce the associated uncertainties. This can be done by intensive radioactive sampling and destructive analysis of beta and alpha content. Available databases maintaining such measurement results require some effort but would be very helpful. Furthermore, technical improvements in the detection capacity of beta-gamma and alpha emitters, together with the development of quality control improvements are processes that lead to a better radiological characterization.

Another important uncertainty related to waste inventory are uncertainties involved in the determination process of the chemical composition of a RW package. Depending on their properties, chemical elements can have a negative influence on the stability of waste forms and waste packages. Chemical characterization of RW can help in the identification of possible chemical reactions that may occur in the waste matrix. Generally, the content of various organic compounds cannot be assessed without detailed destructive analysis of waste forms. Therefore, a database of material composition from wide range of sources could be useful. Moreover, additional and innovative research is necessary, regarding e.g. degradation products and complexing agents enhancing RN mobility, since methodologies and approaches for such characteristics are not common. Additionally, addressing the chemical composition of spent nuclear fuel (impurities) by evaluation in the safety assessment can be a step in the right direction to reduce conservatism, since more information will be available about impurities in the chemical composition. Another way to reduce the impact of uncertainties, is to select waste conditioning processes that are less influenced by initial chemical composition. In general, the overall determination and assessment of uncertainties have to be examined in order to formulate recommendations on their treatment.

Uncertainties with regard to physico-chemical conditions in the storage or disposal facilities determine the long-term behaviour of the waste, as they may have an impact on the stability of waste forms and RW packages during the period of storage or disposal. Therefore, attention should be paid to uncertainties associated with the facility, among which those related to pH and the presence of aggressive ion species in the environment. Various possibilities to reduce these uncertainties are extensive monitoring sensor networks for data collection, and accumulation and development of artificial barriers with high chemical resistance to aggressive media.

5. Conclusions

All uncertainties relevant to the inventory and management of radioactive waste were identified and considered to explore their impact and significance for safety. Small differences are observed in the views of the different actors, which are TSOs, REs and WMOs, after analysis of the 2nd UMAN questionnaire. Although, concerning the most significant uncertainties, the core of the viewpoints is similar for the different actors. Their approaches visualize the interests and necessities of the regulators, the research-oriented organizations and the operators, which are dealing with radioactive waste on daily basis. One should note that only a small part of the existing organizations related to RW management, completed the 2nd UMAN questionnaire, so the survey results lack statistical relevance concerning clear distinction of major differences between associates.

In this work, five high-importance waste types were considered: standard cementitious, organic, graphite, bituminized and reactive waste. The interests in and importance of the different waste types for the three categories of actors are based on what waste they are dealing with, waste that has a lot of attention from regulatory bodies and waste types that require more research with regard to safe final disposal. To get an overall view of the different actors on uncertainties associated with the waste inventory, all answers received from the specific organizations for all waste types (2nd UMAN questionnaire) were considered together. Interestingly, TSOs gave considerably higher safety significance to the uncertainties associated with radiological properties, physico-chemical properties and the long-term behaviour of waste form. Additionally, a high interest in treatment and conditioning techniques was noted for REs. Uncertainties associated with radiological characterization are designated as most significant with regard to waste inventory, because they have a substantial impact on the environment. Determination of the activity of DTM alpha and beta emitting radionuclides is identified as main uncertainty, but the employment of scaling factors has potential to reduce these uncertainties. Subsequently, the chemical composition (especially organic content) should be taken as the uncertainty with the most significant impact on safety with regard to the long-term behaviour of the waste form during storage and final disposal. The knowledge of impurities and the development of databases with regard to material composition should be very useful, as most EURAD organizations are dealing with similar waste inventories.

Generally, it can be stated that all organizations are facing numerous types of uncertainties related to waste inventory. It is also clear that the importance of uncertainties associated with radiological and physio-chemical properties of the waste is recognized by each organization involved in radioactive waste management. In view of uncertainty treatment, this survey is not representative. It is important to properly deal with the uncertainties, and to address this objective, further assessment and quantification of the uncertainties are necessary.

References

1. EURAD project, Milestone 92, Work Package 10, “Milestone 92: UMAN Preliminary list of uncertainties from Subtask 3.2 as input to Subtask 4.2”, date of issue: 23-06-2021.

2. CHANCE project, End-User-Group Questionnaire, Deliverable D2.1, Work Package 2, date of issue: 30-11-2017.

3. CHANCE project, Synthesis of commonly used methodology for conditioned radioactive waste characterization, Deliverable D2.2, Work Package 2, date of issue: 16-07-2019.