Deliverable D10.9: UMAN - Views of the different actors on the identification, characterisation and potential significance of uncertainties associated with spent fuel

Work Package WP10

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.

http://www.ejp-eurad.eu/

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.	**WP10**
Work Package Title	**Uncertainty Management multi-actor Network**
Work Package Acronym	**UMAN**
Deliverable No.	**D10.9**
Deliverable Title	**UMAN - Views of the different actors on the identification, characterisation and potential significance of uncertainties associated with spent fuel**
Lead Beneficiary	**Bel V**
Contractual Delivery Date	**May 2024**
Actual Delivery Date	**June 2024**
Type	**Report**
Dissemination level	**Public**
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To be cited as:

Detilleux V., Cano-Ott D., Diaconu D. (2024): UMAN - Views of the different actors on the identification, characterisation and potential significance of uncertainties associated with spent fuel. Deliverable D10.9 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

Disclaimer

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)	Valéry Detilleux (Bel V)	10/05/2024
Verified (WP Leader)	Daniela Diaconu (RATEN)	11/05/2024
Final version (Lead Beneficiary)	Valéry Detilleux (Bel V)	16/05/2024
Reviewed (Reviewers)	Tobias König (KIT) Artūras Plukis (FTMC)	21/05/2024 26/05/2024
Approved (PMO)	Elisabeth Salat (IRSN)	11/06/2024
Submitted to EC	Andra (Coordinator)	12/06/2024

Executive Summary

UMAN sub-task 3.5 aims at identifying views of the three categories of actors (Research Entities (REs), Technical-Support Organisations (TSOs) and Waste Management Organisations (WMOs)) participating in EURAD, related to:

- the significance for safety of uncertainties related to spent nuclear fuel,
- the preferences in the characterisation of these uncertainties,
- the uncertainties evolution along the disposal programme implementation.

The actors' views have been collected via the 2nd UMAN Questionnaire – Section *Spent Fuel* launched on September 15, 2020, and analysed by the expert group acting in sub-task 3.5 – *Spent fuel related uncertainties*.

This EURAD deliverable 10.9 focuses primarily on the analysis of uncertainties significance from the point of view of the three categories of actors (WMOs, TSOs and REs). This analysis is used as input by UMAN task 4 in the selection of the uncertainties with a significant relevance for safety, as basis for the discussion and identification of the management options and preferences of different actors regarding spent fuel related uncertainties (in the UMAN Workshop #3, see UMAN deliverables D10.11 and D10.12).

The 2nd UMAN questionnaire grouped the uncertainties associated with spent nuclear fuel in 6 groups, considered by the UMAN experts' group of spent nuclear fuel to have a potential significance for safety:

A. Uncertainties associated to the spent nuclear fuel (SNF) characterisation and inventory
B. Uncertainties associated to SNF cladding degradation and radionuclide release processes
C. Uncertainties associated to SNF storage and disposal canisters
D. Uncertainties associated to bolted closure systems of dry storage casks
E. Uncertainties associated to concrete stress-corrosion cracking processes (SSCs) in dry storage/ disposal facilities
F. Uncertainties associated to the neutron shielding in dry storage systems

Each uncertainty group has been refined, the questionnaire addressing in total 57 topical uncertainties associated with the spent nuclear fuel, from fabrication until final disposal.

The analysis was based on the answers received from 16 organisations (representing 8 REs, 4 TSOs and 4 WMOs). On average, uncertainties associated to the SNF inventory (group A) are considered by respondents to have the higher safety significance. Among each group of uncertainties, specific uncertainties considered by the questionnaire respondents to have a higher safety significance than the others were identified.

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Glossary

ASR – Alkali-silica reaction

DEF – Delayed Ettringite Formation

EURAD – European Joint Programme on Radioactive Waste Management

NF – Nuclear Fuel

PDF – Probability Density Functions

RE – Research Entity

SCC – Stress corrosion cracking

SNF – Spent Nuclear Fuel

TSO – Technical Support Organisation

UMAN – Uncertainty Multi-Actor Network

WMO – Waste Management Organisation

WP – Work package

1. Introduction

The UMAN Deliverable 10.9 gathers views of different actors on the characterisation and potential safety significance of the uncertainties related to spent fuel, collected via the 2nd UMAN Questionnaire launched on September 15, 2020. It is based on a list of uncertainties elaborated by the expert group of the UMAN Subtask 3.5, classification schemes provided by the Subtask 2.1 [1] and strategies options developed in Subtask 4.2 [2].

This document focuses primarily on the relevance for safety of the spent fuel related uncertainties for the following three categories of actors participating in EURAD: Research Entities (REs), Technical Support Organisations (TSOs) and Waste Management Organisations (WMOs).

The work of subtask 3.5 provided input for Milestone *MS118: UMAN Draft deliverable D10.11 as input to Subtask 4.3* [2] and for Workshop #3: *Management options and preferences of different actors regarding spent fuel related uncertainties*, organised by Subtask 4.3 [3].

Based on the answers received to the 2nd UMAN questionnaire – *Section Spent fuel,* the expert group of Subtask 3.5 selected uncertainties for which a more detailed analysis of the potential impact on the safety, methods used in their characterisation and their evolution has been developed.

This deliverable was further developed by the members of the expert group which provided details related to the relevance of these uncertainties on the safety of different disposal systems, as compiled from the experience acquired in the national programmes or in other international reports, projects, works.

The views of actors considered in this study covered all phases of a geological disposal programme.

2. Methodology: the identification and characterisation process

2.1 Approach/methodology used for identification

A group of 4 experts representing REs and TSOs from different member states (Spain, Belgium, Germany and Ukraine) with different spent fuel disposal programmes (from the point of view of host rock, repository concepts and implementation stages) established, following a brainstorming organised in the beginning of the UMAN WP, a first list of uncertainties potentially significant for the disposal safety. This preliminary list covers uncertainties associated with the entire fuel cycle (from fabrication to disposal) and reflects the views and experience of the experts gathered in their national radioactive waste management programmes.

In order to complete the list of uncertainties and to have as representative views as possible on how different types of actors perceive the relevance of the identified uncertainties for safety, a wide survey based on a questionnaire, involving several EURAD partners, was conducted.

2.2 List of uncertainties

The possible significance for safety of uncertainties associated with the spent nuclear fuel, their characterisation and possible evolution along the disposal programmes have been addressed via a dedicated questionnaire covering 57 uncertainties grouped in the following 6 groups:

A. Nuclear fuel (NF) fabrication and irradiation at the reactor (11 uncertainties)
B. SNF cladding integrity and degradation (10 uncertainties)
C. SNF storage and disposal canisters (15 uncertainties)
D. Bolted closure systems of dry storage casks (4 uncertainties)
E. Concrete components in dry storage/ disposal facilities (13 uncertainties)
F. Neutron shielding in dry storage systems (4 uncertainties)

The 57 uncertainties, explicitly addressed by the questionnaire, are presented below for each group.

A. Uncertainties associated with Nuclear Fuel (NF) fabrication and irradiation at the reactor

The NF fabrication process and the conditions during its irradiation in the reactor determine key characteristics of the SNF such as its isotopic composition and decay heat [3]. These characteristics, and their associated uncertainties, could affect the thermo-hydro-mechanical-chemical evolution of the SNF and thus the safety of all the SNF management steps. For instance, the initial composition and the irradiation conditions of the NF will be determining factors for the evolution of the inventory of the SNF. Moreover, the composition of the cladding could affect its possible degradation processes and thus the source term released for example in a disposal facility (instant release fraction included). Relevant characteristics and issues (and associated uncertainties) considered in the questionnaire are the following:

A.1. Fabrication process (e.g., annealing), additives, impurities and tolerances of the NF components

A.2. Uncertainties on composition (physicochemical) of the cladding materials

A.3. Uncertainties associated with composition (radio- and physicochemical) and enrichment of the fuel

A.4 Thermo-mechanical and chemical behaviours of the NF components

A.5 Irradiation conditions (dose rate, cumulated doses, types of radiations…)

A.6 Burnup and respective isotopic composition, in case of use of "burnup credit"

A.7 Uncertainties on the instrumental control of SNF burnup, that is applied in case of use of "burnup credit"

A.8 Methodology and nuclear data for SNF inventory calculations: cross-sections, decay properties of the isotopic inventory, dose conversion factors

A.9 Residual heat generation

A.10 Isotope transport properties within the SNF components

A.11 Radiation characteristics, residual heat generation and residual neutron absorption properties of irradiated non-fuel elements (absorbing rods, shim rods…)

B. Uncertainties associated to SNF cladding integrity and degradation

The long-term performance of the fuel cladding during storage[1], transportation and possible disposal in canisters is a very relevant issue, as it provides a safety barrier against the radioactive inventory. The cladding also contributes to maintaining the fuel geometry assumed in the safety cases, under both normal and accident conditions of storage and subsequent transportation and possible disposal. An accurate prediction of the cladding behaviour is key to provide an adequate demonstration of the fuel safety functions fulfilment in the long term. Loss of cladding integrity may allow the release of gases, fuel particulates and pellet fragments. As a result, the geometric distribution of the radioactive material in the canister may be different of that assumed in the safety analysis, thus limiting its validity. Relevant characteristics and issues (and associated uncertainties) considered in the questionnaire are the following:

B.1 Hydrogen embrittlement and hydride reorientations

B.2 Delayed hydride cracking: crack growth due to precipitation of hydrides at the cracks

B.3 Cladding creep: deformation of the cladding material due to stress

B.4 Deformation of cladding material during drying

B.5 Stress and deformation of cladding material during SNF unloading from the dry-type storage

B.6 Cladding and pellet oxidation mechanisms

B.7 Stress corrosion cracking

B.8 Mechanisms for degradation of damaged fuel

B.9 Safety of SNF handling operations in course of its preparation for long-term storage

B.10 Management of damaged and non-tight spent fuel assemblies

C. Uncertainties associated to SNF storage and disposal canisters

SNF will be stored and disposed of in canisters. These canisters are typically made from austenitic stainless steel with an all-welded construction. Their characteristics (and associated uncertainties) could affect the safety of the SNF management steps. For instance, their material composition, fabrication process and environmental conditions will affect their possible degradation processes and thus influence safety. One particular concern is chlorine induced stress corrosion cracking because it is a form of localised corrosion where cracks can propagate through the canister material without requiring substantial loss of material. It can lead to release of radioactive materials and thus influence safety. Relevant characteristics and issues (and associated uncertainties) considered in the questionnaire are the following:

[1] Some degradation mechanisms are of particular importance during dry storage because SNF will be moved from wet (in the reactor and subsequent storage in a spent fuel pond to dissipate the decay heat) to dry conditions. This will affect the cladding environment and thus the importance of some degradation mechanisms.

C.1 Failures of the material used in the fabrication

C.2 Quality of the welds

C.3 Stress level of welds

C.4 Characteristics of the neutron absorbers used for ensuring subcriticality

C.5 SNF loading into canister

C.6 SNF drying inside the container

C.7 Uncertainty in the He filling of the container

C.8 Release of inert gases by the fuel element inside the container

C.9 Radiolysis, hydrogen generation

C.10 Corrosion of external elements due to salt

C.11 Changes in the humidity

C.12 Temperature profiles and thermal modelling applicable in different countries

C.13 Canister degradation due to radiation

C.14 Comprehensive monitoring of parameters for indirect assessment of tightness of canister, condition of fuel, heat removal, gamma, and neutron radiation

C.15 Measurement of the medium in dry airtight or transport canisters, in case of gas leakage

D. Uncertainties associated to bolted closure systems of dry storage casks

Bolted closure systems are an essential component of dry storage casks ensuring the long-term safe enclosure of the radioactive inventory. The performance of the barrier seals during long-term storage and transportation is crucial and ageing effects on the seal function may endanger safety goals. Possible degradation mechanisms (and associated uncertainties) considered in the questionnaire are the following:

D.1 Atmospheric and aqueous corrosion

D.2 Time evolution of the sealing performance and gas leakage

D.3 Radiological ageing

D.4 Time and temperature effects. Corrosion and creep of metals.

E. Uncertainties associated to concrete components in dry storage/ disposal facilities

Concrete casks and vaults have demonstrated to be credible solutions for the long-term storage of SNF. Moreover, concrete overpacks for SNF canisters are considered by some countries in the design of their disposal facility. Extending currently licensed storage periods will require licensees and holders of compliance certificates to renew and extend their initial license term. Thus, as part of the revised ageing management programmes, the licensees need to address the potential degradation mechanisms of concrete casks, as well as consider the use of different inspection techniques to detect these mechanisms in order to monitor cask performance throughout this extended period. Based on [5], it seems that effects of degradation mechanisms on concrete storage casks performances still need further investigations. In particular, the combination of degradation mechanisms and environmental conditions found at storage sites, such as high temperature and ionising radiation, can have a negative impact on concrete longevity and durability. The use of concrete overpacks in disposal facilities creates favourable chemical conditions protecting the inlying steel canister against corrosion. Nonetheless, concrete in disposal facilities will be subjected to different degradation mechanisms depending on the thermo-hydro-mechanical-chemical conditions prevailing in the facility during operations and after its closure. Relevant mechanisms (and associated uncertainties) of concrete degradation and ageing considered in the questionnaire are the following:

E.1 Concrete shrinkage and creep caused by long-term dry out

E.2 Carbonation caused by reaction with CO_2 in the atmosphere

E.3 Ingress of chlorides in disposal conditions

E.4 Freeze-thaw due to use of concrete in cold environments

E.5 ASR within the concrete

E.6 Sulphate attack on the concrete

E.7 Neutron induced radiation damage in the concrete

E.8 Thermal degradation of concrete

E.9 Leaching and efflorescence

E.10 Concrete swelling due to the crystallisation in sub-microcrystals

E.11 Degradation of concrete due to ettringite and thaumasite crystallisation

E.12 Degradation of concrete due to metal corrosion

E.13 Degradation of concrete induced by mechanical stresses

F. Uncertainties associated to the neutron shielding in dry storage systems

Transport and storage of nuclear and radioactive material must fulfil general principles of safety to control hazards, prevent accidents and mitigate any harmful consequences of ionising radiations. All the neutron shielding materials have a high content of hydrogen for attenuation and capture of neutrons. As such, it is important for neutron shielding material to maintain adequate hydrogen content as long as the storage and transportation system remains in operation. Typical neutron shielding materials for storage and transportation systems are:

- Water in leak-tight compartments.
- Polymers and corresponding polymer compounds with high hydrogen content such as polyethylene or polyester. Some polymers may be borated for neutron capture. The shielding performance of polymers is given by their chemical composition, density and thickness.
- Concrete. Although the hydrogen content is lower than for polymers (four times less than polyethylene), leading to an increase of the thickness of shielding layer, it is possible to increase concrete shielding performance by adding fillers. Concrete also performs the function of protection against gamma radiation. It is necessary to consider together the issues of protection from neutron and gamma radiation, as well as strength of concrete shielding.

For welded stainless-steel canisters inside concrete overpack storage systems, both neutron and gamma shielding are provided by the overpack that is primarily composed of a thick layer of concrete. Sources of uncertainty considered in the questionnaire are the following:

F.1 Knowledge on the source term and dose evaluation

F.2 Thermal and thermal oxidative degradation

F.3 Degradation due to irradiation

F.4 Hydrogen quantity

2.3 The Questionnaire

The first purpose of the 2nd UMAN Questionnaire was to collect views of the actors regarding the possible significance of each spent nuclear fuel related uncertainty proposed by the group of experts.

The second aim was to gather supplementary information/data on their characterisation and evolution over time, and collect missing uncertainties, considering the diversity of national disposal programmes in terms of spent fuel management approach and implementation phase.

For each uncertainty addressed in the questionnaire, questions were dedicated to

- Significance for safety, quantified as:
    1. high
    2. medium
    3. low
    4. not known or assessed yet
- Potential impact on safety such as:
    - Impact on the source term assessment for SNF disposal and dose assessment.
    - Impact on transport safety
    - Impact on the operational safety during storage
    - Impact on the operational safety during disposal
    - Impact on the post-closure safety
    - Impact on the safety function(s); please specify
    - Other (please specify)
- Uncertainty characterisation (methods, approaches) - open answer
- Evolution along the programme implementation (from conceptualisation to repository closure) - open answer.

The 2nd UMAN questionnaire has been sent to all partners participating in the EURAD project but the Civil Society organisations. It was available in two formats: word documents and on-line questionnaire. Answers have been received from 16 organisations (*Table 1*), representing, as illustrated in *Figure 1*, REs (8 answers); TSOs (4 answers) and WMOs (4 answers).

Table 1. List of actors answering the questionnaire on spent fuel uncertainties

Affiliation	Country	Type of actor	Considered host rock	Current phase of the programme for: Deep geological disposal
CNRS	FR	RE	Sedimentary	
CVR	CZ	RE	Crystalline	Site evaluation, site selection
Not communicated	DE	RE		Site evaluation, site selection
Slovak University of Technology	SK	RE		Policy, framework, programme establishment
FTMC	LT	RE		
LEI	LT	RE		SNF interim dry storage/operation&closure
RATEN	RO	RE		Policy, framework, programme establishment
CIEMAT	ES	RE		
EIMV	SI	TSO	Crystalline	Policy, framework, programme establishment
SURO	CZ	TSO	Crystalline	Site evaluation, site selection
VTT	FI	TSO	Crystalline	
Bel V	BE	TSO	Sedimentary	Policy, framework, programme establishment

SÚRAO	CZ	WMO	Crystalline	Site evaluation, site selection
NAGRA	CH	WMO	Sedimentary	Site evaluation, site selection
ONDRAF / NIRAS	BE	WMO	Sedimentary	Policy, framework, programme establishment
ANDRA	FR	WMO	Sedimentary	facility construction

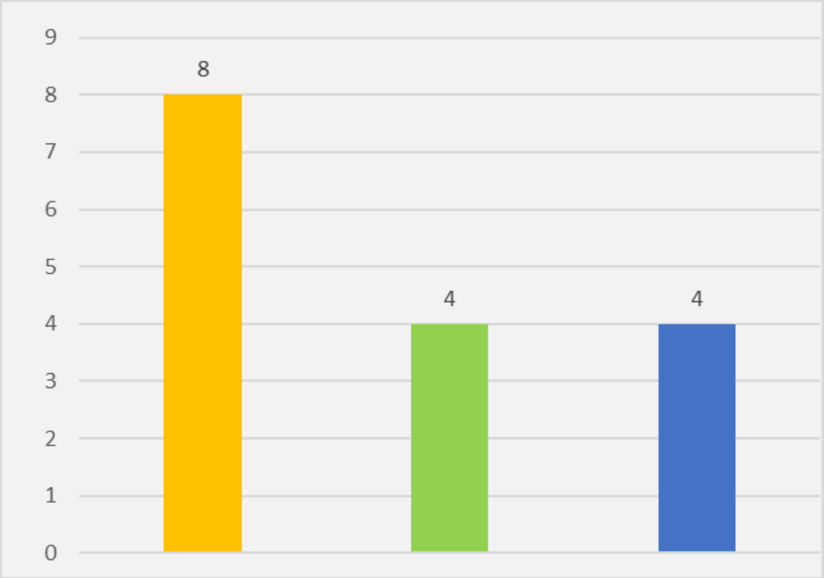

Figure 1. Answers distribution per type of actor (RE, WMO and TSO are respectively represented in orange, green and blue, as in Table 1).

2.4 Analysis of the answers to the questionnaire

To assess and compare the possible relevance for safety of the uncertainties for each type of actors, each uncertainty has been scored. It was agreed in the expert group of subtask 3.5 to score (arbitrarily) the answers as follows:

Score = 3*#high + 2*#medium + 1*#low

where:

#high = number of answers marked as high priority

#medium = number of answers marked as medium priority

#low = number of answers marked as low priority

The safety significance was estimated as:

Safety significance = score / (number of uncertainties * number of answers)

and

Answering ratio = number of answers / number of uncertainties.

Note that the limited number of respondents does not allow to draw conclusions from quantitative comparisons between the answers from the different groups of actors. The study in this deliverable should thus be seen as rather qualitative, with as objective to provide material for discussions in Task 4 of UMAN.

3. Uncertainties associated with the nuclear fuel (NF) fabrication and irradiation at the reactor

3.1 Significance for safety

Figure 2 provides an overview of the safety significance related to A.1 to A.11 uncertainties, according to the respondents to the questionnaire.

The score in each cell corresponds to the sum of the scores from the different institutions. Color code: green - lowest values, red - highest values. Safety significance: High - 3, Medium - 2, Low - 3, not known or not assessed - 0	Safety significance	Safety significance	Impact on source term assessment for SNF disposal and dose assessment	Impact on transport safety	Impact on operational safety during storage	Impact on operational safety during disposal	Impact on postclosure safety	Impact on safety function(s)	Other	Total score
A.1 Fabrication process (e.g. annealing) additives, impurities and tolerances of the NF components	21	21	18	3	8	6	8	4	0	47
A.2 Composition (physicochemical) of the cladding materials	16	16	7	5	5	1	4	3	0	25
A.3 Composition (radio- and physicochemical) end enrichment of the fuel	28	28	23	10	13	13	3	5	0	67
A.4 Thermo-mechanical and chemical behaviours of the NF components	17	17	5	5	9	8	2	2	0	31
A.5 Irradiation conditions (dose rate, cumulated doses, types of radiations…)	26	26	20	14	12	13	8	6	0	73
A.6 Burnup and respective isotopic composition, in case of use of "burnup credit"	30	30	24	12	12	12	11	5	0	76
A.7 Uncertainties on the instrumental control of SNF burnup, that is applied in case of use of "burnup credit"	10	10	6	4	6	6	1	1	1	25
A.8 Methodology and nuclear data for SNF inventory calculations: cross-sections, decay properties of the isotopic inventory, dose conversion factors	28	28	25	2	11	13	9	2	0	62
A.9 Residual heat generation	25	25	10	4	7	7	12	8	3	51
A.10 Isotope transport properties within the SNF components	22	22	9	3	3	3	17	1	0	36
A.11 Radiation characteristics, residual heat generation and residual neutron absorption properties of irradiated non-fuel elements (absorbind rods, shim rods…)	13	13	6	2	4	2	6	0	0	20
Total score	236									

Figure 2. Overview on the safety significance of the uncertainties associated with the nuclear fuel fabrication and irradiation at the reactor (the scales indicated by the colours in the first and second "safety significance" columns are related to a comparison of the safety significance with the other uncertainties in the same group and in the 6 groups, respectively).

A.1 and A2 Fuel fabrication process and composition of the cladding material.

The fuel fabrication process is highly standardised and all technical parameters in this process are strictly controlled by the fuel producers. For instance, before to enter the fabrication, cladding tubes are checked for their structural integrity. Moreover, several physicochemical characteristics of the cladding material are certified by the producers (such as impurity level per element, inner/outer diameter, density, mechanical properties, etc.). Therefore, uncertainty related to physicochemical properties of cladding tubes is considered as well characterised by the respondents to the questionnaire. Compared to the uncertainties A.3, 5, 6, 8 and 9 in Figure 2, the safety significance of uncertainties A.1 and A.2 is considered to be lower by the respondents.

A.3 Composition (radio- and physicochemical) and enrichment of the fuel

Uncertainties associated with isotopic composition of UO_2, pellet density and porosity are given by pdf based on measured values. The radiochemical content is usually well known. The remaining uncertainties are mainly related to measurement errors, natural variation of the composition and properties, and inherent variability due to the fabrication process. Compared to the uncertainties A.1, 2, 4, 7, 10 and 11, the safety significance of uncertainty A.3 is considered to be higher by the respondents to the questionnaire.

A.4 Thermo-mechanical and chemical behaviours of the NF components.

The degradation mechanisms of the nuclear fuel components during and after their irradiation in the reactor is notably a function of its thermo-mechanical and chemical behaviours. Uncertainties associated to these behaviours can therefore affect the safety of SNF transport, storage and disposal. However, compared to the uncertainties A.3, 5, 6, 8 and 9 in Figure 2, the safety significance of uncertainty A.4 is considered to be lower by the respondents to the questionnaire.

A.5 and A.6 Irradiation conditions, burnup and respective isotopic composition in case of burnup credit

Uncertainties on irradiation conditions directly impact the uncertainties on the radionuclide inventory in the spent nuclear fuel. Uncertainties on the operational history of a fuel rod/assembly (including burnup, linear heat generation rate, effective full power days, cycles, date of discharge etc.) can thus be significant for the safety (e.g., if the operational history is not communicated by the vendor/utilities, or if the documentation is incomplete/lost). Compared to the uncertainties A.1, 2, 4, 7, 10 and 11, the safety significance of uncertainty A.5 and 6 is considered to be higher by the respondents to the questionnaire.

A.7 Uncertainties on the instrumental control of SNF burnup, that is applied in case of use of "burnup credit"

Compared to the uncertainties A.3, 5, 6, 8 and 9 in Figure 2, the safety significance of uncertainties A.7 is considered to be lower by the respondents to the questionnaire. It seems thus that, according to the respondents, it is not the uncertainties on the instrumental control of SNF burnup which could affect the uncertainties on operational history, but rather the way this history is managed (traceability, risk of loss…).

A.8 and A.9: Methodology and nuclear data for SNF inventory calculations, residual heat generation

Nuclear data could be the largest contributor to uncertainties on nuclide concentrations. Large variations of calculated uncertainties can be obtained, sometimes up to a factor of 10, especially for specific fission products, which are generally very sensitive to fission yields. It is conceivable that biases in nuclide concentrations might lead to biases for the residual SNF decay heat [4]. In general, experience with computer code calculation and measured values of radionuclide activity has shown a reasonable agreement. However, nuclear data could be improved for reaching more accurate results. Biases between inventory calculations (C) and experiments (E) can be as large as 8.5% for ^{134}Cs and 63% for ^{125}Sb. Consequently, biases in calculated decay heat curves versus cooling times can reach 6% in the first 10 years cooling period and are 2 - 3% during the 10 to 100 years cooling period. Uncertainties on methodology and nuclear data for SNF directly impact the modelling of SNF inventory and residual heat generation. Compared to the uncertainties A.1, 2, 4, 7, 10 and 11, the safety significance of uncertainties A.8 and 9 is considered to be higher by the respondents to the questionnaire.

A.10: Isotope transport properties within the SNF components.

Compared to the uncertainties A.3, 5, 6, 8 and 9 in Figure 2, the safety significance of uncertainties A.10 is considered to be lower by the respondents to the questionnaire. According to the respondents, uncertainties on the inventory of radionuclides in the SNF is thus more significant for safety than the uncertainties on their transport properties within the SNF.

A.11: Radiation characteristics, residual heat generation and residual neutron absorption properties of irradiated non-fuel elements (absorbing rods, shim rods…)

Compared to the uncertainties A.3, 5, 6, 8 and 9 in Figure 2, the safety significance of uncertainty A.11 is considered to be lower by the respondents to the questionnaire

3.2 Actors' views on uncertainty relevance

Figure 3 provides an overview of the significance for safety of uncertainties A.1 to A.11 according to each group of actors. A statistical comparison between the groups of actors cannot be performed. However, it is to be noted that TSOs seem to consider a higher safety significance of uncertainties A.6 to A.11 compared to the other types of actors. Moreover, WMO consider a lower safety significance of uncertainties A.4, 7 and 11 compared to the other types of actors.

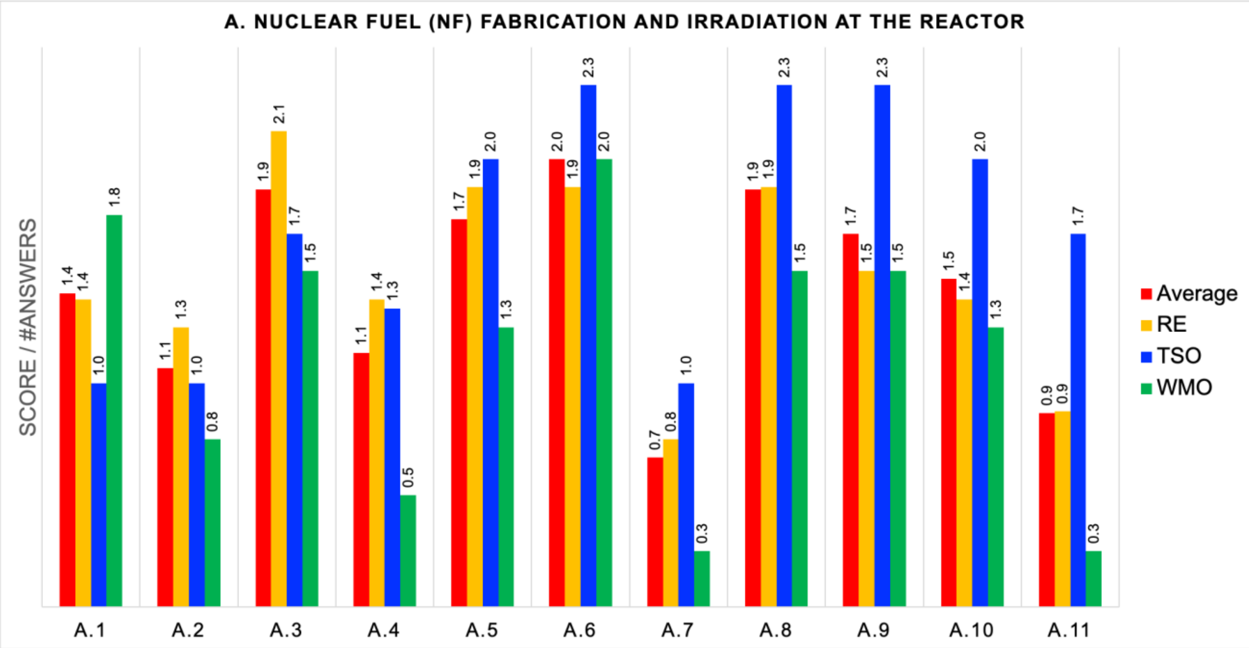

Figure 3. Relevance of uncertainties on fuel fabrication and irradiation for RE, TSO and WMO

3.3 Uncertainty characterisation and evolution

The evolution of the significance for safety along the key SNF management steps, according to the respondents to the questionnaire, is represented in Figure 2. All uncertainties considered as highly significant for safety (A.3, 5, 6, 8 and 9) are considered to be significant for the source term assessment and during the storage and disposal steps. Uncertainties A.3, 5 and 6 are also considered as significant for transport steps. Information about characterisation of these uncertainties was not provided by the respondents.

4. Uncertainties associated with SNF cladding integrity and degradation (B)

4.1 Significance for safety

Figure 4 provides an overview of the safety significance related to B.1 to B.10 uncertainties, according to the respondents to the questionnaire. From a general point of view, based on Figure 2 and *Figure 4*, the significance for safety of the B uncertainties is considered to be lower than the most safety significant A uncertainties. According to the respondents, uncertainties B.1 and B.10 have a slightly higher significance for safety compared to other B uncertainties. Significance for safety of B uncertainties is briefly discussed below.

The score in each cell corresponds to the sum of the scores from the different institutions. Color code: green - lowest values, red - highest values. Safety significance: High - 3, Medium - 2, Low - 3, not known or not assessed - 0	Safety significance	Safety significance	Impact on source term assessment for SNF disposal and dose assessment	Impact on transport safety	Impact on operational safety during storage	Impact on operational safety during disposal	Impact on postclosure safety	Impact on safety function(s)	Other	Total score
B.1 Hydrogen embrittlement and hydride reorientations	15	15	2	6	9	2	0	1	0	20
B.2 Delayed hydride cracking: crack growth due to precipitation of hydrides at the cracks	12	12	4	5	8	3	1	1	0	22
B.3 Cladding creep: deformation of the cladding material due to stress	11	11	2	5	3	0	1	1	0	12
B.4 Deformation of cladding material during crying	8	8	2	2	2	0	1	0	0	7
B.5 Stress and deformation of cladding material during SNF unloading from the dry-type storage	10	10	3	3	6	3	0	0	0	15
B.6 Cladding and pellet oxidation mechanisms	13	13	4	7	9	6	5	4	1	36
B.7 Stress corrosion cracking	10	10	3	3	4	1	1	1	0	13
B.8 Mechanisms for degradation of damaged fuel	14	14	6	6	6	2	0	0	0	20
B.9 Safety of SNF handling operations in course of its preparation for long-term storage	12	12	4	7	7	0	0	0	0	18
B.10 Management of damaged and non-tight spent fuel assemblies	18	18	7	13	13	6	6	0	0	45
Total score	123									

Figure 4. Overview on the safety significance of the uncertainties associated with SNF cladding integrity and degradation (the scales indicated by the colours in the first and second "safety significance" columns are related to a comparison of the safety significance with the other uncertainties in the same group and in the 6 groups, respectively)

B.1 and B.2: Hydrogen embrittlement, hydride reorientations and delayed hydride cracking (DHC).

In Zircaloy, under certain conditions of stress and temperature, incorporated hydrogen can diffuse through the alloy to form high local hydrogen concentrations, which lead to the precipitation of Zr hydrides. These hydrides are brittle and tend to crack. Generally, the most stressed areas in cladding are the heat-affected zones at and near welds. Early fracture of the cladding tube could lead to early radionuclide release from the fuel element in the canister.

B.3, 4 and 5: Cladding creep, deformation of cladding material during drying and unloading from a dry-type storage.

The long-term creep of the Zircaloy cladding is caused by stresses created by pressure build up inside the sealed fuel elements due to the decay-related production of helium gas. This phenomenon weakens the mechanical resistance of the cladding.

As long as the spent fuel bundles are supported by baskets in intact containers, they are usually not subject to significant load-bearing stresses. If tremors (e.g., associated with earthquakes) cause the fuel bundles to vibrate sufficiently, presumably some of the fuel pellets or the cladding could be damaged.

The damaged material would remain in an intact container, and the overall evolution of the spent fuel bundles would *a priori* not be significantly changed.

B.6 Cladding and pellet oxidation mechanisms.

When Zircaloy is exposed to air, a thin passive zirconium oxide film forms rapidly on its surface which then inhibits further corrosion. Moreover, the fuel containers are filled with an inert gas and, in the absence of oxygen, a further growth of a uniform oxidation film on the cladding cannot occur. This uncertainty is thus *a priori* not of a high significance for safety.

A cladding degradation could be driven by the expansion of a fuel pellet (pellet swelling or if in contact with oxidising conditions) in proximity to a defect in the cladding, causing a strain in the cladding that extends the size of the defect. One example of this phenomenon occurs when water enters a fuel element through a pinhole defect and reacts with the fuel, transforming the UO_2 into the less-dense phase U_3O_8. The additional stress exerted on the defect site by the expansion in the volume of the pellet then leads to further cracking of the cladding. More water is then able to enter the fuel element, which in turn leads to more alteration, more swelling, and further deformation of the cladding. In intact containers, there would be no source of water to initiate pellet oxidation. However, under disposal conditions, in the long-term, contact with groundwater will occur.

B.7 Stress corrosion cracking

Stress corrosion cracking of zirconium metal occurs in oxidising environments, in strongly oxidising neutral saline solutions, and in the presence of some metals and gases such as caesium and iodine. Such oxidising conditions are *a priori* not present in a dry environment inside an unbreeched container. Caesium and iodine precipitated in form of CsI are however present in the fuel-cladding interface layer and, through radiation induced dissociation to iodide, may impact the cladding integrity.

B.8 and 10: Mechanisms for degradation of damaged fuel, management of damaged and non-tight spent fuel assemblies.

Fuel rods could become defective during their use in a reactor. Uncertainties associated with their degradation mechanism and management depends on the types and extent of the defects.

B.9 Safety of SNF handling operations in course of its preparation for long-term storage.

Uncertainties about these handling operations can *a priori* be well controlled. The safety of such operations could however be affected by uncertainties on the cladding integrity and degradation (see other B uncertainties).

4.2 Actors' views on uncertainty relevance

Figure 5 provides an overview of the significance for safety of uncertainties B.1 to B.10 according to each group of actors. A statistical comparison between the groups of actors cannot be performed. However, it is to be noted that TSOs seem to consider a higher safety significance of uncertainties B.1, 5 and 8 compared to the other types of actors. Moreover, WMOs seem to consider a lower safety significance of uncertainties B.2, 9 and 10 compared to the other types of actors.

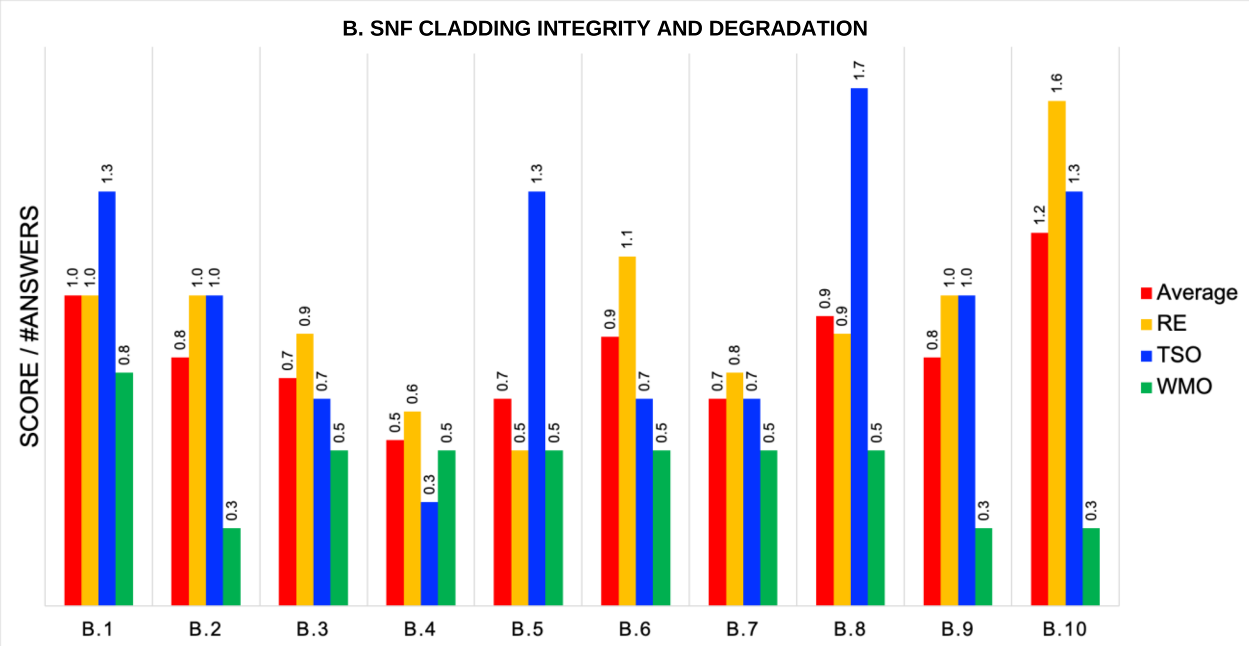

Figure 5. Relevance of uncertainties on SNF cladding integrity and degradation for RE, TSO and WMO

4.3 Uncertainty characterisation and evolution

The evolution of the significance for safety along the key SNF management steps, according to the respondents to the questionnaire, is represented in *Figure 4*. The significance for safety of B uncertainties is mainly related to the predisposal management steps (transport, storage). B uncertainties related to cladding and fuel oxidation, as well as to the management of defect fuel assemblies, are also significant for the disposal safety.

5. Uncertainties associated with SNF storage and disposal canisters

5.1 Significance for safety

Figure 6 provides an overview of the safety significance related to C.1 to C.15 uncertainties, according to the respondents to the questionnaire. From a general point of view, based on the Figure 2 and *Figure 6* the significance for safety of the C uncertainties is considered to be lower than the most safety significant A uncertainties. According to the respondents, uncertainties C.1, 2, 5, 8, 9 and 12 have a slightly higher significance for safety compared to other C uncertainties. Significance for safety of C uncertainties is briefly discussed below.

The score in each cell corresponds to the sum of the scores from the different institutions. **Color code**: green - lowest values, red - highest values. **Safety significance**: High - 3, Medium - 2, Low - 3, not known or not assessed - 0	Safety significance	Safety significance	Impact on source term assessment for SNF disposal and dose assessment	Impact on transport safety	Impact on operational safety during storage	Impact on operational safety during disposal	Impact on postclosure safety	Impact on safety function(s)	Other	Total score
C.1 Failures of the material used in the fabrication	17	17	12	7	7	9	6	4	1	46
C.2 Quality of the welds	17	17	9	6	6	8	6	4	0	39
C.3 Stress level of welds	11	11	4	3	5	5	1	1	0	19
C.4 Characteristics of the neutron absorbers used for ensuring subcriticality	13	13	3	3	5	0	0	0	0	11
C.5 SNF loading into canister. Deviations from criteria	15	15	5	4	6	4	2	1	0	22
C.6 SNF drying inside the container	11	11	3	4	4	2	2	0	0	15
C.7 Uncertainty in the He filling of the container	12	12	2	6	6	0	0	0	0	14
C.8 Release of inert gases by the fuel element inside the container	15	15	5	4	6	6	3	0	0	24
C.9 Radiolysis, hydrogen generation	15	15	6	3	5	2	6	0	0	22
C.10 Corrosion of external elements due to salt	9	9	2	2	2	2	4	0	0	12
C.11 Changes in the humidity	11	11	6	2	2	2	2	2	0	16
C.12 Temperature profiles and thermal modelling applicable in different countries	16	16	5	4	4	2	6	2	2	25
C.13 Canister degradation due to radiation	12	12	5	3	3	3	5	3	1	23
C.14 Comprehensive monitoring of parameters for indirect assessment of tightness of canister, condition of fuel, heat removal, gamma and neutron radiation	8	8	2	2	2	2	0	0	0	8
C.15 Measurement of the medium in dry airtight or transport canisters, in case of gas leakage	7	7	2	2	2	0	0	0	0	6
Total score	189									

Figure 6. Overview on the safety significance of the uncertainties associated with SNF storage and disposal canisters (the scales indicated by the colours in the first and second "safety significance" columns are related to a comparison of the safety significance with the other uncertainties in the same group and in the 6 groups, respectively)

C1 and C2: Failures of the material used in the fabrication, quality of the welds.

Coating (e.g., copper-based) and base material inspections, weld inspections and hydrostatic pressure testing, tested using non-destructive techniques like eddy current, ultrasonic examination and liquid penetrant examination, will contribute to verify that canisters are fabricated according to design and safety requirements. While unlikely, possible failures during manufacturing or quality-assurance practices present the risk for undetected defects. In addition, although strict protocols and procedures for handling canisters will be in place, there is a non-zero probability that a canister may be damaged during handling. Such defects or damages could be significant for safety, for instance if they reduce the lifetime of the leak tight canisters (compared to their design lifetime, e.g., if coating damages lead to an early exposure of the base material to the disposal environment…).

C3: Stress levels of welds

Residual tensile stresses in the canister welded materials could affect its performance (e.g., by inducing stress corrosion cracking). Such stresses are thus possibly safety significant and need to be considered in the design of canisters.

C4: Characteristics of the neutron absorbers used for ensuring subcriticality

Subcriticality of the SNF has to be ensured by design measures. For instance, SNF casks contain neutron absorber materials contributing to the prevention of criticality scenarios during storage and transport. Uncertainties on the characteristics of these materials have thus a possible impact on safety.

C5: SNF loading into canister (deviations from criteria).

Uncertainty on the SNF characteristics loaded in canisters could be safety significant. They are for instance related to the SNF inventory (see A. uncertainties) or the integrity and degradation of the cladding (see B. uncertainties). These uncertainties have to be considered when verifying that the SNF to be loaded in a canister fulfils the safety criteria.

C6: SNF drying inside the container

SNF dry storage is generally preceded by wet storage and drying of the SNF. When drying, several characteristics could be affected (e.g., those related to B. uncertainties). Uncertainties about the SNF drying phase could thus be safety significant.

C7: Uncertainty in the He filling of the container

SNF containers are back-filled with Helium (He) gas to prevent oxidation of materials inside the containers (SNF cladding included). Uncertainties related to the He filling are thus possibly safety significant (they could for instance affect cladding oxidation discussed in uncertainty B.6). A monitoring of the He filling is thus important.

C8: Release of inert gases by fuel elements inside the container

Fuel elements with defective cladding could release some fission gases into the container interior, particularly if the cladding fails after the container is sealed. Uncertainties about the partial pressure and total activity of such released gases could be safety significant.

C9: Radiolysis, hydrogen generation

In practice, it is not possible to completely exclude all traces of air and water vapour in the container (e.g., water could be adsorbed on materials). Therefore, the filling inert gas will include (to some extent) a proportion of air and water. In these conditions, radiolysis could lead to the generation of small quantities of hydrogen and nitric acid. Nitric acid could cause localised corrosion inside the container and thus possibly affect safety. In disposal conditions, groundwater radiolysis could also contribute to the degradation of the disposal canisters.

C10: Corrosion of external elements due to salt

Especially in a marine air environment, chlorine induced stress corrosion cracking may cause container degradations during storage. Such degradations could for instance lead to He gas leakage from the container (see uncertainty C.7). In a disposal environment, salt (e.g., in saline groundwater) could come in contact with the disposal canisters and contribute to their degradation by corrosion.

C11: Changes in the humidity

The distribution of water molecules in the materials inside the container could vary with time, as the fuel cools down. In disposal conditions, the water content in the surrounding of the canisters will also evolve.

These variations could affect different material degradation mechanisms and thus have a safety significance.

C12: Temperature profiles and thermal modelling applicable in different countries.

The temperature at the container surface and in its surrounding environment is affected by the remaining SNF decay heat and several other characteristics such as the nature of the container materials and of its surrounding environment. Temperature profiles around containers are important inputs for safety assessments.

C13: Canister degradation due to radiation.

Properties of containers could be affected by radiation-induced damages and should thus be considered in the safety assessment.

C14 and C15: Comprehensive monitoring of parameters for indirect assessment of tightness of canister, condition of fuel, heat removal, gamma and neutron radiation. Measurement of the medium in dry airtight or transport canisters, in case of gas leakage.

Different measurement and monitoring systems can be used to assess container characteristics which could have a significant impact on safety. Uncertainties related to these measurements and monitoring systems could also be safety significant.

5.2 Actors' views on uncertainty relevance

Figure 7 provides an overview of the significance for safety of uncertainties C.1 to C.15 according to each group of actors. A statistical comparison between the groups of actors cannot be performed. However, it is to be noted that TSOs seem to consider a higher safety significance of uncertainties C.1, 2, 12 and 13 compared to the other types of actors.

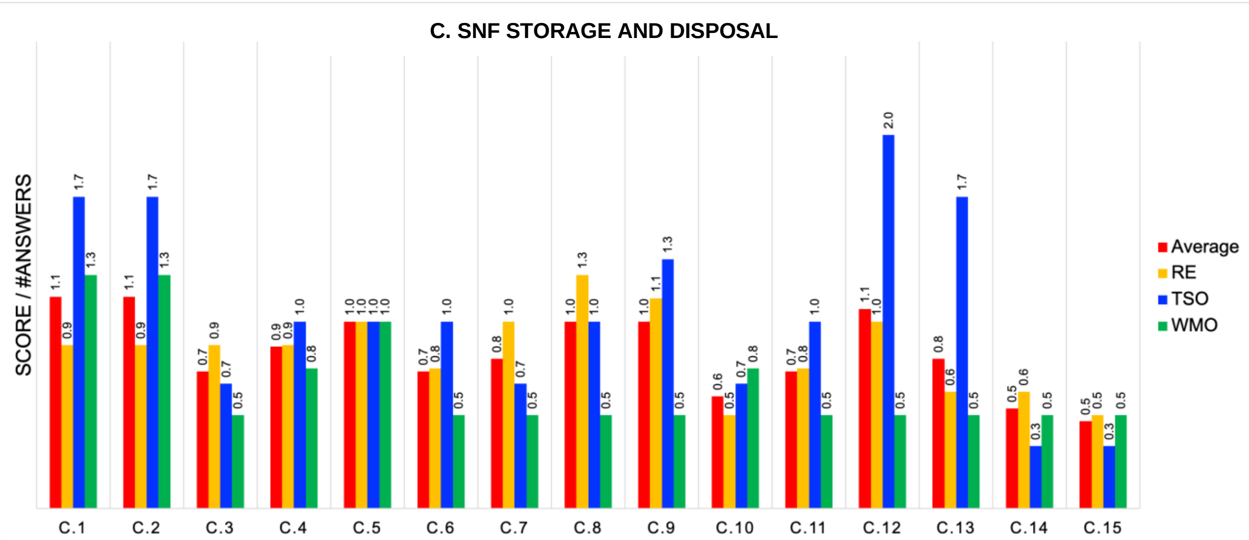

Figure 7. Relevance of uncertainties on SNF storage and disposal canisters for RE, TSO and WMO

5.3 Uncertainty characterisation and evolution in time

The evolution of the significance for safety along the key SNF management steps, according to the respondents to the questionnaire, is represented in *Figure 6*. The significance for safety of C uncertainties is related to the SNF predisposal management steps (transport, storage) and, for some of the C uncertainties (in particular uncertainties C1, 2, 9, 12 and 13), to post closure safety of a disposal facility.

6. Uncertainties associated with bolted closure systems of dry storage casks

6.1 Significance for safety

Figure 6 provides an overview of the safety significance related to D.1 to D.5 uncertainties, according to the respondents to the questionnaire. From a general point of view, based on the Figure 2 and *Figure 8*, as for B and C uncertainties, the significance for safety of the D uncertainties is considered to be lower than the most safety significant A uncertainties. According to the respondents, uncertainties D.1 and 2 have a slightly higher significance for safety compared to other D uncertainties. Possible significance for safety of D uncertainties is briefly discussed below.

The score in each cell corresponds to the sum of the scores from the different institutions. **Color code**: green - lowest values, red - highest values. **Safety significance**: High - 3, Medium - 2, Low - 3, not known or not assessed - 0	Safety significance	Safety significance	Impact on source term assessment for SNF disposal and dose assessment	Impact on transport safety	Impact on operational safety during storage	Impact on operational safety during disposal	Impact on postclosure safety	Impact on safety function(s)	Other	Total score
D.1 Atmospheric and aqueous corrosion	9	9	3	3	3	3	0	0	0	12
D.2 Time evolution of the sealing performance and gas leakage	10	10	3	4	6	1	0	0	0	14
D.3 Radiological ageing	8	8	2	4	4	4	0	0	0	14
D.4 Time and temperature effects. Corrosion and creep of metals	7	7	2	2	4	2	0	0	0	10
Total score	34									

Figure 8. Overview on the safety significance of the uncertainties associated with bolted closure systems of dry storage casks (the scales indicated by the colours in the first and second "safety significance" columns are related to a comparison of the safety significance with the other uncertainties in the same group and in the 6 groups, respectively)

D.1: Atmospheric and aqueous corrosion

For instance, water intrusion near the lid bolts and outer metallic seals of a bolted closure system could cause their corrosion and thus affect the tightness of bolted-closure storage casks. A loss of tightness may have a significant safety impact.

D.2: Time evolution of the sealing performance and gas leakage

With time, the closure system of a bolted-closure cask may undergo a loss of sealing forces due to, for instance, a stress relaxation and creep of its rings. To some extent, this could lead to a loss of the container tightness and therefore have possible impact on safety.

D.3 and D.4: Radiological ageing. Time and temperature effects.

Temperature and irradiation may affect the ageing phenomena of the bolted closure systems over time and thus possibly affect its tightness (and therefore the safety).

6.2 Actors' views on uncertainty relevance

Figure 9 provides an overview of the significance for safety of uncertainties D.1 to D.4 according to each group of actors. A statistical comparison between the groups of actors cannot be performed. The RE group seems to see a higher safety significance of the D uncertainties, compared to WMO and TSO groups.

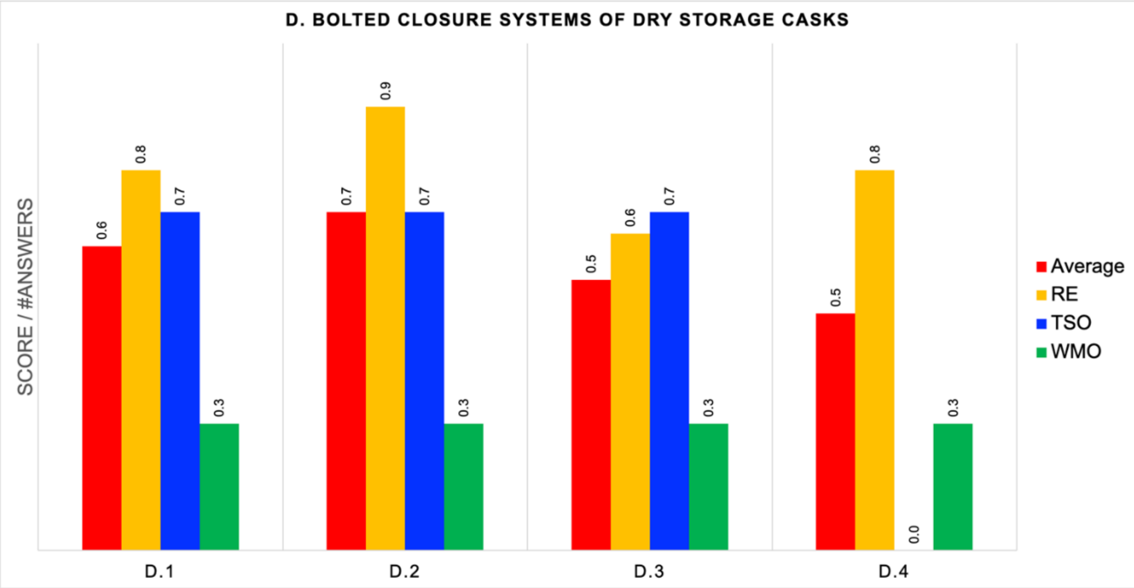

Figure 9. Relevance of uncertainties on bolted closure systems of storage casks for RE, TSO and WMO

6.3 Uncertainty characterisation and evolution

As bolted closure systems are used in storage conditions (and not in disposal conditions), D uncertainties are only considered as possibly safety significant during predisposal management steps (essentially during storage).

7. Uncertainties associated with concrete components in dry storage/ disposal facilities (E)

7.1 Significance for safety

Figure 10 provides an overview of the safety significance related to E.1 to E.13 uncertainties, according to the respondents to the questionnaire. From a general point of view, based on the Figure 2 and Figure 10, as for B, C and D uncertainties, the significance for safety of the E uncertainties is considered to be lower than the most safety significant A uncertainties. According to the respondents, uncertainties E.3 and E.8 have a slightly higher significance for safety compared to other E uncertainties. Possible significance for safety of E uncertainties is briefly discussed below.

The score in each cell corresponds to the sum of the scores from the different institutions. Color code: green - lowest values, red - highest values. Safety significance: High - 3, Medium - 2, Low - 3, not known or not assessed - 0	Safety significance	Safety significance	Impact on source term assessment for SNF disposal and dose assessment	Impact on transport safety	Impact on operational safety during storage	Impact on operational safety during disposal	Impact on postclosure safety	Impact on safety function(s)	Other	Total score
E.1 Concrete shrinkage and creep caused by long term dry out	8	8	3	3	3	3	0	1	0	13
E.2 Carbonation caused by reaction with CO2 in the atmosphere	9	9	2	2	2	2	0	1	0	9
E.3 Ingress of chlorides in disposal conditions	13	13	7	2	2	2	2	4	0	19
E.4 Freeze-thaw due to use of concrete in cold environments	9	9	3	3	3	3	0	0	0	12
E.5 Alkali-silica reaction (ASR) within the concrete	9	9	5	1	1	3	2	3	0	15
E.6 Sulphate attack on the concrete	10	10	5	1	1	3	3	1	0	14
E.7 Neutron induced radiation damage in the concrete	6	6	1	1	1	1	0	1	0	5
E.8 Thermal degradation of concrete	13	13	7	2	2	2	2	4	0	19
E.9 Leaching and efflorescence	10	10	4	2	2	2	4	1	0	15
E.10 Concrete swelling due to the sub-microcrystals crystallization	6	6	2	2	2	2	0	1	0	9
E.11 Degradation of concrete due to ettringite and thaumasite crystallization	6	6	3	1	1	1	2	1	0	9
E.12 Degradation of concrete due to metal corrosion	7	7	4	2	2	4	0	0	0	12
E.13 Degradation of concrete induced by mechanical stresses	8	8	4	2	2	2	2	1	0	13
Total score	114									

Figure 10. Overview on the safety significance of the uncertainties associated with concrete components in dry storage/ disposal facilities *(the scales indicated by the colours in the first and second "safety significance" columns are related to a comparison of the safety significance with the other uncertainties in the same group and in the 6 groups, respectively)*

E.1: Concrete shrinkage and creep caused by long-term dry out

Concrete shrinkage may cause cracks and promote other degradation mechanisms, for instance by making the structure more susceptible for ion ingress. This phenomenon could affect concrete performance and its related uncertainties may thus have a safety significance.

E.2: Carbonation caused by reaction with CO_2 in the atmosphere

Carbonation leads to a decrease in concrete pH, which affects the passivity of the reinforcing steel, accelerating corrosion if the threshold chloride concentration at the steel is reached. This phenomenon could affect concrete performance and its related uncertainties may thus have a safety significance.

E.3: Ingress of chlorides in disposal conditions

The ingress of chlorides into concrete overpacks, used to protect canisters in certain disposal concepts, will contribute to decrease the pH of the concrete and, when the chlorides will come into contact with steel components of the canisters, contribute to the corrosion of the steel components. Such ingress of chlorides, and their related uncertainties, have thus a possible safety significance.

E.4: Freeze-thaw due to use of concrete in cold environments

Cyclic freezing and thawing could lead to mechanical stresses in concrete (from the expanding ice during cooling). Such mechanical stresses could lead to crack formation, promoting the diffusion of aggressive species inside the concrete. This phenomenon could affect concrete performance and its related uncertainties may thus have a safety significance.

E.5: Alkali-silica reaction (ASR) within the concrete

The ASR (between Alkali, Silica and water) produce a hydrophilic gel like substance which, when expanding, induces mechanical stresses in concrete. Such mechanical stresses could lead to crack formation, promoting the diffusion of aggressive species inside the concrete. This phenomenon could affect concrete performance and its related uncertainties may thus have a safety significance.

E.6 and E.11: Sulphate attack on the concrete, DEF and thaumasite formation.

The ingress of sulphate ions in concrete may lead to the formation of expansive products such as gypsum and Ettringite. Sulphate attack can lead to expansion, cracking, strength loss, and disintegration of the concrete. Thaumasite is a calcium sulphate carbonate silicate hydrate, formed from the reaction of sulphates with silicate and carbonate in concrete. Ettringite can also be formed by DEF (Delayed Ettringite Formation), without external ingress of sulphate in concrete. These phenomena could affect concrete performance and their related uncertainties may thus have a safety significance.

E.7: Neutron induced radiation damage in the concrete

Deterioration of concrete due to neutron radiation involves a possible reduction of concrete stiffness, a formation of cracks, and changes in the microstructure of concrete elements. This could lead to a higher reactivity of the concrete to certain aggressive chemicals. This phenomenon could affect concrete performance and its related uncertainties may thus have a safety significance.

E.8: Thermal degradation of concrete

Exposition of concrete to elevated temperature leads to mechanical stresses which could induce mechanical damages. Morover, elevated temperature could cause a partial dry out of the concrete, leading to its enhanced carbonation. This phenomenon could affect concrete performance and its related uncertainties may thus have a safety significance.

E.9: Leaching and efflorescence

Leaching of concrete can change its porosity and decrease the concrete pH, which notably affects the passivity of the reinforcing steel. This phenomenon could affect concrete performance and its related uncertainties may thus have a safety significance.

E.12: Degradation of concrete due to metal corrosion

Metal corrosion induces tensile stresses in the concrete, which can eventually cause cracking. This phenomenon could affect concrete performance and its related uncertainties may thus have a safety significance.

E10, E13: Degradation of concrete induced by mechanical stresses

Mechanical stresses in concrete (e.g., couple to certain chemical reactions within the concrete material) could lead to damages in the concrete via cracks. This phenomenon could affect concrete performance and its related uncertainties may thus have a safety significance.

7.2 Actors' views on uncertainty relevance

Figure 11 provides an overview of the significance for safety of uncertainties E.1 to E.13 according to each group of actors. A statistical comparison between the groups of actors cannot be performed. However, it is to be noted that TSOs seem to consider a higher safety significance of uncertainties E.5, 6, 9 and 13 compared to the other types of actors. All groups of actors consider that uncertainty E7 as a very low safety significance.

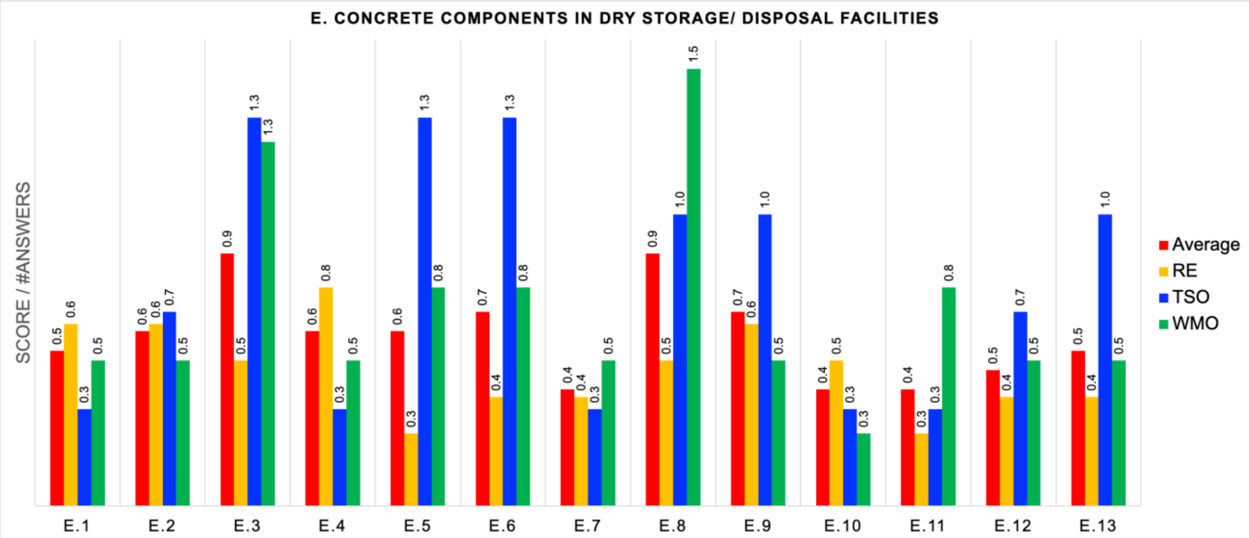

Figure 11. Relevance of uncertainties on concrete components in dry storage/ disposal facilities for RE, TSO and WMO

7.3 Uncertainties characterisation and evolution

The evolution of the significance for safety along the key SNF management steps, according to the respondents to the questionnaire, is represented in Figure 10. In principle, as concrete SSCs can be used in predisposal and disposal concepts, E uncertainties may have a safety significance at all management steps. No clear evolution of E uncertainties can thus be deduced from Figure 10. Actors consider uncertainties E.3 and E.8 as the most safety significant. However, this safety significance seems essentially related to the impact of the uncertainties on the coupling between the cementitious material (around the canister, in the engineered barrier system) degradation and the canister degradation (affecting the source term).

8. Uncertainties associated with the neutron shielding in dry storage systems (F)

8.1 Significance for safety

Figure 12 provides an overview of the safety significance related to F.1 to F.13 uncertainties, according to the respondents to the questionnaire. From a general point of view, based on the Figure 2 and *Figure 12*, as for B, C, D E uncertainties, the significance for safety of the F uncertainties is considered to be lower than the most safety significant A uncertainties. According to the respondents, uncertainty F.1 has a higher significance for safety compared to other F uncertainties. Possible significance for safety of F uncertainties is briefly discussed below.

The score in each cell corresponds to the sum of the scores from the different institutions. Color code: green - lowest values, red - highest values. Safety significance: High - 3, Medium - 2, Low - 3, not known or not assessed - 0	Safety significance	Safety significance	Impact on source term assessment for SNF disposal and dose assessment	Impact on transport safety	Impact on operational safety during storage	Impact on operational safety during disposal	Impact on postclosure safety	Impact on safety function(s)	Other	Total score
F.1 Knowledge on the source term and dose evaluation	17	17	10	8	10	10	5	0	0	43
F.2 Thermal and thermal oxidative degradation	9	9	3	3	3	3	0	0	0	12
F.3 Degradation due to irradiation	9	9	2	2	2	0	0	0	0	6
F.4 Hydrogen quantity	7	7	2	2	2	0	0	0	0	6
Total score	42									

Figure 12. Overview on the safety significance of the uncertainties associated with concrete components in dry storage/ disposal facilities (the scales indicated by the colours in the first and second "safety significance" columns are related to a comparison of the safety significance with the other uncertainties in the same group and in the 6 groups, respectively)

F.1: Knowledge on the source term and dose evaluation

The SNF radionuclide content is an input to define the required neutron shielding components and design in a dry storage container. Uncertainties on this radionuclide content have thus a possible safety significance.

F.2, F.3 and F.4: Thermal and thermal oxidative degradation, degradation due to irradiation, hydrogen quantity in the shielding material.

The ageing of the shielding material could affect its hydrogen content and thus its shielding characteristics. Uncertainties related to this ageing have thus a possible safety significance.

8.2 Actors' views on uncertainty relevance

Figure 13 provides an overview of the significance for safety of uncertainties F.1 to F.4 according to each group of actors. A statistical comparison between the groups of actors cannot be performed. However, it is to be noted that TSOs and REs seem to consider a higher safety significance of uncertainty F.1, compared to WMOs.

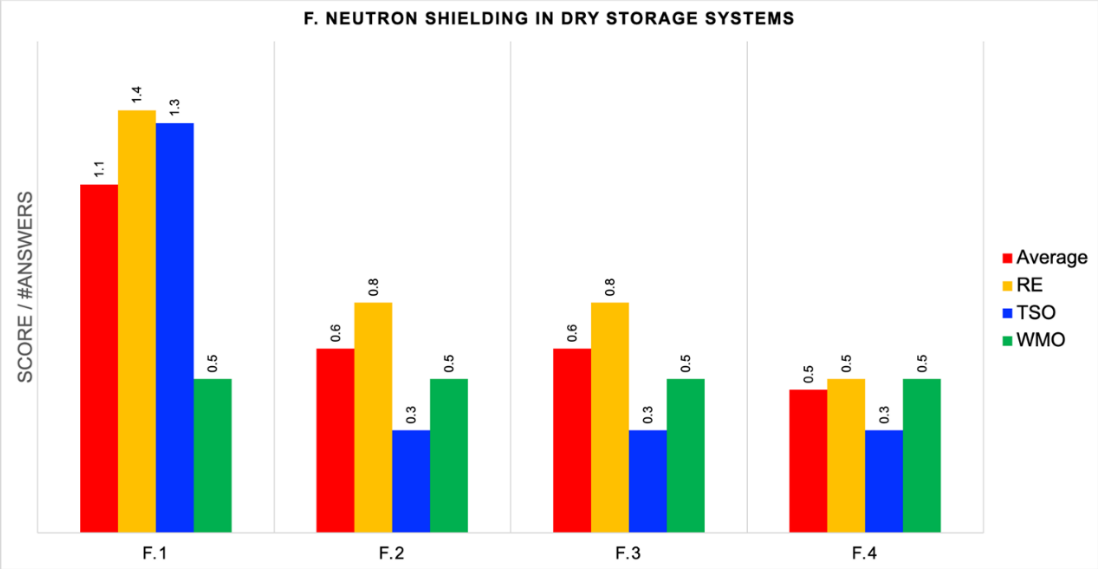

Figure 13. Relevance of uncertainties on neutron shielding in dry storage systems for RE, TSO and WMO

8.3 Uncertainty characterisation and evolution

As neutron shielding components are used in storage conditions (and not in disposal conditions), F uncertainties are only considered as possibly safety significant during predisposal management steps (essentially during storage).

9. Summary of uncertainties with higher safety significance

Among the 6 groups of uncertainties (see A. to F. below), according to the answers to the questionnaire, A. uncertainties are considered as the most safety significant (see *Figure 14*).

A. Uncertainties associated to the SNF characterisation and inventory
B. Uncertainties associated to SNF cladding degradation and radionuclide release processes
C. Uncertainties associated to SNF storage and disposal canisters
D. Uncertainties associated to bolted closure systems of dry storage casks
E. Uncertainties associated to concrete SSCs in dry storage/ disposal facilities
F. Uncertainties associated to the neutron shielding in dry storage systems

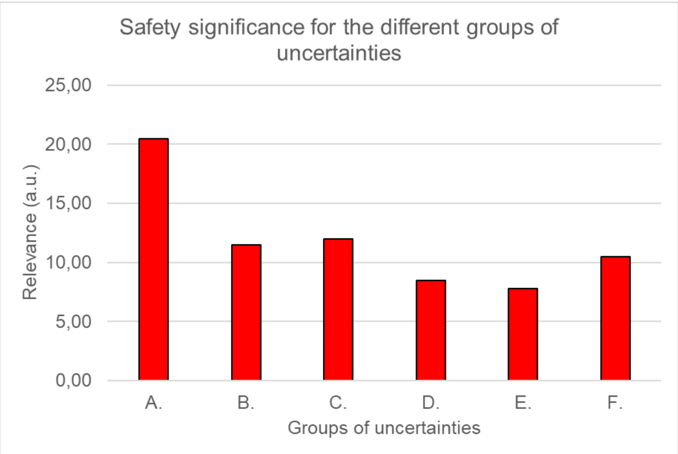

Figure 14. Global safety-significance per group of uncertainties

Among each group of uncertainties, the following specific uncertainties were considered by the questionnaire respondents to have a higher safety significance than the others:

A.3 Composition (radio- and physicochemical) and enrichment of the fuel
A.5: Irradiation conditions.
A.6: Burnup and respective isotopic composition in case of burnup credit.
A.8: Methodology and nuclear data for SNF inventory calculations
A.9: Residual heat generation
B.1: Hydrogen embrittlement, hydride reorientations.
B.10: Management of damaged and non-tight spent fuel assemblies.
C.1: Failures of the material used in the fabrication
C.2: Quality of the welds
C.5: SNF loading into canister (deviations from criteria).
C.8: Release of inert gases by fuel elements inside the container
C.9: Radiolysis, hydrogen generation
C.12: Temperature profiles and thermal modelling applicable in different countries.
D.1: Atmospheric and aqueous corrosion
D.2: Time evolution of the sealing performance and gas leakage
E.3: Ingress of chlorides in disposal conditions
E.8: Thermal degradation of concrete
F.1: Knowledge on the source term and dose evaluation

10. Conclusions

The questionnaire was answered by 16 EURAD participants: 4 WMOs, 4 TSOs and 8 REs. On average, uncertainties associated to the SNF inventory (group A) are considered by the respondents to have the higher safety significance. Among each group of uncertainties, specific uncertainties considered by the questionnaire respondents to have a higher safety significance than the others were identified. The analysis presented in the present deliverable was used as input by UMAN Subtask 4.2 to prepare a Workshop organised by Subtask 4.3 on SNF related uncertainties (see UMAN deliverables D10.11 [2] and D10.12 [3]).

11. References

[1] Brendler, V., Pospiech, S. (2022): Uncertainty identification, classification and quantification. Final version as of 05.08.2022 of UMAN deliverable D10.3 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593

[2] Th. U. Kaempfer, X. Li, J.-N. Dumont, J. Mertens, M. Herm, A. Strusińska-Correia, A. Göbel, F. Lemy, J. Mikšová, H. Vojtěchová, D. Diaconu, M. Hayek, D. Grigaliuniene, G. Poskas (2024): Study on management options for different types of uncertainties and programme phases. Final version as of 07/05/2024 of deliverable D10.11 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

[3] Haverkate B., van Gemert M., Strusińska-Correia A., Göbel A., Mertens J., Detilleux V., de Gregorio y Robledo S., Grigaliūnienė D. (2024): UMAN – Preferences of different actors on uncertainty management. Final version as of 15/05/2024 of deliverable D10.12 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

[4] D. Rochman et al., "On the estimation of nuclide inventory and decay heat: a review from the EURAD European project", EPJ Nuclear Sci. Technol. 9, 14 (2023). https://doi.org/10.1051/epjn/2022055

[5] IAEA2019. Demonstrating Performance of Spent Fuel and Related Storage System Components during Very Long Term Storage, IAEA-TECDOC-1878 (2019). http://www-pub.iaea.org/MTCD/Publications/PDF/TE-1878web.pdf, 2019