UMAN deliverable 10.18 UMAN - Views of the different actors on the identification, characterization and potential significance of uncertainties on the near-field.

Work Package WP10

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Executive Summary

UMAN Deliverable 10.18 has as primary objective to provide information on the views of three categories of actors (Research Entities (REs), Technical-Safety Organisations (TSOs) and Waste Management Organisations (WMOs) related to:

- the significance for safety of uncertainties related to the near-field,
- the preferences in uncertainties characterisation
- the uncertainties evolution along the disposal programme implementation

During the implementation of the UMAN Subtask 3.6 as part of EURAD extension, the draft version of this Deliverable has been used in:

- selection of the uncertainties with a significant relevance for safety, as basis in the identification of the options and actors' preferences with regard to the near-field uncertainties management (in Task 4), and in
- preparation of the dialogue with Civil Society foreseen for Seminar 5, organized under Task 5

This deliverable analyses the views of the three categories of actors collected via the new UMAN Questionnaire on **near-field uncertainties** (see attachment 1), launched on April 5, 2022. It includes also the results of Task 3.6 Workshop held at RATEN, Romania 24-25 November 2022, where the replies to the questionnaire and the SotAs of CONCORD [1] and MAGIC [2] have been presented and discussed. In addition, discussion within Seminar 5 (at BelV, Brussels 06-07 December 2023) were taken into account, where CS representatives joint the discussion on near-field uncertainties with WMOs TSOs and REs.

The questionnaire grouped the uncertainties related to near-field into 6 topics, gathering in total 37 parameters and processes considered by the UMAN experts' group to have a potential significance for safety. The six topics have been structured in three main categories:

I. Uncertainties associated with the processes governing or altering radionuclide migration and the performance of disposal system components
II. Uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers
III. Uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems

The analysis performed is based on the (5+4+9=18) replies received from 17 organisations, representing 5 REs, 4 TSOs and 8 WMOs (one with two replies), which address all the disposal concept of geological disposal (DGD), one reply is related to salt host rock, which has been not considered here (due to financial limitations, the disposal concepts for near surface (NSD) and sub-surface (SSD) were not included in the scope of the work on near-field uncertainties as well as salt as host rock. A detailed description on the significance for safety, characterization and evolution was provided for the uncertainties evaluated as having a relevant impact on the disposal safety, by majority of actors.

Answers compilation revealed that there was no group of uncertainties scored with medium and high significance by all categories of actors, which was abolished by low significance answers, especially by individual advanced WMOs. Ignoring individual WMOs low significance answers, the uncertainties involved in this survey with medium and high significance are:

- uncertainties related to partition coefficient Kd (Kd values are the result of assumptions associated with the conceptual model (i.e., linear kinetics for sorption / desorption process);

Kd could also depend on redox conditions, and could be affected by the near-field evolution);

- uncertainties related to metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different barriers (waste package, liners…), lifetime, gas generation and pressure build-up, other degradation processes, pH-, Eh-evolution, pit corrosion, colloid formation (continuous or step functions?)
- uncertainties related to evolution of diffusion coefficient, De (De will change due to temperature evolution, porosity changes as result of mineral reactions)
- uncertainties associated with hydraulic properties of the bentonite (re-saturation and swelling pressure evolution might be heterogeneous and preferential flow paths could develop.
- uncertainties related to permeability associated with two-phase flow (barriers are considered homogeneous in terms of permeability, while anisotropy given by e.g., preferential flow paths, fractures/pores, … can lead to increased flow).

According to the questionnaire results, there was no group of uncertainty scored with low relevance for safety by the three categories of actors; mostly lower relevance and a few medium relevance replies have been obtained for uncertainties associated with:

- evolution of diffusion coefficient De (De will change due to temperature evolution, porosity changes (mineral reactions)
- concrete parameters and associated processes used in near-field conceptualisation (carbonation processes during operational phase and re-saturation phase could have an impact on mechanical parameters)
- permeability measurement methods (for two-phase flow, permeability has very low values and depends on the accuracy of the measurement method).

As a result of the replies to the questionnaire, of CONCORD and MAGIC SotAs, and the workshop discussions, the uncertainties with high impact for safety considered for a more detailed analysis at this stage were:

- uncertainty related to metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different barriers (waste package, liners…)
- uncertainty related to hydraulic properties of the bentonite
- uncertainty related to modelling of radionuclide transport: full 4 D description or 1 D or mixed compartment.

As a general observation, there are differences between the importance given by the three categories of actors to the same group of uncertainties, with WMOs and REs generally giving more significance to uncertainties and their impact on safety than TSOs.

By far the largest difference for safety significance between the different categories of actors is associated with the topics related to uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems. REs giving generally a much higher (twice as high) significance than TSOs and WMOs, where several replies to these topics indicate uncertainty not assessed or not known, especially from less advanced or early stage programme countries.

For all other topics REs and WMOs consider importance of the uncertainties similar, REs mostly slightly higher than WMOs

Each category of actors use in the uncertainties' characterisations a diversity of methods, adequate to the uncertainty type (parametric, scenario, conceptual, etc.), which complement each other, with the aim to reduce the uncertainty level. A general trend is not obvious.

In contrary to the outcome of the questionnaire on site and geosphere, where generally all actors' opinions converge on the fact that uncertainties will decrease along the programme phases, as the knowledge of the site and scientific accumulations evolve until a certain level, for the questionnaire on near-field uncertainties, there was not such an convergence that uncertainties decrease along the programme phase. For some uncertainties it is just the opposite. A reason might be, that site and geosphere uncertainties have to be reduced during the site selection and site characterisation phase, otherwise there will be no site selected, while for near-field uncertainties there is still some time during design optimisation and construction to reduce near-field uncertainties.

Also, there was no difference in the replies when considering replies from advanced and less advanced programmes.

Although there were no uncertainties ranked with high priority by all repliers from the different colleges at the same time, several topics dominated the discussions on their uncertainty and related influence on safety. These need dedicated actions to be implemented with priority. Therefore, according to the all actors' opinions, further *R&D activities* should be performed to improve understanding of near-field processes and parameters and related model und parameter uncertainties.

Re-saturation of bentonite seems to be a complex thermo-hydraulic-geochemical coupled process in the near-field of high-level waste disposal when use as buffer material or for plugs & seals, which is disposal concept dependent. Nevertheless, re-saturation has a strong influence on the safety function of the bentonite used as buffer material, as well as for seals and plugs. Complex thermohydraulic-geochemically coupled processes are also strongly involved in the degradation of waste canisters, because evolution of canister degradation depends on the near-field evolution (THMCBR) and near-field evolution is influenced by canister degradation. And the canister degradation (safety function) defines the release of radionuclides into the near-field (source term). Of high significance for the REs appears the modelling of coupled processes on different scales, performing global sensitivity analysis on near-field processes and parameters, performing comprehensive code benchmarking also using dedicated data from sophisticated laboratory experiments as well as from larger scale experiments (e.g. FE experiment at Mont Terri) taking into account heterogeneity on a larger scale, too. This would lead to a future approach to deal with model/parameter uncertainty by taking advantage of virtual twins of repositories including all kinds of THMCRB processes on multiple scales using data driven and physics based models. Having such tools available, targets like dose limits could be defined, sensitivity analysis on all models` parameters with respect to a defined dose limit could be performed using parameter uncertainties for all parameters. A statistical framework will yield most important or dominating parameters for related parameter uncertainties. Since fully coupled models are used, non-linearities are included in the modelling. No concern about conservative estimates is necessary or has to be defended. Spatial heterogeneities, evolving boundary conditions etc. can be tested. Model predictions can be used to be compared with experimental data from which data driven models can be deduced. Surrogate models may help to produce a high number of model realisations to allow good statistical predictions/analysis. Such tools would allow to manage dominant uncertainties according to their mathematical quantification in a transparent way and not according to vague arguments, model simplifications and simplified models. Such use of knew knowledge should be evaluated in strategic studies.

Table of content

List of Tables

List of Figures

List of Abbreviations

BEACON	EU HORIZON 2020 project "bentonite mechanical evolution
CONCORD	EURAD Work Package "CONtainer CORrosion under Disposal conditions"
CS	Civil Society
DECOVALEX	DEvelopment of COupled models and their VALidation against EXperiments
DGD	Deep geological disposal
DDM	Data driven modelling
EBS	engineered barrier system
EDZ	excavation damaged zone
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
FORGE	EU project FP7-Fission-2008: "fate of repository gases"
FUTURE	EURAD Work Package "Fundamental understanding of radionuclide retention"
GAS	EURAD Work Package "Mechanistic understanding of gas transport in clay materials"
HLW	high level waste
HR	host rock
IAEA	International Atomic Energy Agency
MAGIC	EURAD Work Package "Chemo-Mechanical AGIng of Cementitious materials"
NSD	near-surface disposal
PBM	physics based modelling
RE	Research Entity
RS	radionuclide sorption
RN	radio nuclide
RWM	radioactive waste management
SSD	sub-surface disposal

SoTA	state-of-the-art report
THMCBR	thermo-hydro-mechanical-chemical-biological-radilogical
TSO	Technical Safety Organisation
UMAN	EURAD Work Package “Uncertainty Management multi-Actor Network”
WMO	Waste Management Organisation
WP	Work Package

1. Introduction

The UMAN Deliverable 10.18 gathers the views of the different actors on the characterization and potential significance of the uncertainties related to near-field collected via the 3rd UMAN Questionnaire (see attachment 1) launched on April 5, 2022. The deliverable includes also the results of Task 3.6 Workshop held at RATEN, Romania 24-25 November 2022, where the replies to the questionnaire and the SotAs of CONCORD [1]and MAGIC [2] have been presented and discussed.

It also considers the preliminary list of uncertainties elaborated by the expert group of the Sub-task 3.6 (see Attachment 2), classification schemes provided by the UMAN Subtasks 2.1 [3] and strategies options developed in subtask 4.2 [4].

The categories of actors included in this survey were: Research Entities (REs), Technical Safety Organisations (TSOs) and Waste Management Organisations (WMOs). The views of the Civil Society (CS), a very important actor in the decision-making process, were collected from Seminar 5, and integrated in this deliverable.

In a draft of this deliverable, the expert group focused primarily on the relevance of the near-field uncertainties for three categories of actors, with a two-fold aims:

- Provide *UMAN Draft deliverable D10.18 as input to Task 4.3* and related Workshop: *Management options and preferences of different actors regarding near-field*, organized by Subtask 4.3;
- Provide relevant input on near-field uncertainties for the dialogue with Civil Society foreseen for Seminar 5 organized under Task 5.

Based on the answers received to the 3rd UMAN questionnaire – *near-field,* the expert group of subtask 3.6 selected 3 uncertainties for which a more detailed analysis of the potential impact on the safety, of methods used in their characterisation and their evolution have developed.

This deliverable integrates the views of members of the expert group relevant to near-field related uncertainties and their impact on the safety of different disposal systems, as compiled from the experience acquired in the national programmes or from other international reports, projects, works.

2. Methodology: the identification and characterization process

2.1 Approach/methodology used for identification

A Group of 4 Experts representing RESs, TSOs and WMOs, from Member States with different disposal programmes, both from the view of the repository type, i.e., here geological disposal only, which is different compared to UMAN 2nd questionnaire (see attachment 1) focusing also at surface and near-surface disposal, and stage of implementation, established, as result of a brainstorming organized in the beginning of the project, a first list of uncertainties relevant, from their perspective, for the disposal safety.

This preliminary list reflects the experience of the 4 experts gathered in the RWM national programmes developed in Czech Republic, France, Belgium and Switzerland as well as results achieved by other advanced RWM programmes in the world (Sweden, Finland).

In a second step, the preliminary list of uncertainties related to near-field (see attachment 2) was further completed with new uncertainties resulted from the IAEA recommendations for Deep Geological Disposal (DGD) [5] and from Strategic Research Agenda for RWM.

In order to have a representative view of how different type of actors are perceiving the relevance for safety of these uncertainties, a wide survey based on a questionnaire was elaborated and sent to the EURAD participants. Actually, a lot of uncertainties identified here have been already identified within subtask 3.3 (uncertainties for site and geosphere), were similar processes and parameters are involved [6].

2.2 List of uncertainties

Characterisation of the host rock, especially the excavation damaged zone surrounding a radioactive waste repository is an important issue for the site selection process and for the safety case associated with such facilities.

Significance for safety, characterization and evolution along the disposal programme have been addressed via the questionnaire for the following three groups of uncertainties:

- I. Uncertainties associated with the processes governing or altering radionuclide migration and the performance of disposal system components ;
- II. Uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers
- III. Uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems

The processes and parameters related to these uncertainties are manifold and their characterisation requires knowledge ranging from information about possible evolution of the host rock on a larger scale to more detailed information on radionuclide transport in the evolving technical (mineralogy, hydrology, bio-geochemistry, material properties evolution, …) on a smaller scale. Especially, information on interface processes between the different barrier materials due to strong temperature, material properties and geochemical gradients will be of interest, since interface processes influence strongly the mass transport/flux (radionuclides, major ions) across the interfaces of the technical barrier materials..

All these elements have been considered by the expert group early in drafting the preliminary list of uncertainties in the first stage of the process, and further on, in designing the questionnaire.

The questionnaire grouped the uncertainties related to the near-field in 6 topics, gathering in total 37 parameters and processes considered by the experts group to have a potential significance for safety. Similarities to the topics identified for uncertainties related to site and geosphere (subtask 3.3) are obvious; however, here we tried to formulate the topics in more detail as a lesson learned from replies to the 2nd questionnaire, to receive more specific answers. These 37 uncertainties are related to:

I. Uncertainties associated with the processes governing or altering radionuclide migration and the performance of disposal system components

A. Uncertainties associated with the transport properties of major ions and RN within the considered barrier media

- **Accessible porosity** - in numerical models, accessible porosity is generally deduced from the measured total porosity in an arbitrary manner
- **Diffusion coefficient De** - Values for the neutral elements, the cations and anions in numerical models are generally those obtained experimentally for most representative RN and extrapolated for the other elements.
- **Partition coefficient Kd** - Kd values are the result of assumptions associated with the conceptual model (i.e., linear kinetics for sorption / desorption process). Kd could depend on redox conditions, and could be affected by the near-field evolution.
- **Solubility limit** - Values for each element in numerical models are typically deduced from lab measurements for very few elements and are extrapolated for the other elements. Due to strong chemical gradients within the near-field, precipitation / dissolution fronts will develop in the near-field influencing solubility limits of elements
- **Time evolution of transport properties** - Reactions caused by the diffusion of reactants from different sources (container, backfill, liner) can alter rock diffusivity
- **Microbiology** - Microbiological processes can impact the pH, Eh, speciation and transport behaviour of elements
- **Seals evolution** - Seals specific uncertainties include chemical and hydraulic transients due to contact with concrete, aggressive ground-waters / re-saturation kinetics … They could influence bentonite swelling properties, homogeneous swelling / fingering, dry zones, preferential migration paths (gas flow / pressure build up, …). The question is which related transport parameter uncertainty is acceptable?

B. Uncertainties associated with heat transport properties of barriers

- **Variation of thermal conductivity**, specific heat capacity, bulk density, … due to re-saturation -Heat transport is influenced by re-saturation and or gap evolution with consequences for maximum temperature at the canister surface and mechanical properties of materials in the near-field
- **Variation of thermal conductivity**, specific heat capacity, bulk density, …due to the chemical conditions - Heat transport is influenced by chemical reactions due to changing material and transport properties in the near-field
- **Duration of the “thermal pulse”**

C. Uncertainties associated with flow properties through barriers

- **Kinematic porosity** – Kinematic porosity is generally deduced in an arbitrary manner (a half, the quarter…) from experimental measurements of total porosity
- **Permeability – two phase flow** - barriers are considered homogeneous in terms of permeability, while anisotropy given by e.g., preferential flow paths, fractures/pores, … can lead to increased flow.
- **Permeability measurement methods** (for– two phase flow) - Permeability has very low values and depends on the accuracy of the measurement method.
- **Hydraulic head gradient** - Numerous measurements in well-distributed boreholes around the site would be necessary to have a constrained hydrogeological near-field model.
- Vertical hydraulic gradient from aquifers above and below may not be realistic.
- **Hydraulic properties of EDZ** (conductivity, storativity, …) - Due to the repository construction (excavation), excavation damaged zones (EDZ) may have different horizontal and vertical extensions, different hydraulic properties and long term evolutions – different for different host rocks.
- **Hydraulic properties of the bentonite** - (effects of re-saturation and swelling pressure evolution) Bentonite re-saturation is considered to be homogenous, to the expected swelling pressure, but preferential flow paths could develop.
- **Seals evolution** - Seals specific uncertainties include chemical and hydraulic transients due to contact with concrete, aggressive ground-waters / re-saturation kinetics … They could influence bentonite swelling properties, homogeneous swelling / fingering, dry zones, preferential migration paths (gas flow / pressure build up, …) – which related hydraulic parameter uncertainty is acceptable?

D. Uncertainties associated with mechanical properties of the barriers

- **Mechanical behaviour of the EDZ** - Mechanical integrity of the EDZ can depend on temperature dependent (near-field) material properties – how is it optimised / assessed?
- **Mechanical behaviour of the EDZ** - Mechanical integrity of the EDZ can depend on fractured material properties, plasticity, thermal hardening, evolution of interfaces / gaps between different materials (clogging preferential migration path – how is it optimised / assessed?
- **Mechanical behaviour of the EDZ** - Mechanical integrity of the EDZ can depend on time-dependent gas release (H_2, CO_2, …) and pressure build up – how is it optimised / assessed?
- **Mechanical behaviour of the bentonite** - Mechanical integrity of bentonite depends on homogeneity / heterogeneity of bentonite backfill emplacement – how is it designed / optimised / assessed?
- **Mechanical behaviour of the bentonite** - Mechanical integrity of bentonite depends on homogeneity / heterogeneity of re-saturation / water inflow – how is it designed / optimised / assessed?
- **Mechanical behaviour of the bentonite** - Mechanical integrity of bentonite depends on potential gaps, displacement of waste canisters, … – how is it designed / optimised / assessed?

II. Uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

E. Uncertainties associated with …

- **Metallic material behaviour** (steel, copper, copper coated steel, composite, super container, etc.) in different barriers (waste package, liners…) - how is lifetime of waste packages, gas generation and pressure build-up, other degradation processes, pH-, Eh-evolution, pit corrosion, colloid formation handled in the modelling -evolving processes or as step functions?

- **Interface processes** may occur at different time scales and with varying spatial extension. - Pore clogging and no further gas transport might be a serious problem in tight host rocks (clays), at bentonite-crystalline, or cement-bentonite interfaces. How the influence on RN transport is conceptualised? How are specific designs optimised to prevent unwanted processes? How are the remaining uncertainties assessed/limited? Clogging – pressure build-up – may induce integrity problems. Matrix sealing may induce reduced RN retardation. …
- **Extent of EDZ**, geometry and opening of fractures. These parameters are influenced by the operation conditions (moisture, temperature of ambient air)
- **Concrete parameters** and associated processes used in near-field conceptualisation - Carbonation processes during operational phase and re-saturation phase could have an impact on mechanical parameters
- **Alternative conceptual models of solute diffusion** in the near-field:
  i. The single interlayer-porosity Donnan equilibrium model
  ii. The electrochemical model based on the Nernst-Planck Eq.
  iii. The multiple porosity (interlayer, double layer, free) model.
  iv. The use of different effective diffusion coefficients for each chemical species while preserving charge balance.
  v. Fracture-matrix or equivalent porous medium?
  Conceptual diffusion models i-v yield different De, with different uncertainties. Which concept for RN transport and/or major ion transport (near-field evolution)? Which concept is the less uncertain? Consistent concepts?
- **Coupling influences** - In performance assessment, near-field evolution calculations and RN transport calculations are not coupled. For RN transport calculations, stepwise (spatial, temporal) constant transport parameters are assumed. Is this concept valid? Which uncertainties are accompanied /neglected/? Is it valid to choose “conservative values” in case of non-linearly coupled processes and long time scales?
- **Monitoring influences -** Uncertainties associated with installation of monitoring equipment and potentially induced

III. Uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems

F. Uncertainties associated with …

- **Evolution of the accessible porosity -** Accessible porosity will change due to reactive transport processes and strong (geo-) chemical gradients between barrier and host rock porewater compositions
- **Evolution of diffusion coefficient De** - De will change due to temperature evolution, porosity changes (mineral reactions)
- **Evolution of partition coefficient Kd** - Kd will change due to porosity changes (mineral reactions) degradation/reaction fronts (canister corrosion) changes of mineral surface areas and/or changes in pH, Eh, … neglecting competitive sorption
- **Influence of temperature** - Temperature has an influence on dissolution and precipitation of mineral phases (thermodynamic and materials data)
- **Full 4 D description or 1 D or mixed compartments**,… ? - The often used 1D RN transport modelling/prediction includes a lot of assumptions / uncertainties – would there be a reduction of uncertainties by 4D? Direct comparison is difficult to perform because of long computational times in 4D. Confirmation of simplification - a large uncertainty?

- **Multiphase flow** - The complex porosity structure of the bentonite requires the use of dual or triple continuum models – which model uncertainty comes along with which simplified models? The retention curve of the bentonite (and other buffer materials and host rock), gas entry pressure, hysteresis and temperature dependence are described by several different models) – which are the individual model parameters uncertainties and how do they compare among each other?
- **Preference/necessity for coupled description** - Ranking/importance of: T+H+M+C+B+R - Need for transient phase description – which phase which processes? E.g., MC coupling is often excluded, but high pH liner/construction material with bentonite interaction may weaken mechanical and retardation properties of bentonite.

2.3 The Questionnaire

The major aim of the 3rd UMAN questionnaire (see attachment 1) was to complete the topics addressed in by the 2nd UMAN questionnaire, which covered uncertainties on waste inventory, spent fuel, human aspects and site and geosphere, by near-field uncertainties. The major aims, i.e., to collect the relevance of each identified uncertainty for different kinds of actors, to gather supplementary information/data on their characterisation and potential significance for safety, to assess their evolution over time and collect missing uncertainties, considering the diversity of national disposal programmes for DGDs and their implementation phase, as well as the diversity of actors. From the experience of the 2nd UMAN questionnaire, the individual questions in the 3rd UMAN questionnaire have been formulated in more detail to get more specific replies.

The questionnaire addressed sections 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:
  a. impact on the radiological dose or risk during operation
  b. impact on the radiological dose or risk after closure
  c. impact on safety functions (please specify which functions and disposal system components could be impacted)
  d. others potential impact(s) (please specify)
- Uncertainty characterization (methods, approaches), in which the following pre-set answers have been proposed:
  a. quantification by expert judgement
  b. applying statistical methods on relevant (measured) data
  c. modelling (likelihood of events, geochemical databases…)
  d. accuracy of measurements and detection limit of equipment
  e. exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty)

f. other (please specify)

- Evolution along the programme implementation, from conceptualization to repository closure)

The 3rd UMAN questionnaire has been sent to all partners participating in the EURAD project but not to the Civil Society organisations. It was available only in word format on EURAD Projectplace, different from the 2nd UMAN questionnaire, which was available in two formats: word documents and on-line questionnaire (https://inr-eu.ro/). Latter format seemed to be more difficult to handle and was no longer supported here.

Answers have been received from 17 organisations (*Table 1*), representing, as illustrated in *Figure 1*, REs (5 answers); TSOs (4 answers) and WMOs (9 answers from 8 WMOs) for the disposal concept of geological disposal. It should be mentioned that some organisations replied although there is no HLW in the country or the programme is at a very early stage. One reply was related to salt host rock, which was not taken into account, because the 3rd UMAN questionnaire focusses only on sedimentary and crystalline rock, and only on DGD due to budget limitations. It should also be mentioned that all responses were treated anonymously.

Table 1. List of actors answering the questionnaire, with details on the disposal programmes and status in implementation of a deep geological disposal

Affiliation	**Country**	**RE, WMO, TSO,**	**Rock type**	**Current phase of programme**
Amphos21	ES	RE	Sedimentary rock	Site characterisation
Institute of Nuclear Chemistry, Mineral& Energy Research Economy Institute	PL	RE	Sedimentary rock	Side evaluation and site selection
LEI	LI	RE	Crystalline rock	Policy, framework and programme establishment
PSI	CH	RE	Sedimentary rock	Side evaluation and site selection
Slovak University of Technology	SK	RE	Not specified	Site evaluation and site selection
IRSN	FR	TSO	Sedimentary rock	Site Characterisation
SURO	CZ	TSO	Crystalline rock	Side evaluation and site selection
SSTC	UK	TSO	Crystalline rock	Policy, framework and programme
VTT	FL	TSO	Crystalline rock	Facility construction

ANDRA	FR	WMO	Sedimentary rock	Side characterisation
BGE	GE	WMO	Salt rock - no HLW	Facility operation and closure
Enresa	ES	WMO	Sedimentary rock	Policy, framework and programme establishment,
Greek Atomic Energy Commission (EEAE)	GR	WMO	No HLW	Site evaluation and site selection
INPP	LI	WMO	Sedimentary rock	Site evaluation and site selection
Nagra	CH	WMO	Sedimentary rock	Site evaluation and site selection
ONDRAF/NIRAS	BE	WMO	Sedimentary rock	Policy, framework and programme establishment,
SÚRAO	CR	WMO	Crystalline rock	Site evaluation and site selection

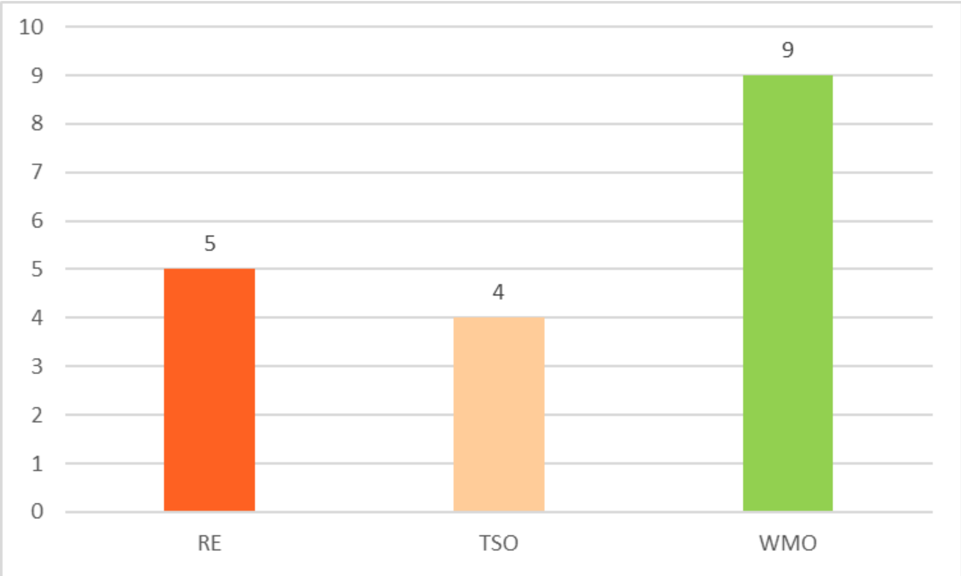

Figure 1. Distribution of the questionnaire answers per type of actor

The answers reflect the concern of each type of actor. Significance for safety as perceived by each actor strongly depends on the current stage of the disposal programme and the experience accumulated in the implementation process. As seen in *Figure 2*, most respondents are in the initial phases of programme implementation (policy, framework and programme establishment and site evaluation and siting, site evaluation and site selection). This is a similar situation for answers related to site and geosphere uncertainties for geological disposal (2nd questionnaire) [6]. In addition, answers from individual WMOs from advanced countries differ in the significance of individual uncertainties strongly compared the rest of the repliers, which indicates their advanced programme with obviously reduced uncertainties on parameters and processes in the near-field.

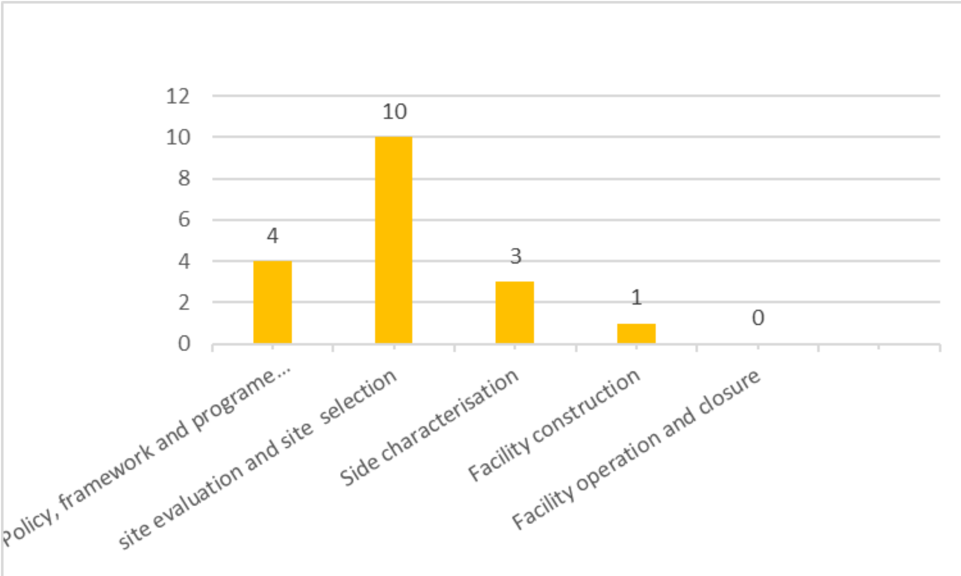

Figure 2. Distribution of the answers per disposal programmes phase and disposal types

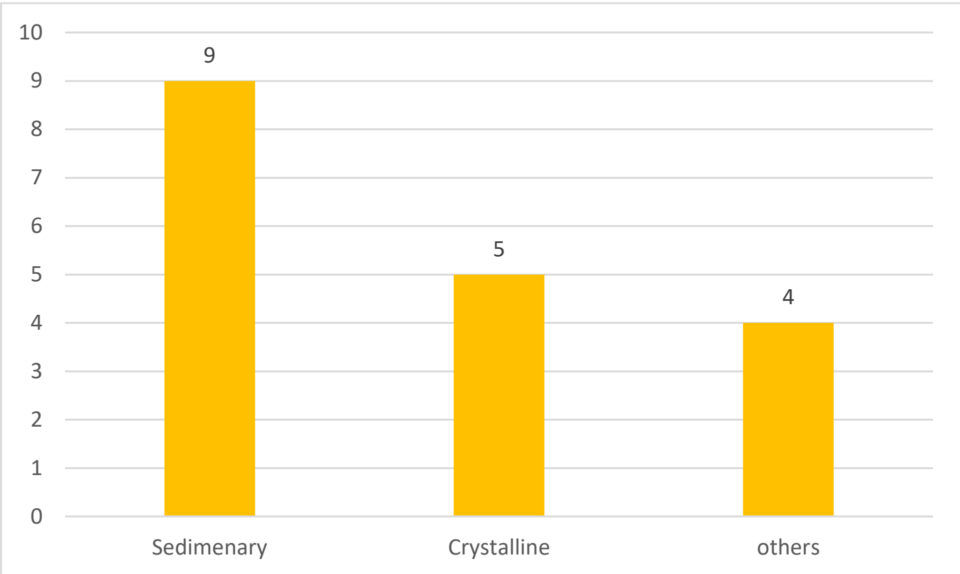

Figure 3. Distribution of the answers per type of rock (others include "not given")

The answers cover the near-field specific uncertainties for DGD in sedimentary, crystalline or salt host rock, which are under consideration in Europe, where most of the replies are related to sedimentary rock (*Figure 3*). Answers related to salt rock were out of scope of this survey and not taken into account.

2.4 Statistical analysis of the answers to the questionnaire

In order to quantify the degree of relevance for safety of the uncertainties addressed in the questionnaire, the answers have been scored, for each type of actor. The total score of an uncertainty was calculated based on:

- 3 points for high significance for safety

- 2 points for medium significance for safety

- 1 point for low significance for safety

- 0 points for “not known or addressed yet”

To normalize the score obtained by each uncertainty, for each type of actor, the resulting amount was divided by the total number of responses non zero in each category of actors.

The answers “not known or addressed yet” have not been considered in the analysis of the uncertainty significance for safety since being not known or not considered yet; it does not mean that it has no impact.

Figure 4 shows that there are groups of uncertainties scored with medium and high significance for the geological disposals safety by many actors involved in this survey. It is also obvious from Figure 4 that REs give generally higher scores for uncertainties than TSOs and WMs, especially for the last (right) block of uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems. Higher common scoring could be for:

- Partition coefficient Kd (Kd values are the result of assumptions associated with the conceptual model (i.e., linear kinetics for sorption / desorption process; Kd could also depend on redox conditions, and could be affected by the near-field evolution).
- Hydraulic properties of the bentonite - (effects of re-saturation and swelling pressure evolution) Bentonite re-saturation is considered to be homogenous, to the expected swelling pressure, but preferential flow paths could develop.
- Mechanical behaviour of the bentonite - mechanical integrity of bentonite depends on homogeneity / heterogeneity of re-saturation / water inflow – how is it designed / optimised / assessed?
- Metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different barriers (waste package, liners…). Lifetime, gas generation and pressure build-up, other degradation processes, pH-, Eh-evolution, pit corrosion, colloid formation (continuous or step functions?)

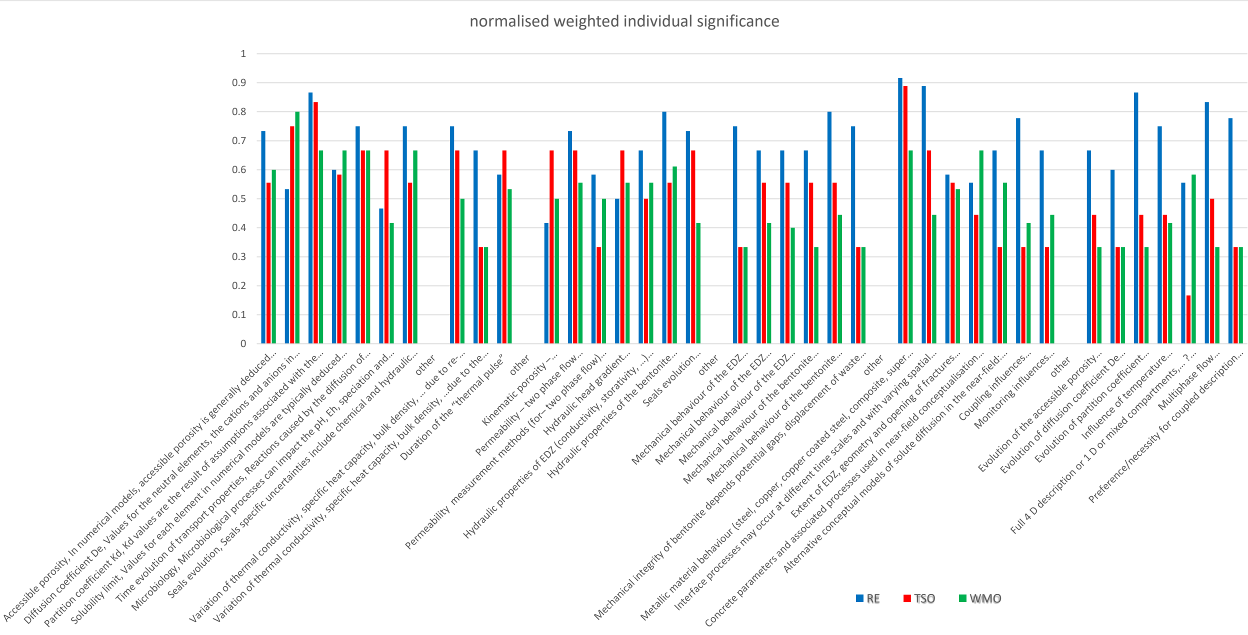

Figure 4. Distribution of “significance for safety” level for different colleges (without “not known or addressed yet” answers included)

According to the questionnaire results, lower relevance for geological disposal safety have been obtained for:

- Variation of thermal conductivity, specific heat capacity, bulk density, due to the chemical condition. Heat transport is influenced by chemical reactions due to changing material and transport properties in the near-field
- Kinematic porosity – Kinematic porosity is generally deduced in an arbitrary manner (a half, the quarter…) from experimental measurements of total porosity

Taking into consideration the “not known or addressed yet” answers, the distribution of “significance for safety” level slightly changes, as shown comparing *Figure 4* and *Figure* .

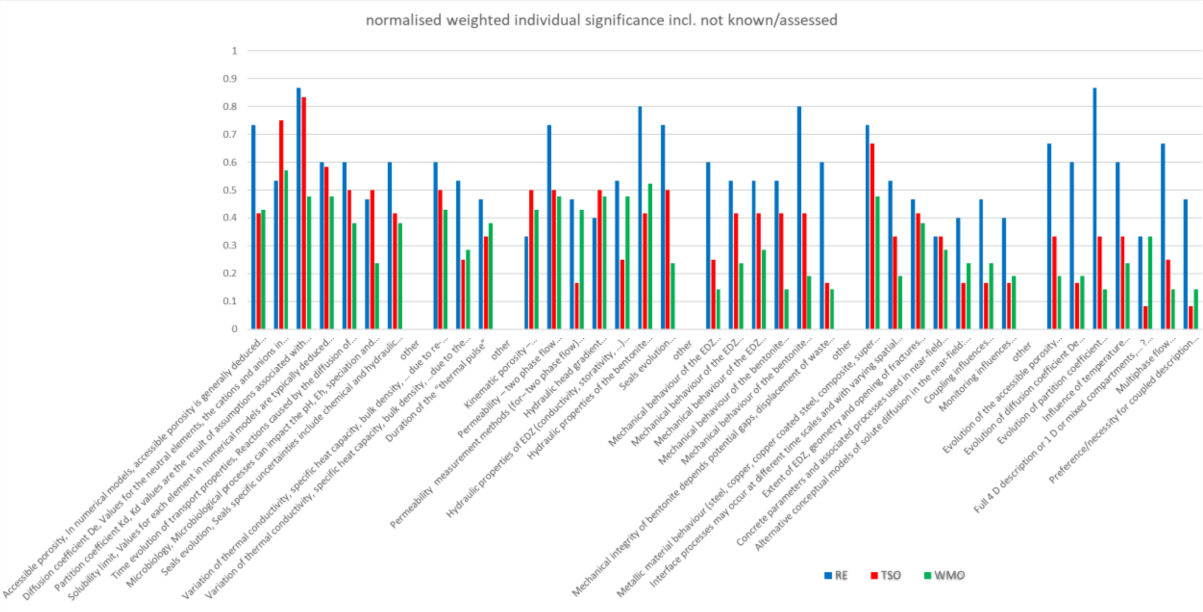

Figure 5. Distribution of “significance for safety” level for different colleges (with “not known or addressed yet” answers included)

When looking at the overall significance to safety by all actors the results are given in *Figure 6* (without not know, not accessed) and *Figure 7* (with not know, not accessed), no big differences can be observed in the significance distribution among the different topics of uncertainty.

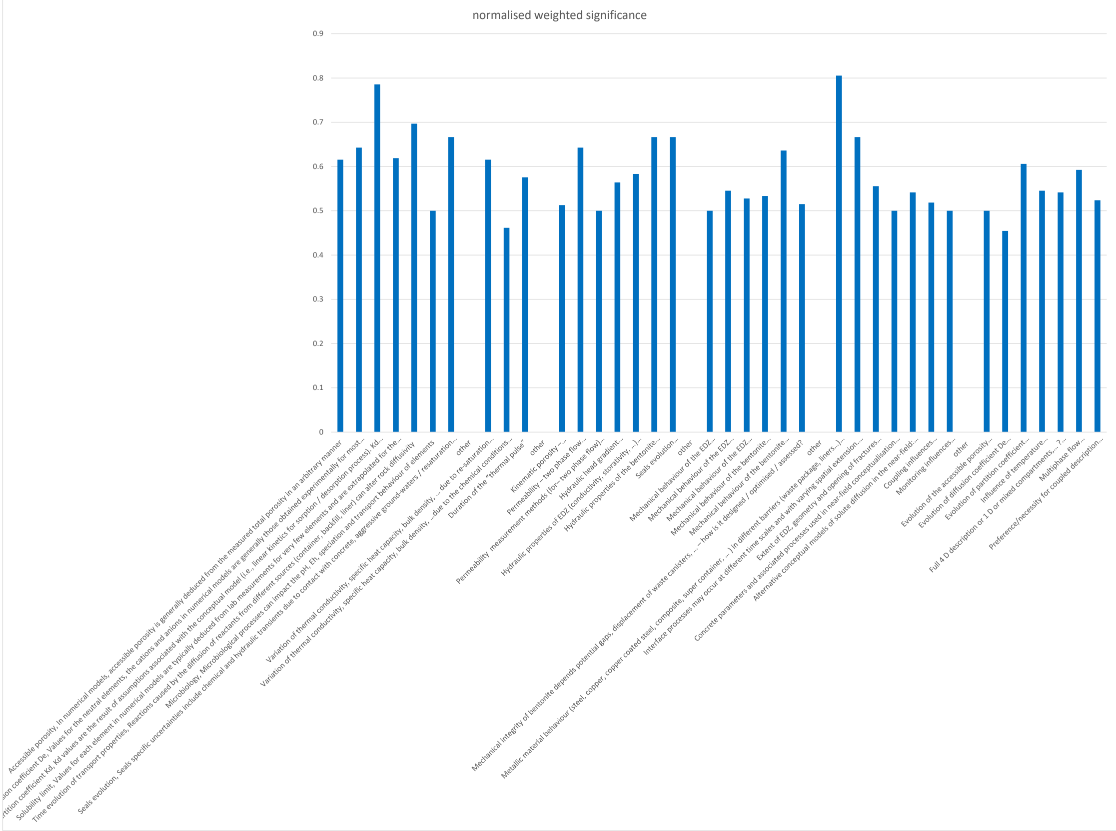

Figure 6. Overall distribution of “significance for safety” level for all colleges (without “not known or addressed yet” answers included)

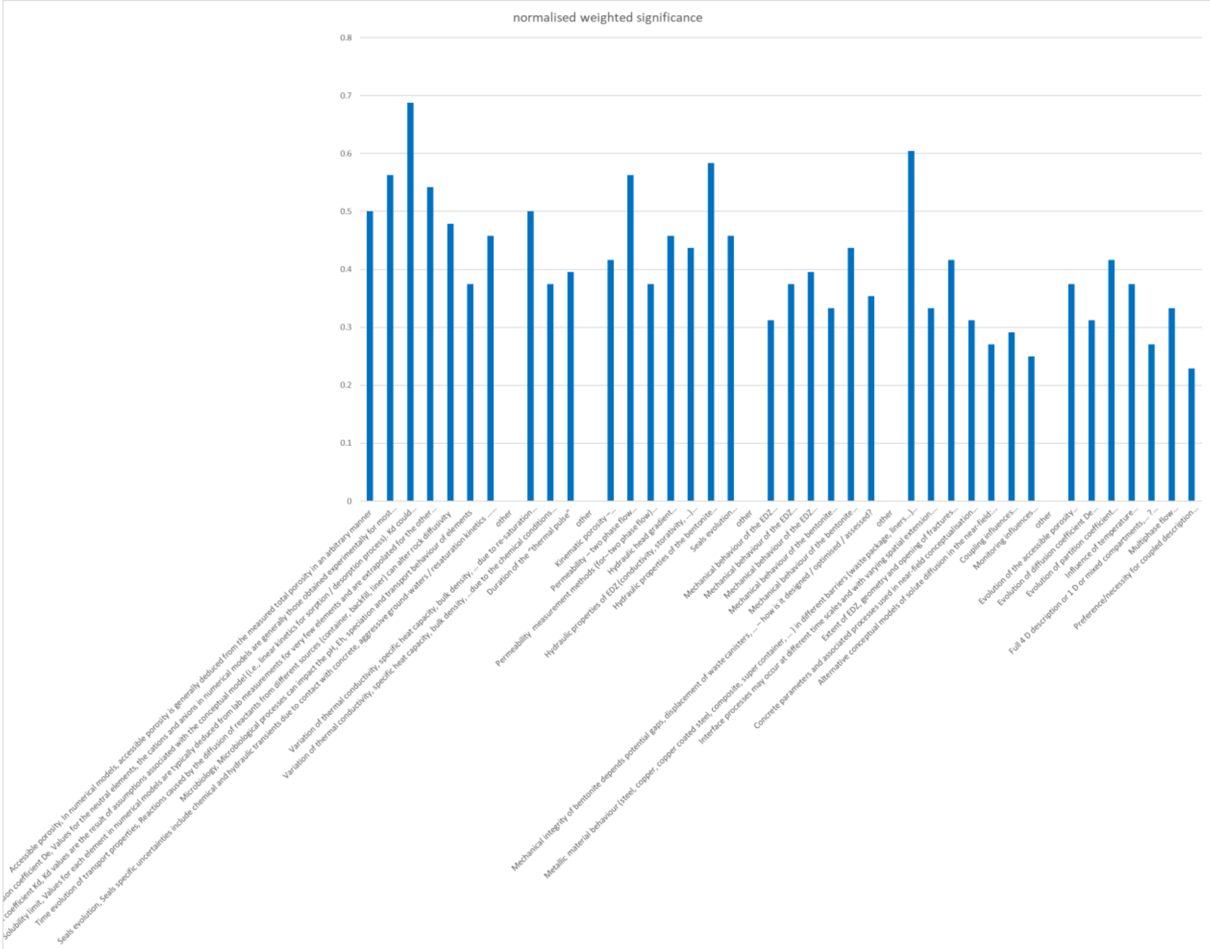

Figure 7. Overall distribution of "significance for safety" level for all colleges (with "not known or addressed yet" answers included)

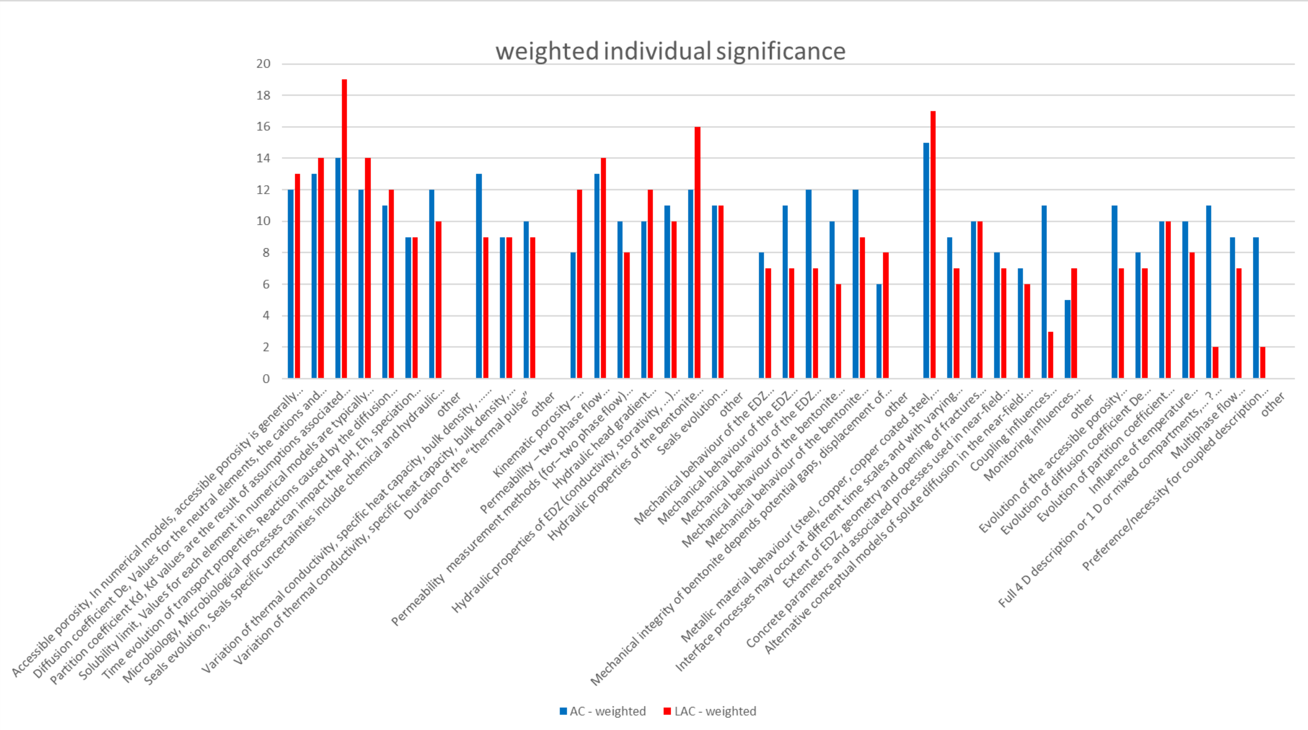

Figure 8. Overall distribution of “significance for safety” level for advanced and less advanced countries

A further comparison concerns the overall ranking of significance among the different topics by replies from less advanced countries compared to actors from advanced countries, which shows similar distributions for significance, except for the topics uncertainty on mechanical behaviour of EDZ and bentonite and evolution of porosity, full 4D compared to 1D and preferences for coupled processes, where advanced countries repliers indicate generally higher significance for safety (*Figure 8*).

Finally, when looking at the significance for safety among the overall answers/replies, the number of answers of “not known or not assessed yet” increases from the left to the right of the uncertainty topics, which correlates to the more complex processes and parameters of these topics (*Figure 9*). Also indicating that at early stage programmes, complex processes and parameters are not looked at yet.

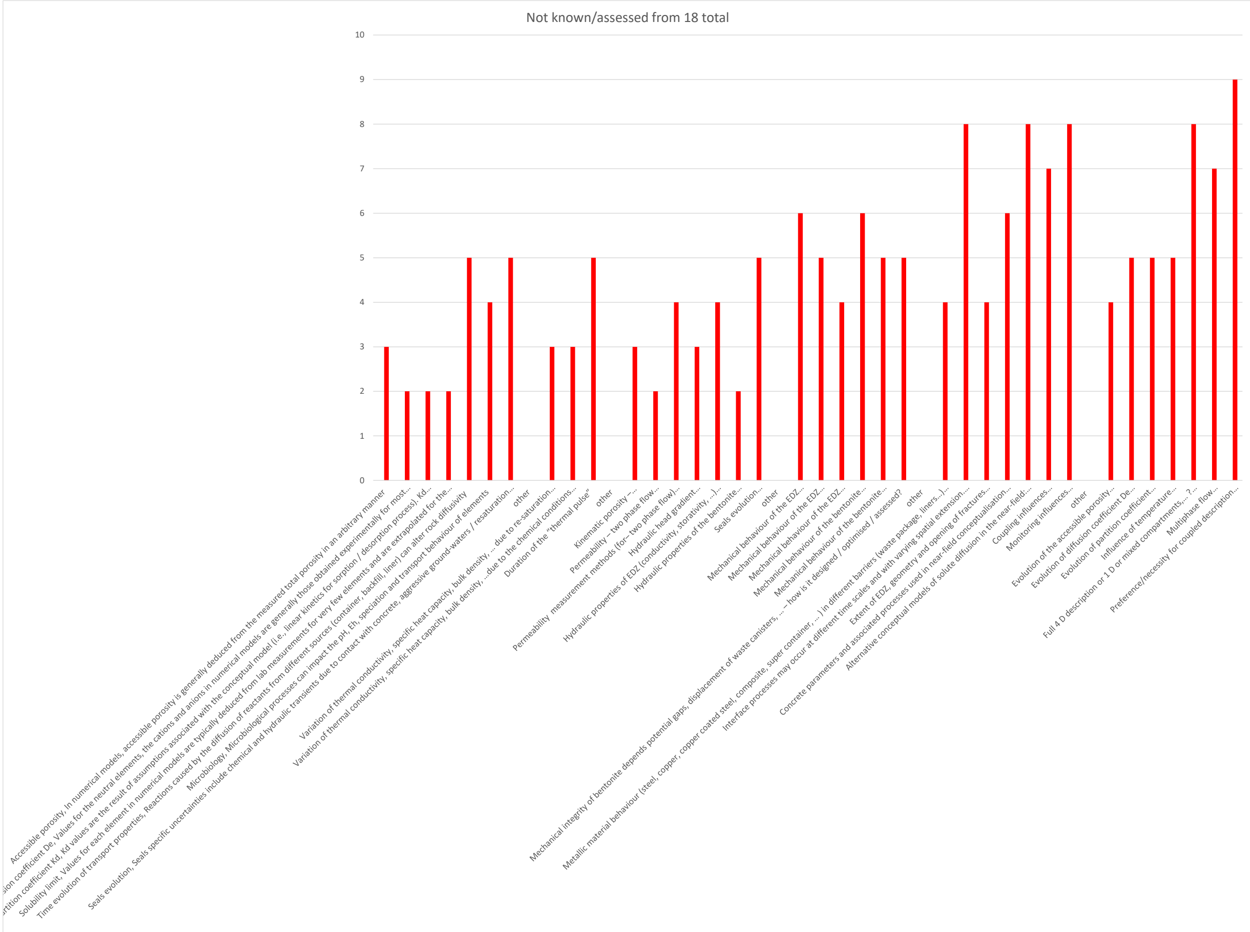

Figure 9. Overall distribution of “not known or addressed yet” answers among the different uncertainty topics.

3. Uncertainties associated with the processes governing or altering radionuclide migration and the performance of disposal system components

The near-field is the area with the largest material heterogeneity (metal, bentonite, clay or crystalline rock and concrete). There are the largest temperature, hydraulic and stress gradients (related to the materials properties), and also the largest chemical gradients between different porewater compositions (e.g., cement – clay). Therefore, a complex evolution of the near-field has to be expected, which needs to keep its barrier functionality for radionuclides in the very long term. In the safety case and safety assessment, each safety-related aspect of the near-field has to be considered, analysed, understood and integrated, together with their associated uncertainty (see attachment 2 and references therein).

The main remaining uncertainties related to conceptualisation of the technical barriers in scenario and model development selected by the expert group of subtask 3.6 relate to the evolution of the near-field as expected with focus on the topics described and analysed below.

3.1 Uncertainties associated with the transport properties for major ions and RN within the considered barrier medium (A)

3.1.1 Significance for safety

Transport properties for major ions and RN within the near-field, i.e., the different barrier media, are the major elements considered in the development of the model for radionuclide transport and retention within having strong influence on the performance of the repository and related safety analyses. Similarly, uncertainties on solubility limits, transport parameters evolution with time, microbial influences and the evolution of seals transport parameters are looked at as of high significance, influencing also long-term evolution. They are dose relevant and important for the radiologic impact assessment of the disposal.

Uncertainties associated with transport properties for major ions and RN within the near-field, by most of the actors involved in the survey, seem to have a medium and high significance for the disposal safety (see *Table 2* and *Figure 10*).

Table 2. Synopsis of the actors' views on uncertainties related to the transport properties for major ions and RN within the considered barrier medium

Uncertainty	Score of uncertainty relevance for safety						Impact on		
		REs		TSOs		WMOs	Operational dose/risk	Post-closure dose/risk	Safety functions
Accessible porosity, In numerical models, accessible porosity is generally deduced from the measured total porosity in an arbitrary manner	0.73	2h; 2m;1l	0.55	2m; 1l;1n	0.6	1h; 2m; 2l, 2n	2	9	8
Diffusion coefficient De, Values for the neutral elements, the cations and anions in numerical models are generally those obtained experimentally for most representative RN and extrapolated for the other elements.	0.55	1h;1m;3l	0.58	1h; 1m; 2l;	0.8	3h; 1m; 1l; 2n	3	10	7
Partition coefficient Kd, Kd values are the result of assumptions	0.86	3h;2m	0.83	2h; 2m	0.66	2h; 1m; 2l; 2n	2	12	6

associated with the conceptual model (i.e., linear kinetics for sorption / desorption process). Kd could depend on redox conditions, and could be affected by the near-field evolution.									
Solubility limit, Values for each element in numerical models are typically deduced from lab measurements for very few elements and are extrapolated for the other elements. Due to strong chemical gradients within the near-field, precipitation / dissolution fronts will develop in the near-field influencing solubility limits of elements	0.6	1h;2m;3l;	0.58	1h;1m;2l	0.67	1h;3m;1l;2n	2	12	7
Time evolution of transport properties, Reactions caused by the diffusion of reactants from different sources (container, backfill, liner) can alter rock diffusivity	0.75	2h;2m;1l;1n	0.66	1h;1m;1l;1n	0.67	1h;2m;1l;3n	2	8	4
Microbiology, Microbiological processes can impact the pH, Eh, speciation and transport behaviour of elements	0.46	2m;3l	0.67	1h;1m;1l;1n	0.42	1m;3l;3n	4	9	4

Seals evolution, Seals specific uncertainties include chemical and hydraulic transients due to contact with concrete, aggressive ground-waters / re-saturation kinetics … They could influence bentonite swelling properties, homogeneous swelling / fingering, dry zones, preferential migration paths (gas flow / pressure build up, …) – which related transport parameter uncertainty is acceptable?	0.75	2h;1m;1l;1n	0.55	1h;2l;1n	0.67	1h;2m;1l;3n	3	6	7

The uncertainties associated with the porosity, diffusion coefficient, partition coefficient, solubility limits and seals evolution are of the greatest importance for all REs, TSOs and WMOs (*Figure*). Due to their role in radionuclides retention and retardation, being especially associated with the impact that these uncertainties may have on the post-closure radiological dose assessment, as well as on the safety functions assigned to the technical barrier. Only for uncertainties associated with microbiology, TSO indicated a higher significance than REs and WMOs; for all other topics REs and WMOs indicated (slightly) higher significance than TSO, except for Diffusion coefficient De, where REs indicate the lowest significance.

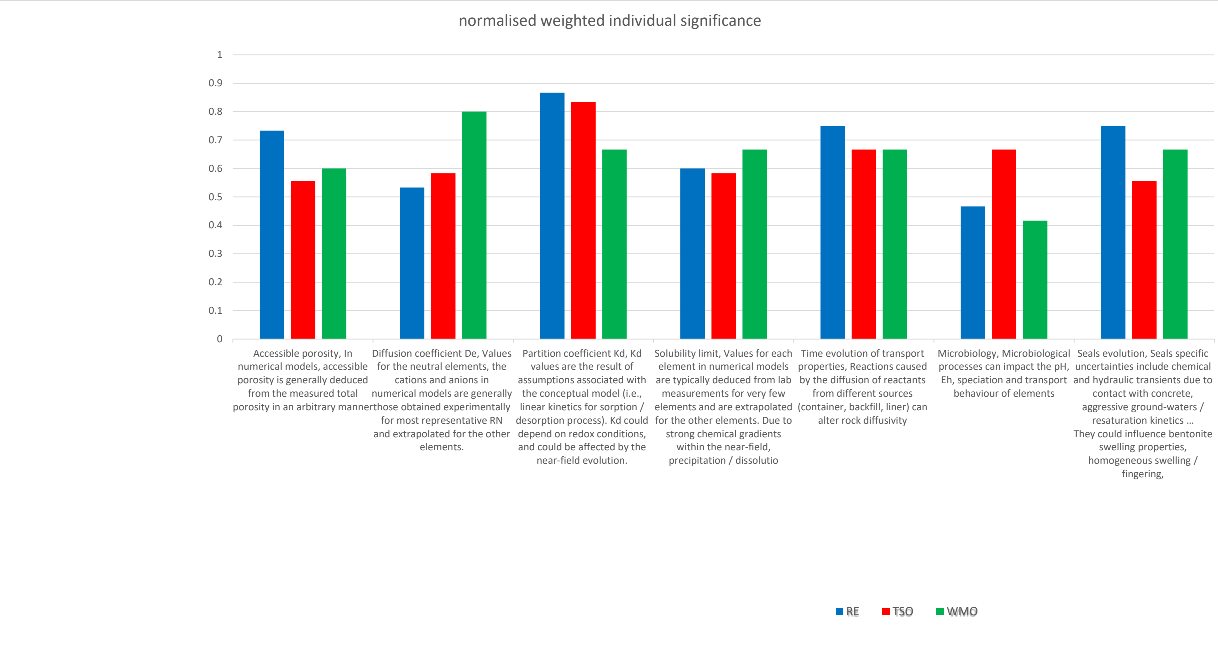

Figure 10. Significance for safety of uncertainties related the transport properties for major ions and RN within the considered barrier medium

For uncertainties related to the transport properties for major ions and RN within the considered barrier medium additional comments were added within the replies, which might be looked at as specific concerns of the repliers depending on near-field design, host rock, regulations, or programme phase dependant issues under discussion in their countries.

The REs pointed out that

… full or partial clogging of diffusive pathways occurs due to mineral reactions, or also where sustained unsaturated conditions remain that have the effect of reducing the diffusion through the aqueous fraction of porous media.

… for "after closure", the near field evolution is complex, often involving THCM processes and gas migration. Using predefined Kd values that cannot evolve as the near-field does, introduces uncertainties and use of conservative estimates is then the main option.

Once a good knowledge of how the Kd of each barrier can evolve over time and in space due to physical and chemical evolution of the near-field, it would be possible to have sound time-dependent Kd values to be used in the calculations

Solubility modelling considering more radionuclides released from waste matrix and dissolving at the same time

… for "after closure", solubility limits are key to determine the release of radionuclides into the near-field and highly depending on the chemical interactions of the different barriers. In the cases where lab measurements are not possible and analogies are performed, the systems selected to perform thermodynamic data analogies should be consistent and appropriate

Improvement of coupled process models will help in better constraining the evolution of these complex systems. These models, when applied to the seal scale (spatial and temporal) can be used to quantify uncertainties and to help prioritizing experimentation of key processes.

The TSOs highlighted the role of

… the number of available pores determines the amount of water in the considered porous barrier medium. Porosity will also depend on the pore size, which might be changing with time due to interface reactions – which should be chosen?

… the alteration of seals may change RN release and transport mechanisms in near-field, lowering isolation time.

the diffusion coefficients in porous media (eg concrete, bentonite) differ from molecular diffusion coefficients in solutions due to the porosity of the medium and the tortuous path of diffusion. The so-called "effective" diffusion coefficient is obtained from the experiment. In numerical models the values of molecular diffusion coefficients D0 are often used when specific data are unavailable. This approach tends to overestimate the contribution of diffusion to transport.

… It is often assumed that Kd is constant. For geological repositories, due to the different properties of barrier materials and the possible change in these properties over time, it can be expected that the sorption characteristics will change both in space and in time. In addition, many radionuclides can change their valence state and chemical composition under various groundwater chemical conditions. These features must be taken into account when choosing Kd values to use in the model. For example, the use of low Kd values in the near field and geosphere models is not always a conservative approach. This is not always the case, for example when parent radionuclide produces progeny of higher radiotoxicity.

The WMOs underlined that

… De is a key parameter for mobile radionuclides. It is well known with low uncertainty thanks to the numerous measurements on samples

More than one hundred of steady state measurements in through diffusion cells: The uncertainty is very low

… Kd is a key parameter. In some cases, uncertainties are high. However, this uncertainty does not concern mobile radionuclides (that determine the long-term impact).

Necessary concordance between the different measurements (batch, column etc.)

… the uncertainty on Kd is high but the impact should be favourable, promoting redox processes. It is therefore not implemented in safety calculations

… limit advective transport, but the risk of alteration of seals should not be underestimated.

… safety models allow to assess the expected performance and the potential impact of unexpected evolutions of seals through Altered Evolution Scenarios

In general, all actors agree that the uncertainty related on the transport properties for major ions and RN within the considered barrier media have little influence on the radiological dose or risk during operation. Then their impact increases for the radiological dose or risk after closure for all actors, whereas the impact on safety functions seems to be lower always for REs, slightly lower mostly for TSOs and WMOs, where for WMOs the impact remains at a higher level than for TSOs (*Figure 11*).

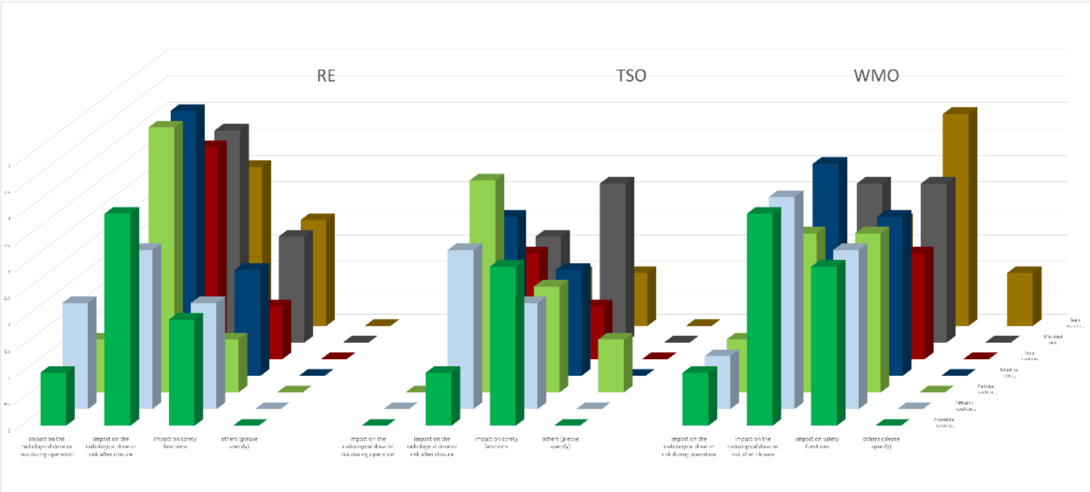

Figure 11. Actors views on impact for safety-significant uncertainties (topics 1-7 - porosity, De, Kd, solubility limit, microbiology, time evolution of transport parameters, seals) *on radiological dose/ risk during operation, on radiological dose/risk after closure, on safety functions or on other potential impact(s)*

3.1.2 *Uncertainties characterisation*

There are many methods available and already used in the characterisation of the uncertainty related to the transport properties for major ions and RN within the considered barrier medium, because these are the same or similar methods used also for parameter characterisation in EDZ or geosphere, which were dealt with in the 2nd questionnaire [6]. This might be the reason that only a few repliers indicated their preferences as can be seen in the *Figures 12- 18*. A statistical analysis about which actor prefers a method more or less than others seem to be not possible here.

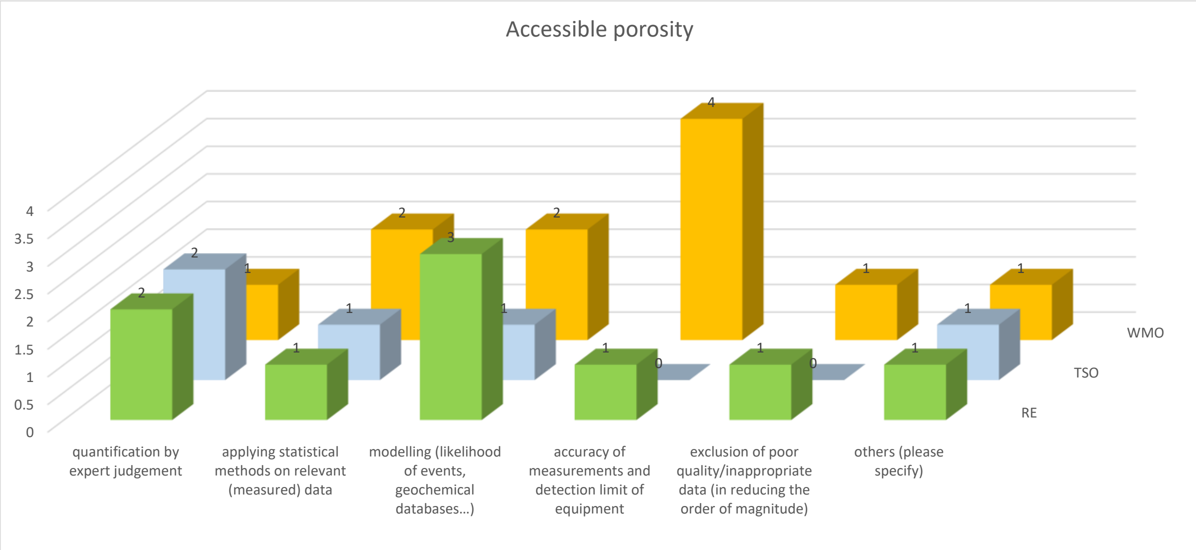

Figure 11. Frequency of the methods used in characterisation of uncertainties related to the transport properties for major ions and RN within the considered barrier medium – accessible porosity

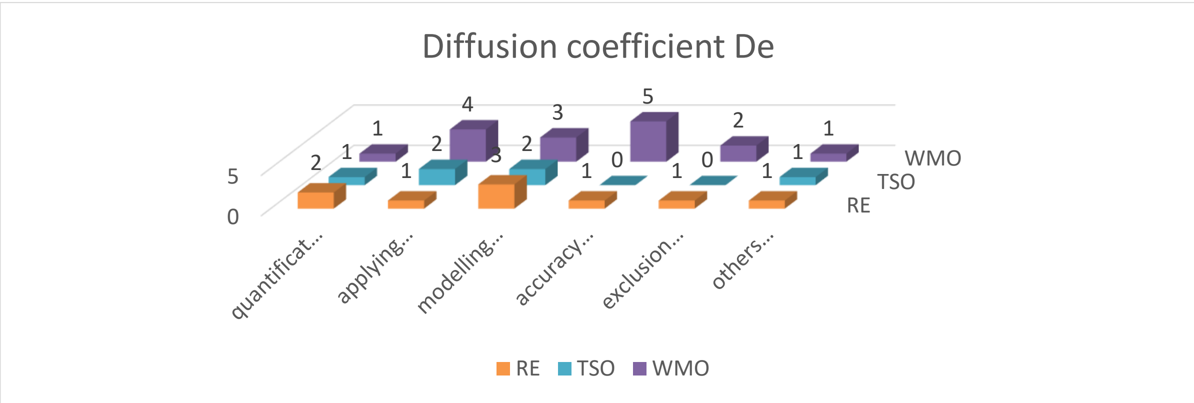

Figure 12. Actors' preferences in the characterisation of uncertainties on the transport properties for major ions and RN within the considered barrier medium – diffusion coefficient De

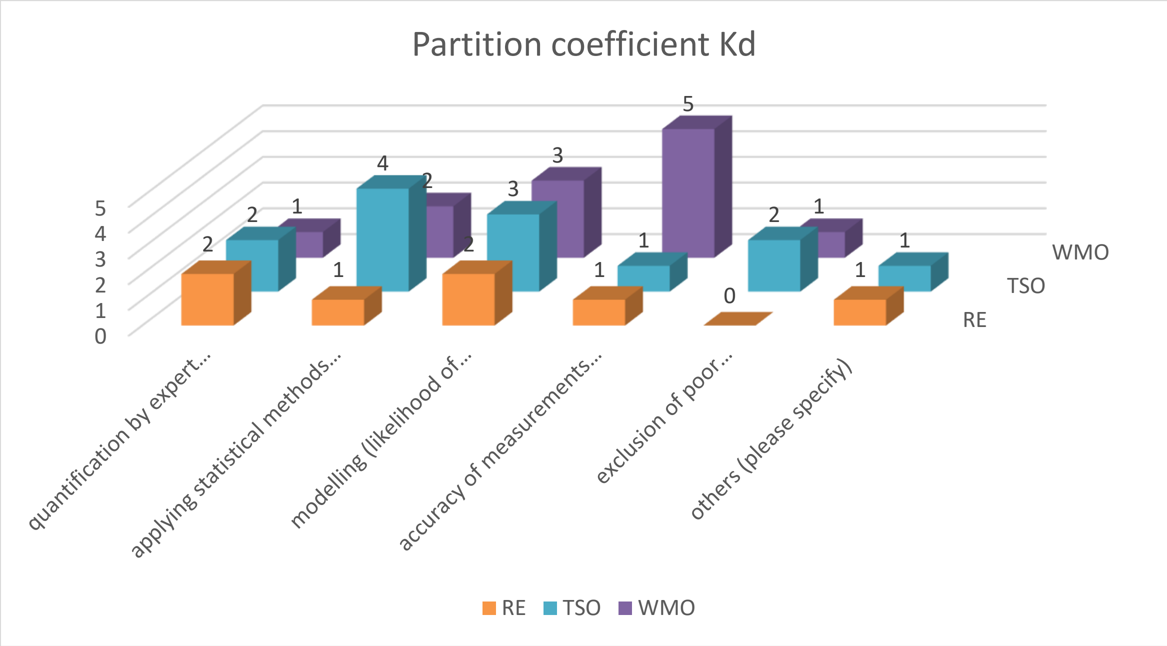

Figure 13. Actors' preferences in the characterisation of uncertainties on the transport properties for major ions and RN within the considered barrier medium – partition coefficient Kd

Figure 14. Actors' preferences in the characterisation of uncertainties on the transport properties for major ions and RN within the considered barrier medium – solubility limit

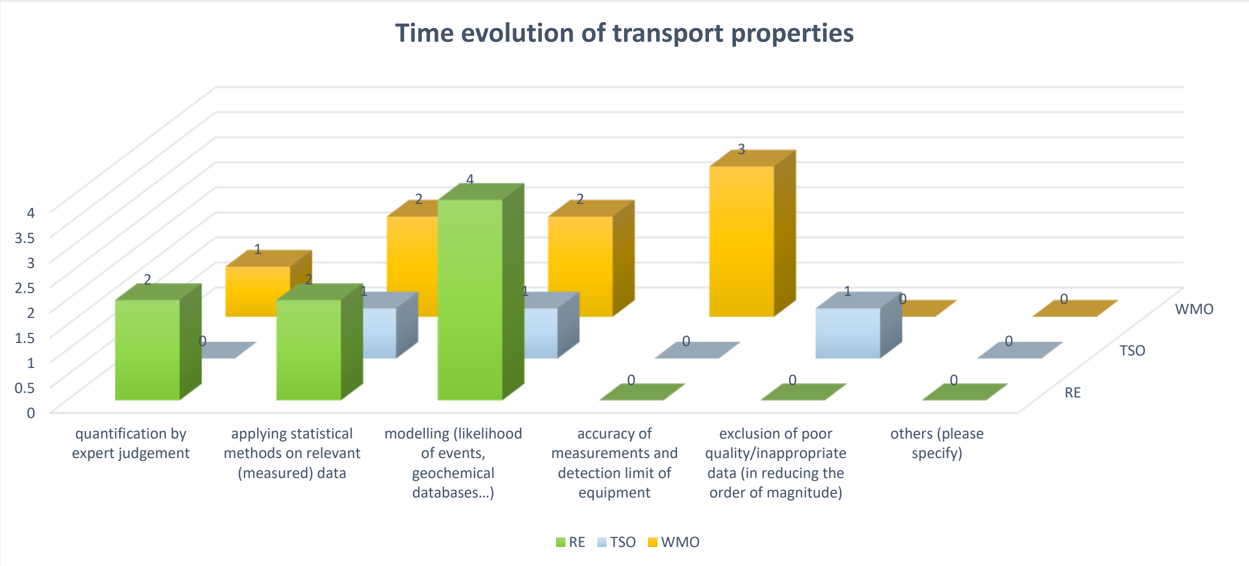

Figure 15. Actors' preferences in the characterisation of uncertainties on the transport properties for major ions and RN within the considered barrier medium – time evolution of transport properties

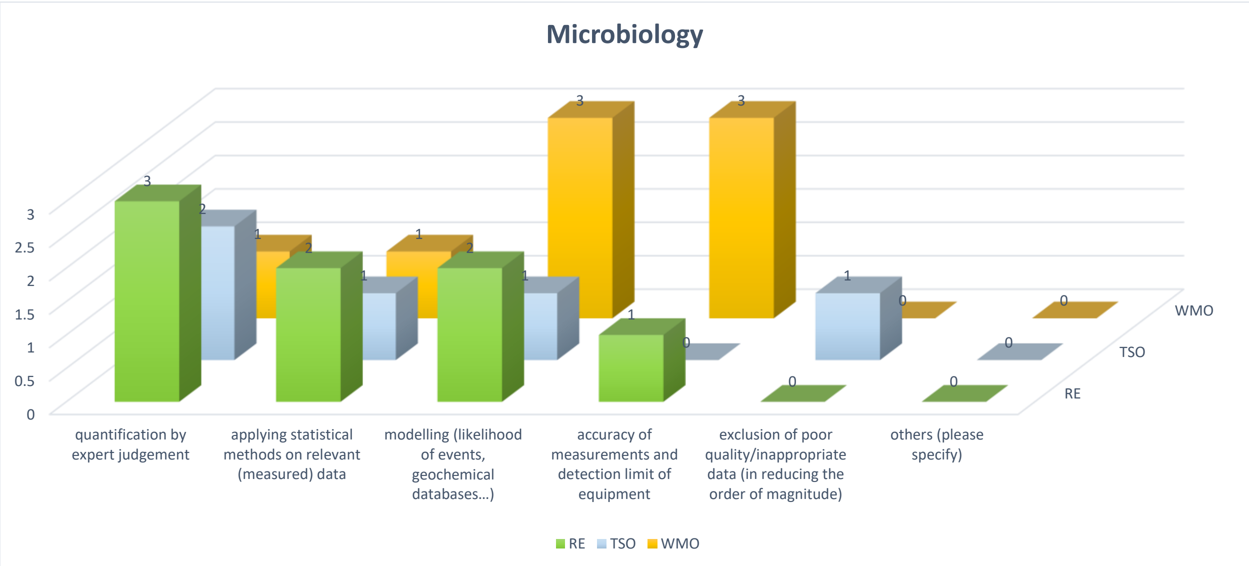

Figure 16. Actors' preferences in the characterisation of uncertainties on the transport properties for major ions and RN within the considered barrier medium – microbiology

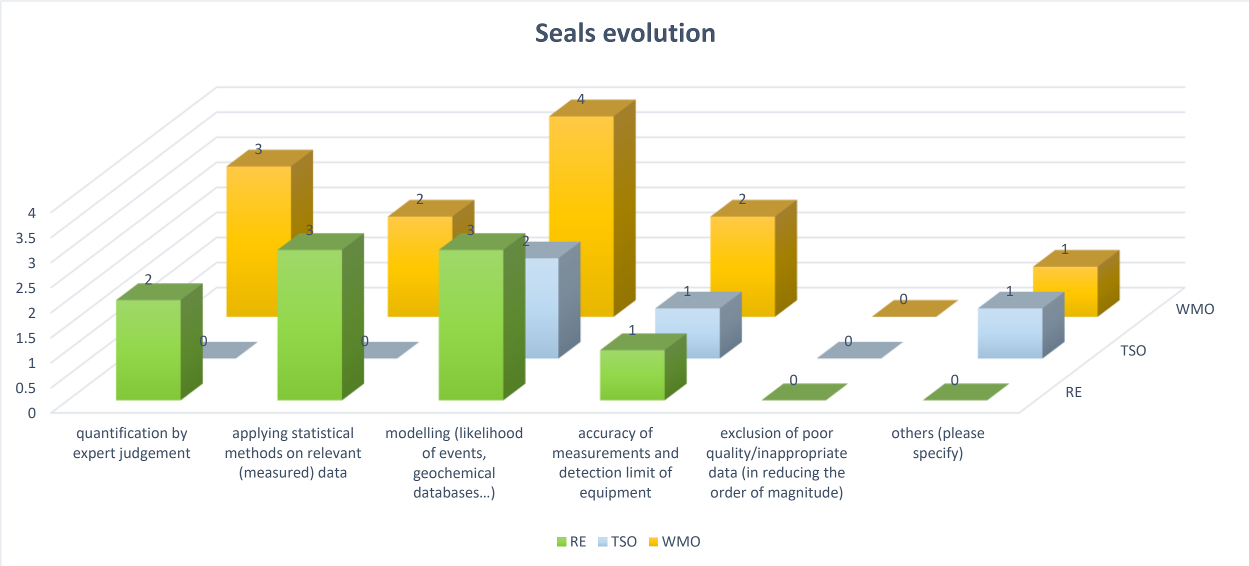

Figure 17. Actors' preferences in the characterisation of uncertainties on the transport properties for major ions and RN within the considered barrier medium – seals evolution

3.1.3 Uncertainty evolution in time

When looking at the overall uncertainties evolution with time (programme phase), no general trend is recognised (*Figure 19*); partly the red (high significance) increases with time (top to bottom), e.g. for “De”, partly it is vice versa, as for example, for “solubility limit” and “microbiology”. A reason could be that replies predominantly reflect the way of addressing uncertainties specific to the site evaluation phase and near-field uncertainties are not yet analysed in detail.

*Figure 18. Global uncertainties evolution f*or porosity, De, Kd, solubility limit, microbiology, time evolution of transport parameters, seals *(from left to right) along the disposal programme phases*

3.2 Uncertainties associated with heat transport properties of barriers (B)

3.2.1 Significance for safety

There is no common view of the three categories of actors related to the uncertainties associated with heat transport properties of barriers. The replies indicated from low to high significance for safety, where impact on radiological dose or risk after closure is dominating (*Table 3* and *Figure 20*).

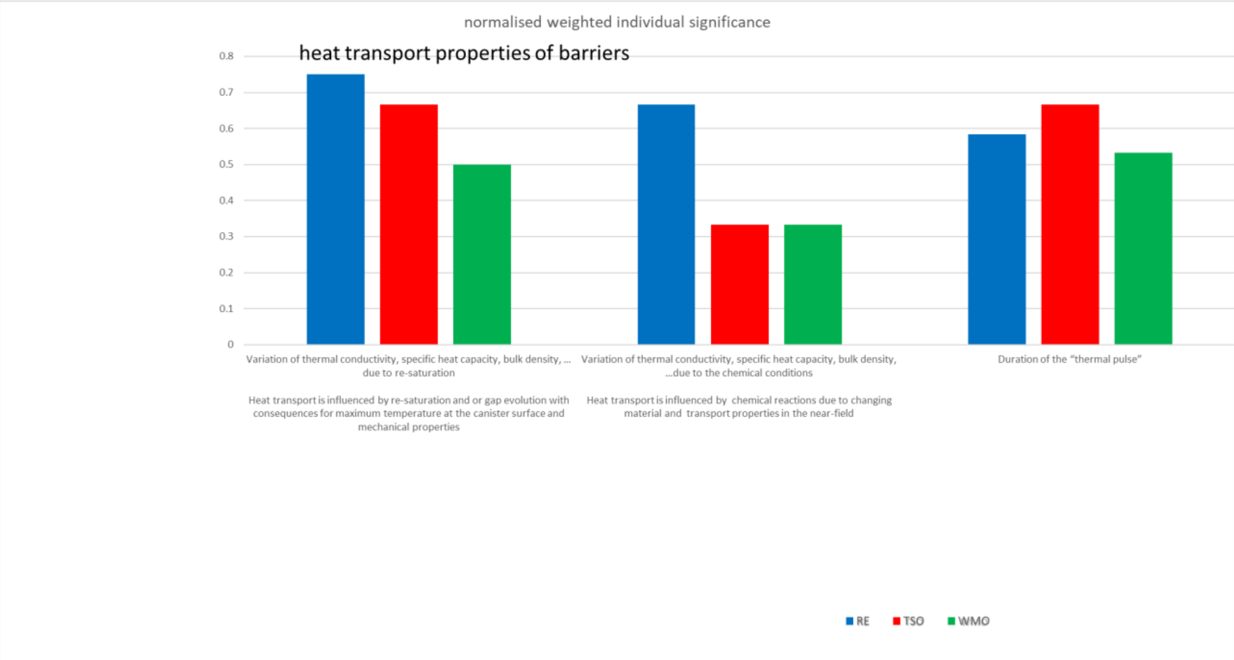

Figure 19. Significance for safety of uncertainties related to heat transport properties of barriers

Table 3. Synopsis of the actors' views on uncertainties related to heat transport properties of barriers

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
		REs		TSOs		WMOs	Operational dose/risk	Post-closure dose/risk	Safety functions
Variation of thermal conductivity, specific heat capacity, bulk density, … due to re-saturation Heat transport is influenced by re-saturation and or gap	0.75	1h;3m;1n	0.67	1l; 1h; 1m; 1n	0.5	1h;1m;4l;1n	4	8	7

evolution with consequences for maximum temperature at the canister surface and mechanical properties of materials in the near-field									
Variation of thermal conductivity, specific heat capacity, bulk density, …due to the chemical conditions Heat transport is influenced by chemical reactions due to changing material and transport properties in the near-field	0.67	1h;2m;1l;1n	0.33	3l;1n	0.33	1m; 4l;1n	4	5	4
Duration of the "thermal pulse"	0.58	1h;1m;2l;1n	0.67	1h; 1l; 2n	0.53	1h; 1m; 3l;2n	3	8	5

With respect to the topics of uncertainty, **the REs** pointed out that

… for bentonite barriers the coupled thermo-hydraulic processes dictate the evolution of the physical properties of bentonite, such as plasticity and swelling pressure, needed to comply with their safety functions

… there is good level of knowledge for temperatures below 100ºC, but new data and models will need to be developed and validated for higher temperatures

… material properties such as porosity and permeability might be affected due to changes in stress state determined by coupled THM processes (thermal pressurisation). Changed porosity and permeability will influence radionuclide transport in the near field.

… if porosity and permeability change is related to plastic strains induced by heat load, this impact will remain even after heat dissipation

The TSOs pointed out that

… life time of barriers and their performance can be affected by thermal effects

The WMOs pointed out that

… un-saturation can lead to less favourable heat transfer properties. This is taken into account in heat transfer models and temperature dependant processes

… the "thermal pulse" is to be compared to the RN travel time. It can be significant for altered scenarios

The uncertainties are assessed to be higher after repository closure, also with impact on the safety function, by REs and WMOs, while TSOs replies showed no trend (*Figure 21*). However, overall less significance for safety was identified than for all the other topics of this questionnaire, maybe because several repliers did not assess the uncertainties associated with heat transport properties of barriers yet.

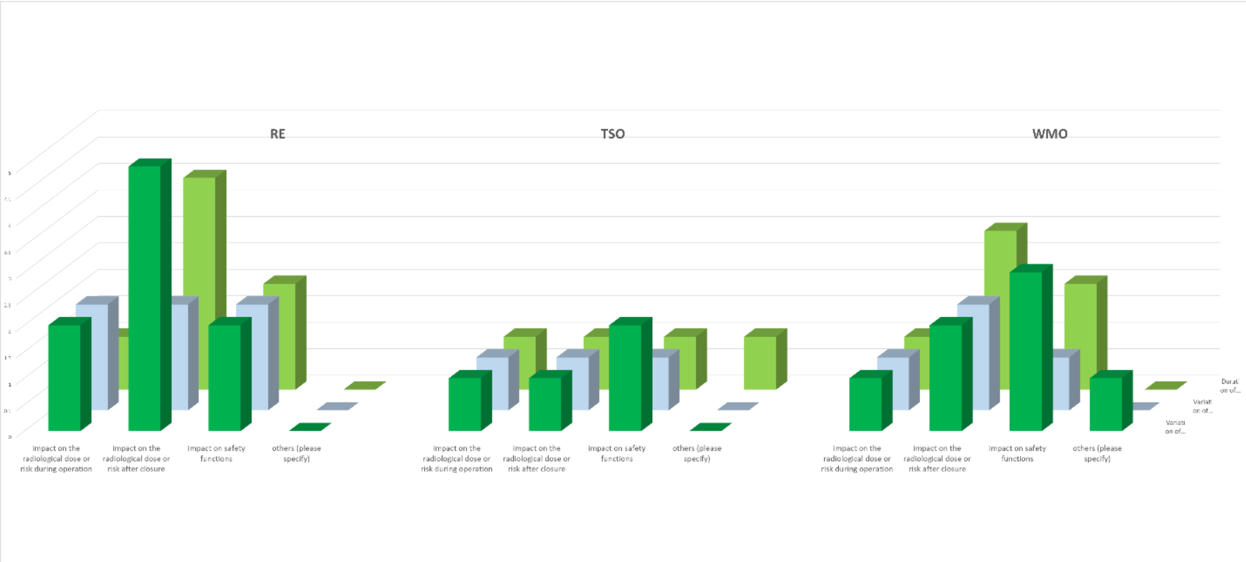

Figure 20. Actors views on impact for safety-significant uncertainties (topics 1-3 - variation of thermal conductivity, … due to re-saturation, variation of thermal conductivity, … due to the chemical conditions, and duration of thermal pulse) on radiological dose/ risk during operation, on radiological dose/risk after closure, on safety functions or on other potential impact(s)

3.2.2 Uncertainty characterisation

Uncertainty characterisation by the three categories of actors is also poorly indicated in the replies due to the fact that low indication for safety significance does not require for characterisation preferences. What could be seen in *Figures 22 – 24* is that all methods are used except the “exclusion of poor quality/inappropriate data”, and that there is no preferred method by the different actors.

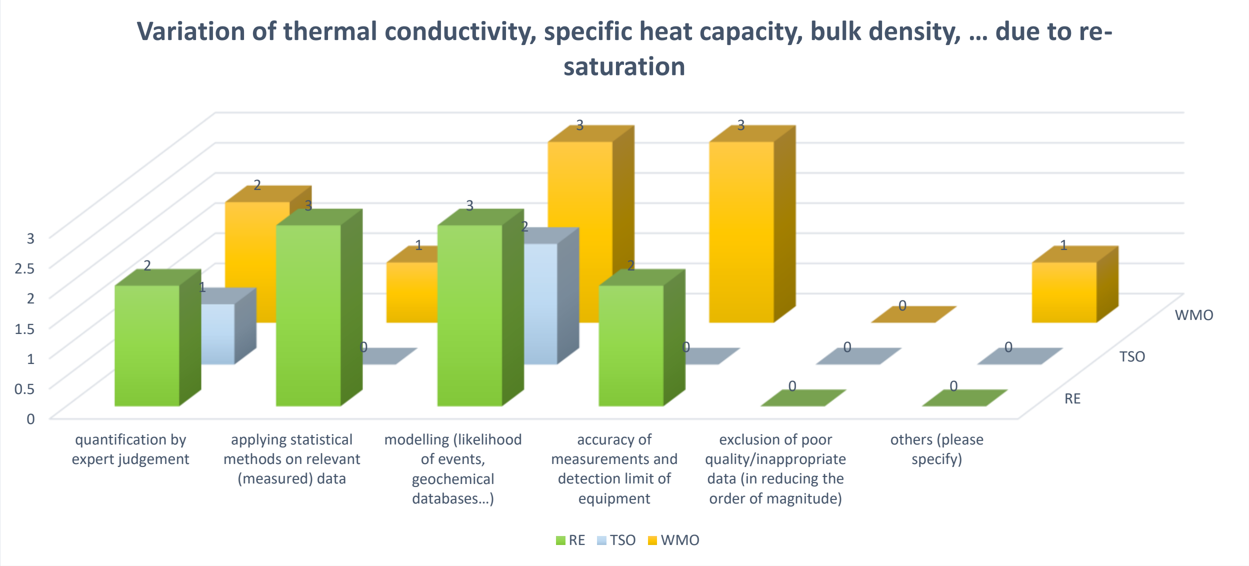

Figure 21 Actors' preferences in the characterisation of uncertainties on heat transport properties of barriers – variation of thermal conductivity, … due to re-saturation.

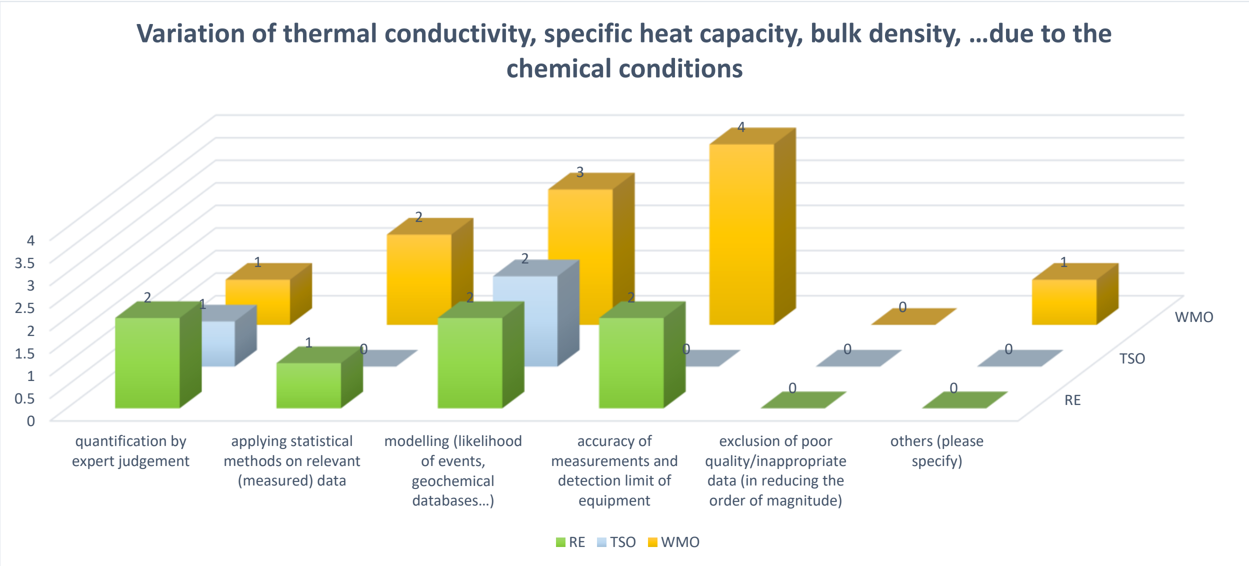

Figure 22. Actors' preferences in the characterisation of uncertainties on heat transport properties of barriers – variation of thermal conductivity, … due to the chemical conditions

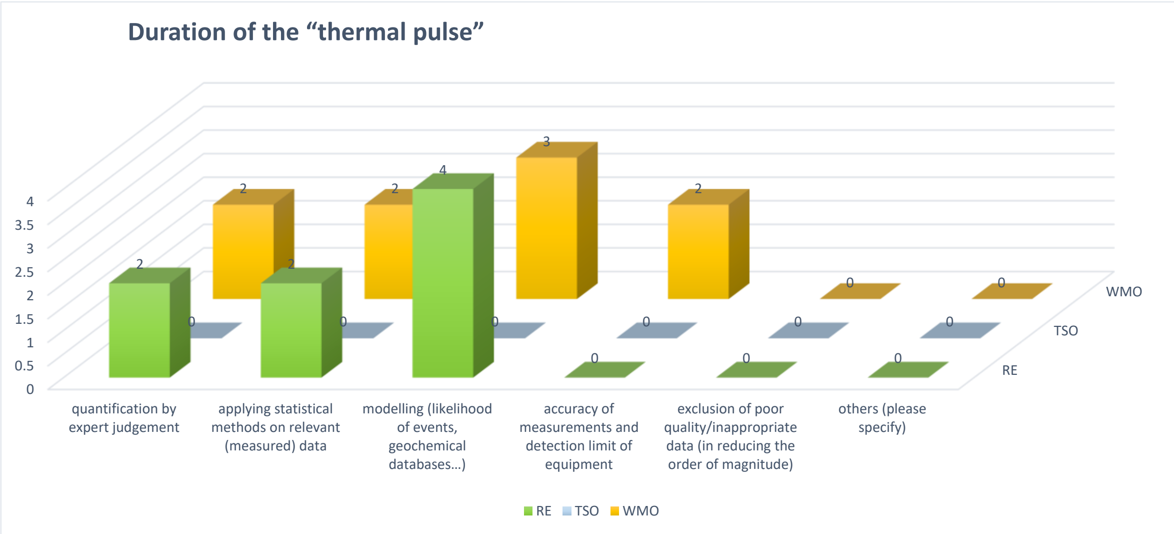

Figure 23. Actors' preferences in the characterisation of uncertainties on heat transport properties of barriers – duration of thermal pulse

3.2.3 Uncertainty evolution in time

The overall evolution of uncertainties associated with processes along programme implementation phases considered here does not show a clear trend (*Figure 25*); there are high uncertainties for each of the 3 phases considered.

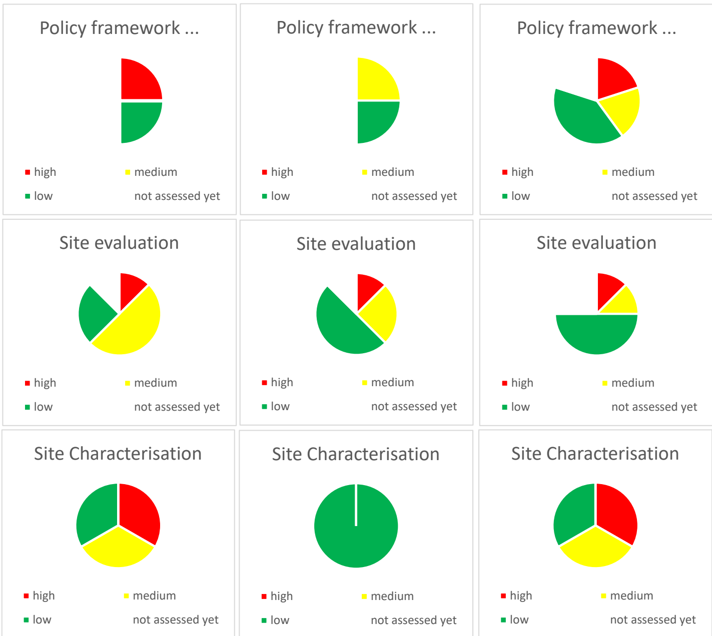

Figure 24. Actors' views on the evolution of uncertainties with time / programme phase associated with variation of thermal conductivity, … due to re-saturation, variation of thermal conductivity, … due to the chemical conditions, and duration of thermal pulse

Also here, replies are predominantly from actors being in the site evaluation phase, when near-field uncertainties are not looked at in detail yet.

3.3 Uncertainties associated with flow properties through barriers (C)

3.3.1 Significance for safety

Liquid and gas flow in the undisturbed host rock is the main process contributing to the radionuclide transport from the repository to the biosphere. Kinematic porosity, hydraulic conductivity, hydrostatic pressure and hydraulic gradients, together with the gas phase properties are the main parameters defining the water and gas flow field, the key vector of the radionuclide transport.

In the view of all three actors (REs, TSOs and WMO), the uncertainties on these parameters and processes have a great relevance for the disposal safety (medium to high) (*Figure*), due to the impact on the post closure assessment and on the safety functions of the natural barriers.

Of all these uncertainties, hydraulic conductivity of the bentonite has been rated with the highest score for its significance-for-safety (*Table 4*), and will be in detail analysed in the following.

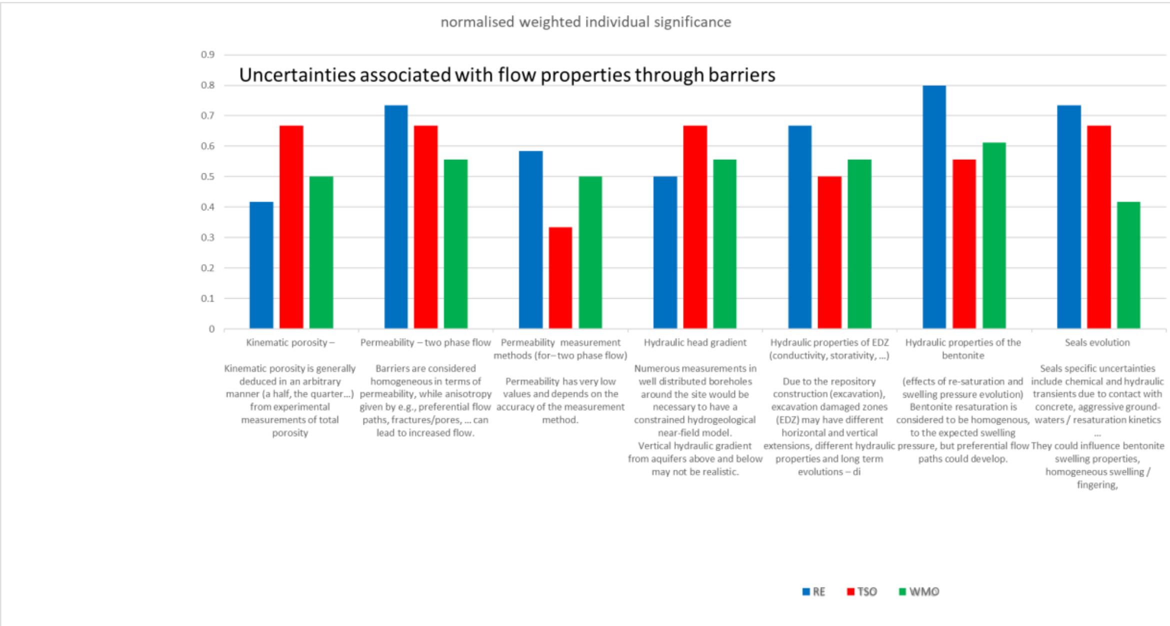

Figure 25. Significance for safety of uncertainties associated with flow properties through barriers

Table 4. Synopsis of the actors' views on uncertainties related to uncertainties associated with flow properties through barriers

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
		REs		TSOs		WMOs	Operational dose/risk	Post-closure dose/risk	Safety functions
Kinematic porosity – is generally deduced in an arbitrary manner (a half, the quarter…) from experimental measurements of total porosity	0.41	1m;3l;1n	0.0.67	1h; 1m; 1l;1n	0.5	1h; 1m; 4;1nl	2	8	4
Permeability – two phase flow – Barriers are considered homogeneous in terms of permeability, while anisotropy given by e.g., preferential flow paths, fractures/pores, … can lead to increased flow.	0.73	2h; 2m; 1l	0.67	1h; 1m;1l; 1n	0.55	4m; 2l;1n	2	10	8
Permeability measurement methods (for– two phase flow) - Permeability has very low values and depends on the accuracy of the measurement method.	0.58	3m; 1l; 2n	0.33	2l; 2n	0.5	3m; 3l;1n	2	10	5
Hydraulic head gradient - Numerous measurements in well distributed boreholes around the site would be necessary to have a constrained hydrogeological near-field model. Vertical hydraulic gradient from aquifers above and below may not be realistic.	0.50	2m; 2l;1n	0.67	1h; 1m; 1l;1n	0.55	1h; 2m; 3l;1n	3	8	2
Hydraulic properties of EDZ (conductivity, storativity, …) – Due to the repository construction (excavation), excavation damaged zones (EDZ) may have different horizontal and vertical extensions, different hydraulic properties and long term evolutions – different for different host rocks.	0.67	1h;2m;1l ;1n	0.5	1m'1l;2 n	0.55	1h;2m;3l ;1n	3	10	6
Hydraulic properties of the bentonite - (effects of re-saturation and swelling pressure evolution) Bentonite re-saturation is considered to be homogenous, to the	0.8	2h;3m;	0.55	2m;1l; 1n	0.61	2h; 1m; 3l, 1n	2	10	7

expected swelling pressure, but preferential flow paths could develop.									
Seals evolution - Seals specific uncertainties include chemical and hydraulic transients due to contact with concrete, aggressive ground-waters / re-saturation kinetics … They could influence bentonite swelling properties, homogeneous swelling / fingering, dry zones, preferential migration paths (gas flow / pressure build up, …) – which related hydraulic parameter uncertainty is acceptable?	0.73	2h;2m;1l	0.66	3m;1n	0.41	2m;1l;4n	3	8	11

The high level of significance **for REs**

… uncertainties in permeability are affecting re-saturation times and thus the time of functioning of the barriers under saturated conditions. However, in some sedimentary rocks, the permeability of the barriers is higher than the host rock, and in those cases the re-saturation is governed by the host rock properties. For gas migration, e.g. hydrogen, the issue of preferential pathways can be very important.

… the uncertainties in re-saturation times will probably not be significantly reduced until more good quality experimental data can be used to derive better conceptual models and numerical models (retention properties, relative permeabilities, which are very sensitive parameters, and treatment of preferential pathways)

… permeabilities for water and gas are very important to determine the hydro-mechanical state in the barrier and its evolution under repository conditions. If during re-saturation the plastic strain will occur, it will influence the porosity and permeability even after full re-saturation and thus impact the radionuclide transport

… much more systematic work is needed to build more confidence in the permeability values used in two-phase flow simulations (intrinsic and relative permeabilities). Uncertainties in this field will decrease with time when better equipment and more data is available.

… properties of the EDZ are important because it can act as a longitudinal or axial bypass of RN to engineered barriers, thus impacting the dose.

… of course such bypass can impact the safety function of the barriers put in place in tunnels with an EDZ

… current and future efforts in characterizing EDZ properties affected by THMC processes will reduce for sure this uncertainty over time

… these efforts might influence the hydraulic conditions for other engineered barriers (accessibility of water)

For TSOs,

… higher kinematic porosity leads to higher flows, and consequently to higher potential doses

… hydraulic head controls the flow in the near field, i. e. it affects the transport of radionuclides.

… hydraulic properties of EDZ can affect the flow in the near field, and the transport of radionuclides as well.

… saturation of near field as well as state of sealing controls the flow magnitude.

… models of material evolution/ durability (concrete) and erosion of bentonite risks (impacted by flow)

… their evolution is well based on testing, models. Evaluating alternative techniques and methods for sealing.

WMOs

… seals permeability impacts the disposal performance

… safety relevance mostly for gas phase

… the permeability of the host rock is a key parameter. It is significantly increased in the EDZ, but the self-healing properties of clay rocks allow to recover a low permeability. In seals, gas transfer helps to limit the post-closure gas pressure

… hydraulic head gradient must be low enough to limit hydraulic flow along galleries

… EDZ contributes to longitudinal pathway from disposal cells to the shafts. Its permeability decrease by self-healing is a key issue. Its extension is different around galleries performed parallel or perpendicular to the main strain direction

… hydraulic properties of the disturbed host rock (outside the zone affected by the alkaline plume) are well characterized. Uncertainties in Hydraulic properties of the EBS and of the part of the HR affected by the alkaline plume have a limited effect in the RS on radionuclide transport at the scale of the disposal system.

… permeability of the bentonite plug (mainly made of sand) must be low: it is a key parameter for the seals' performance.

Seals must let the gas pass in order to reduce the pressure during the post-closure hydraulic-gas period.

… gas pressure and alkaline plume from the tunnels could affect the long-term efficiency of the seals. This is controlled thanks to the design of the repository

… the design of seals still needs to be developed. The presence of seals is also not represented in models associated with the RS where it is assumed that transport through the host rock constitutes the most critical radionuclides pathway to the biosphere

As noticed by **all actors,** hydraulic conductivity of the barrier materials, EDZ and seals are important in ensuring the safety functions of the disposal system related to radionuclides immobilization, retention and slow release. A low hydraulic conductivity is important in limiting the water flow through the barrier, reducing the radionuclide transport rate.

REs and **WMOs** pointed out the importance of gas permeabilities and related hydro-mechanical stability within the near-field.

The uncertainty on flow properties through barriers will increase with time, as the near-field evolves. All actors indicate low significance during operational phase, but increased uncertainty and related impact on post closure phase and on the safety function, whereas REs and WMOs indicated generally a higher impact associated with the different flow properties through the barriers (*Figure 27*). Processes are coupled and parameters (evolution) difficult to measure, therefore additional modelling and scenario analyses are expected.

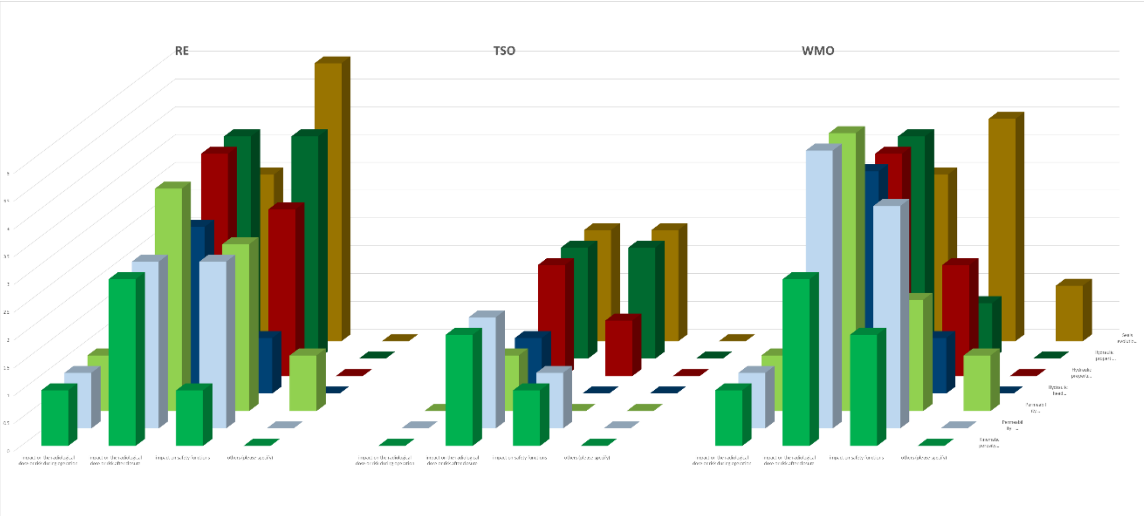

Figure 26 Actors views on impact for safety-significant uncertainties (topics 1-7, related to flow properties through barriers) on radiological dose/ risk during operation, on radiological dose/risk after closure, on safety functions or on other potential impact(s)

3.3.2 Uncertainties characterisation

There is a variety of methods which can be used for the uncertainty characterisation of flow properties through barriers (*Figure 27-33*). **REs, TSOs** and **WMOs** indicated statistical analysis of relevant/measured data, based on laboratory and in-field measurements, modelling and accuracy of measured data and detection limit as the most applied methods in uncertainty characterisation. Also quantification by expert judgement is used in some cases, whereas exclusion of poor quality / inappropriate data is rarely used. And again, preferences of different actors are not really seen.

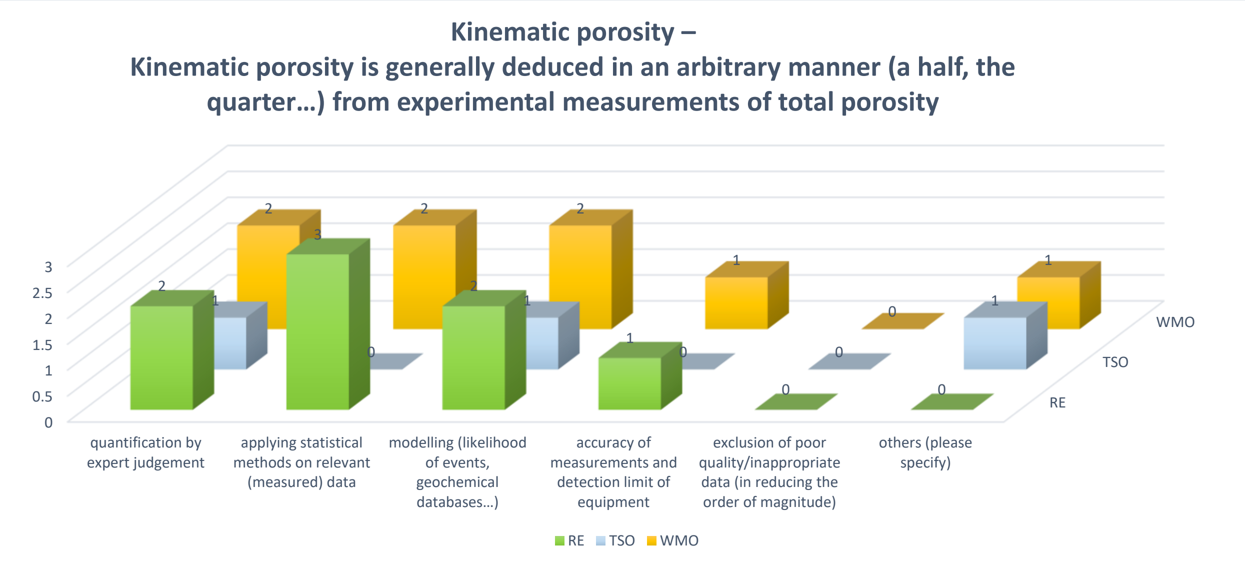

Figure 27. Actors' preferences in the characterisation of uncertainties associated with flow properties through barriers – kinematic porosity

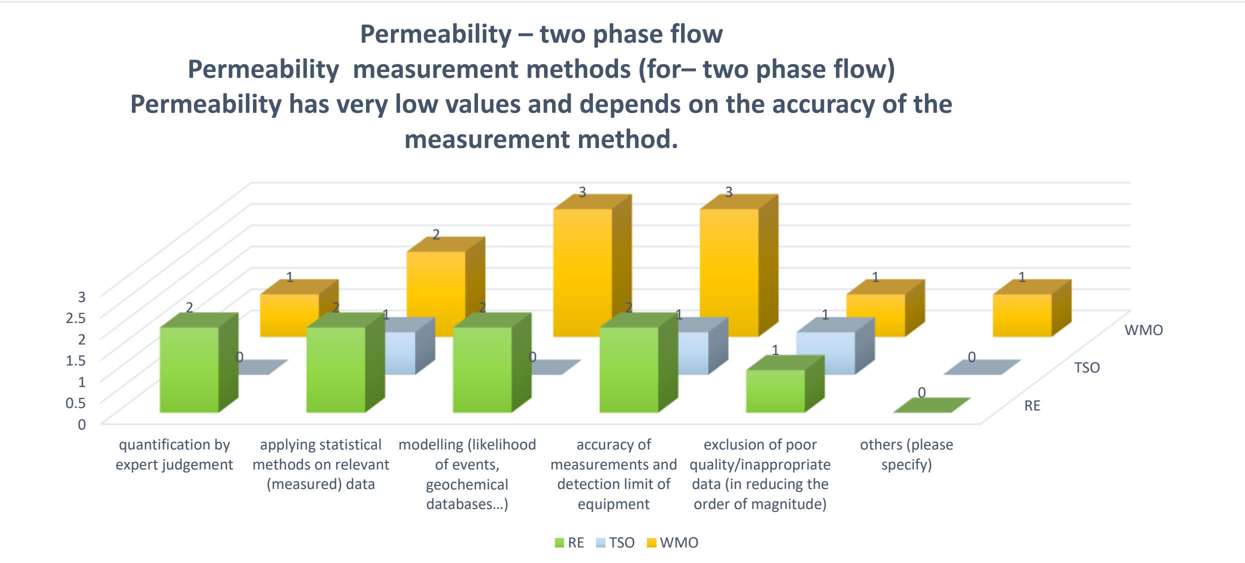

Figure 28. Actors' preferences in the characterisation of uncertainties associated with flow properties through barriers – two phase flow

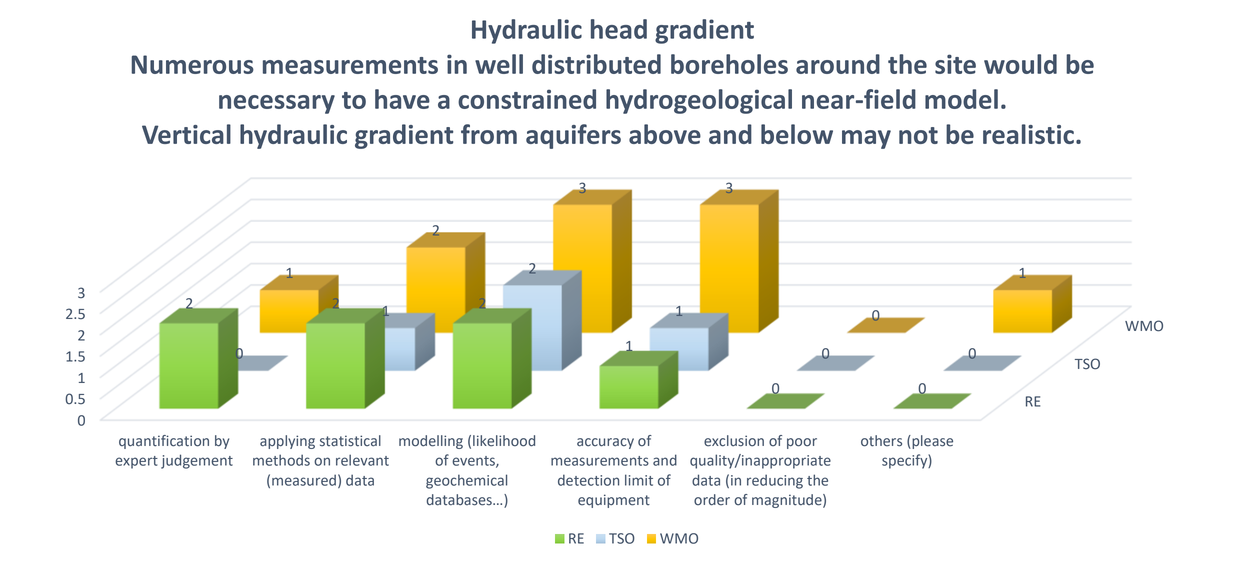

Figure 29. Actors' preferences in the characterisation of uncertainties associated with flow properties through barriers – hydraulic head gradient

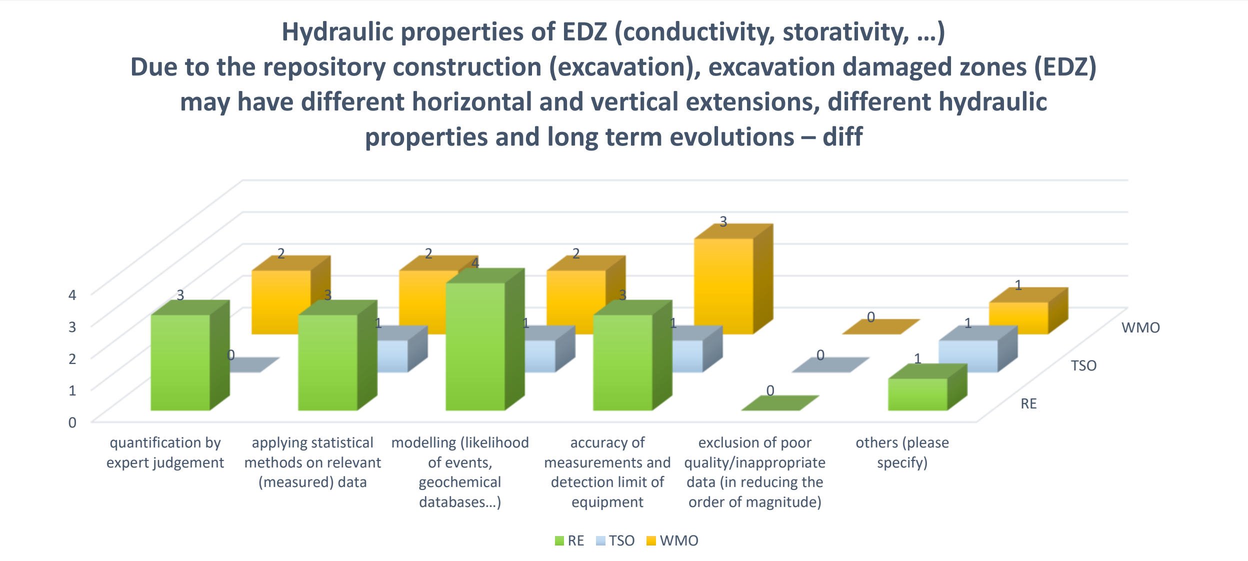

Figure 30. Actors' preferences in the characterisation of uncertainties associated with flow properties through barriers – hydraulic properties of EDZ

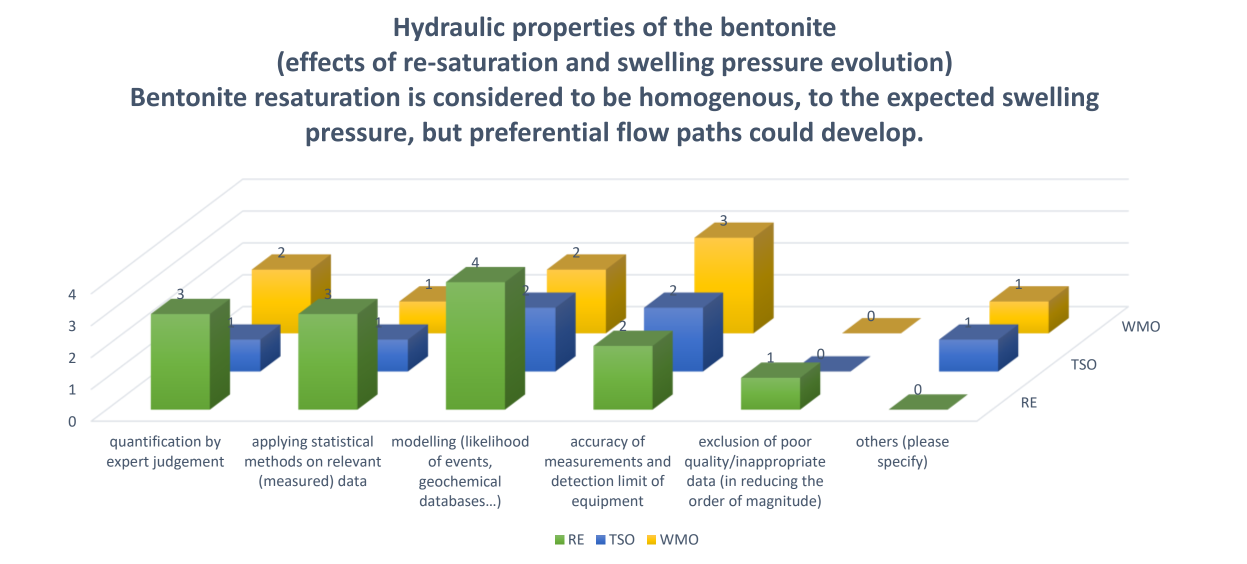

Figure 31. Actors' preferences in the characterisation of uncertainties associated with flow properties through barriers – hydraulic properties of bentonite

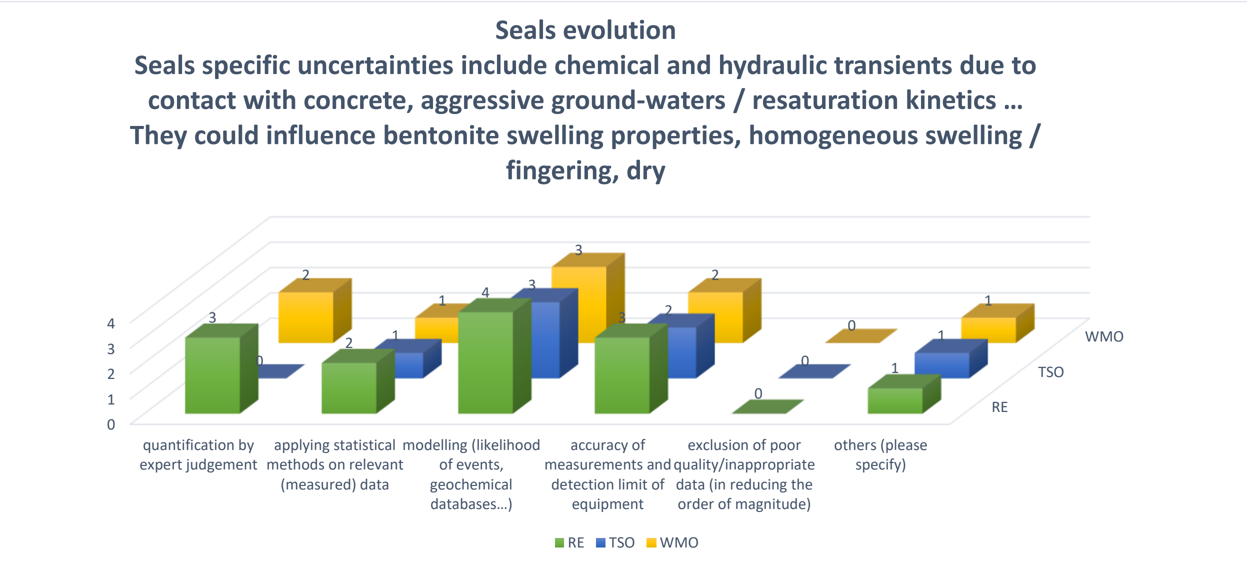

Figure 32. Actors' preferences in the characterisation of uncertainties associated with flow properties through barriers – seals evolution

3.3.3 Uncertainty evolution in time

The overall evolution of uncertainty of processes related to flow properties through barriers with time/programme phase shows this time a different picture than before. It seems that uncertainties decrease with progressing programme phase indicating a better understanding of involved processes (*Figure 34*). Initial high and medium significance change to medium and low significance during site characterisation phase. But again, replies are predominantly from actors being in the site evaluation phase and near-field uncertainties are not looked at in detail yet.

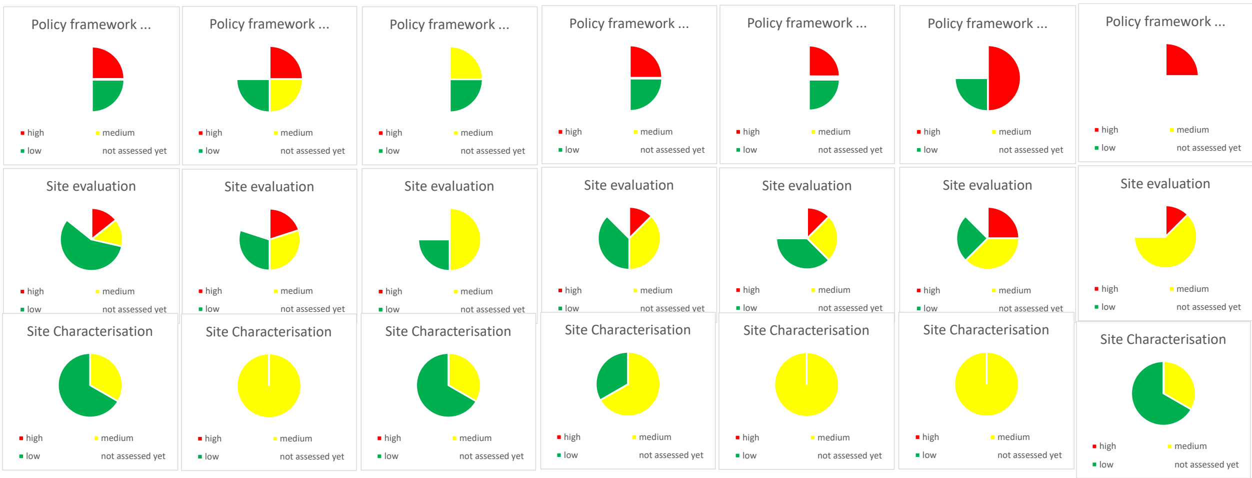

Figure 33. Actors' views on the evolution of uncertainties with time / programme phase associated with flow properties through barriers (for uncertainties see Figure 26 and Table 4 from left to right)

3.4 Uncertainties associated with mechanical properties of the barriers (D)

3.4.1 Significance for safety

The significance of uncertainties associated with mechanical properties of the barriers such as the mechanical behaviour of the EDZ or bentonite is shown in *Figure 35* and *Table 5* for the different actors. The mechanical integrity of the EDZ can depend on temperature dependent (near-field) material properties, on fractured material properties, plasticity, thermal hardening, evolution of interfaces / gaps between different materials (clogging or preferential migration paths), on time-dependent gas release (H_2, CO, …) and pressure build up. Similarly, the mechanical behaviour of the bentonite depends on homogeneity / heterogeneity of bentonite backfill emplacement, homogeneity / heterogeneity of re-saturation / water inflow, on potential gaps and displacements of waste canisters.

In the view of REs, the uncertainties related to mechanical properties of the barriers have always higher significance for safety than for TSOs. WMOs indicate low significance for safety for most topics; a few times with medium significance; also a high number of WMOs replies indicated not known/assessed yet (*Figure* 35 and *Table 5*).

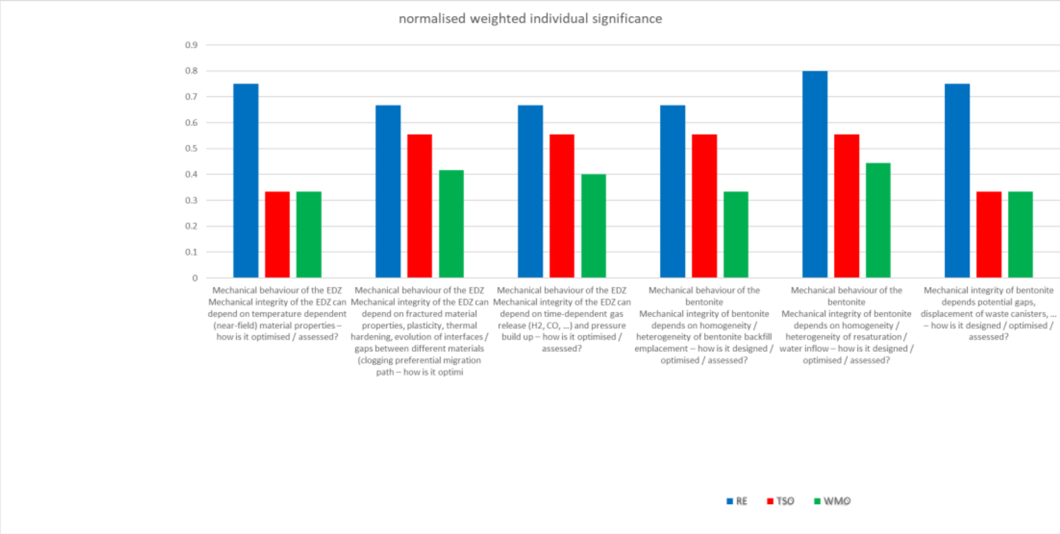

Figure 34. Significance for safety of uncertainties associated with mechanical properties of the barriers

Table 5. Synopsis of the actors' views on uncertainties related associated with mechanical properties of the barriers

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
		REs		TSOs		WMOs	Operational dose/risk	Post-closure dose/risk	Safety functions
Mechanical behaviour of the EDZ Mechanical integrity of the EDZ can depend on temperature dependent (near-field) material properties – how is it optimised / assessed?	0.75	2h; 1m; 1l;1n	0.33	3m; 1n	0.33	3l; 4n	5	6	5
Mechanical behaviour of the EDZ Mechanical integrity of the EDZ can depend on fractured material properties, plasticity, thermal hardening, evolution of interfaces / gaps between different materials (clogging preferential migration path – how is it optimised / assessed?	0.67	4m; 1n	0.56	1h; 2l; 1n	0.42	1m;3l; 3n	5	8	4
Mechanical behaviour of the EDZ	0.67	1h; 2m; 1l; 1n	0.56	1h; 2l; 1n	0.56	1m; 4l;2n	5	8	7

Mechanical integrity of the EDZ can depend on time-dependent gas release (H2, CO, …) and pressure build up – how is it optimised / assessed?									
Mechanical behaviour of the bentonite Mechanical integrity of bentonite depends on homogeneity / heterogeneity of bentonite backfill emplacement – how is it designed / optimised / assessed?	0.67	1h; 2m; 1l;1n	0.56	1h; 2l; 1n	0.33	3l; 4n	4	7	5
Mechanical behaviour of the bentonite Mechanical integrity of bentonite depends on homogeneity / heterogeneity of re-saturation / water inflow – how is it designed / optimised / assessed?	0.8	2h; 3m	0.56	1h; 2l; 1n	0.44	1m; 2l; 4h	3	9	8
Mechanical integrity of bentonite depends potential gaps, displacement of waste canisters, … – how is it designed / optimised / assessed?	0.75	1h; 2m; 2l	0.33	2l; 2n	0.33	3l; 4n	3	7	5

Replies to these topics of the questionnaire include also specific comments to uncertainties, their significance or temporal evolution, which are listed below according to the different actors:

REs noted that

… modelling in-situ pore water response, temperature with different constitutive models for rock behaviour might be important

… analysis of the potential of gas build-up, dissolution or consumption for different gas generation rates should be considered

… scenarios considering: limited/unlimited groundwater supply + technical voids or displacement of waste canister should be looked at

TSOs noted that

… if temperature limited to 90°C on the host rock, impact of temperature on EDZ is limited too

… mock-up experiments, EBS TaskForce, DECOVALEX modelling benchmark, international workshops / projects (FORGE, BEACON, EURAD…), small and large scale experiments (Sealex, VSeal…) for better understanding of these processes; experiment results and feedback are already available. Progress expected from the pilot phase and from long term in situ experiments to reduce uncertainties in the near-field

… EDZ is expected to self-seal quickly with the support of the liners. Otherwise, EDZ could e.g. increase the HLW-cells/drifts exchanges during the operational period, or decrease the effectiveness (short-circuiting) of the seals. In the very long term (when liners no longer support the rock and waiting for the backfill to assume this function), EDZ could impact sound rock thickness above the repository

… design improvements, in situ feedback experience, studies of long-term behaviour, etc. may reduce uncertainties

… bentonite mechanical behaviour related to bedrock shear displacement scenarios (earthquake) for granitic host rock could be “medium” risk, if this should be included here? Not a high risk, but this issue of bentonite stiffness should be considered (?). Waste canister displacement is not a risk (low).

WMOs noted that

… technological demonstrators are in operation

… the design allows to control the thermal phase and to limit the extension of the chemical disturbances. This ensures the absence of mineral degradation, especially at the level of the seals.

… other lab tests at different scales are ongoing

… the transient hydraulic-gas phase is important and thoroughly studied. It has low effect on the self-healing properties

… the already carried out large-scale tests will be completed by technological demonstrators carried out during the operation phase

… what-if scenarios that consider dysfunctionning sealing point out limited impacts, thanks to the location and the dead-end architecture

All the comments show that there is still some uncertainty associated with mechanical properties of the barriers, but a lot of activities are ongoing (experiments at different scales, demonstrators, options during constructions as well as complex modelling and related benchmarks) aiming at better process understanding and further reduction of uncertainties.

The evolution of uncertainties *associated with mechanical properties of the barriers* shows different trends for the three actors. While TSOs and WMOs replies indicated a decreasing impact of uncertainties with time / programme phase (except for WMOs for “mechanical behaviour of the EDZ - mechanical integrity of the EDZ can depend on time-dependent gas release (H2, CO, …) and pressure build up”, where an increase with time is indicated), the REs replies show predominantly increasing or at least constant impact with time / programme phase (*Figure 36*). The largest impact overall all repliers and programme phase seems to have the uncertainties on “*mechanical behaviour of the bentonite*”. Even so there has been already an EU project BEACON related to this topic. Altogether, it is expected that results from ongoing research, lab and field and demonstrator experiments will reduce the uncertainty associated with these topics.

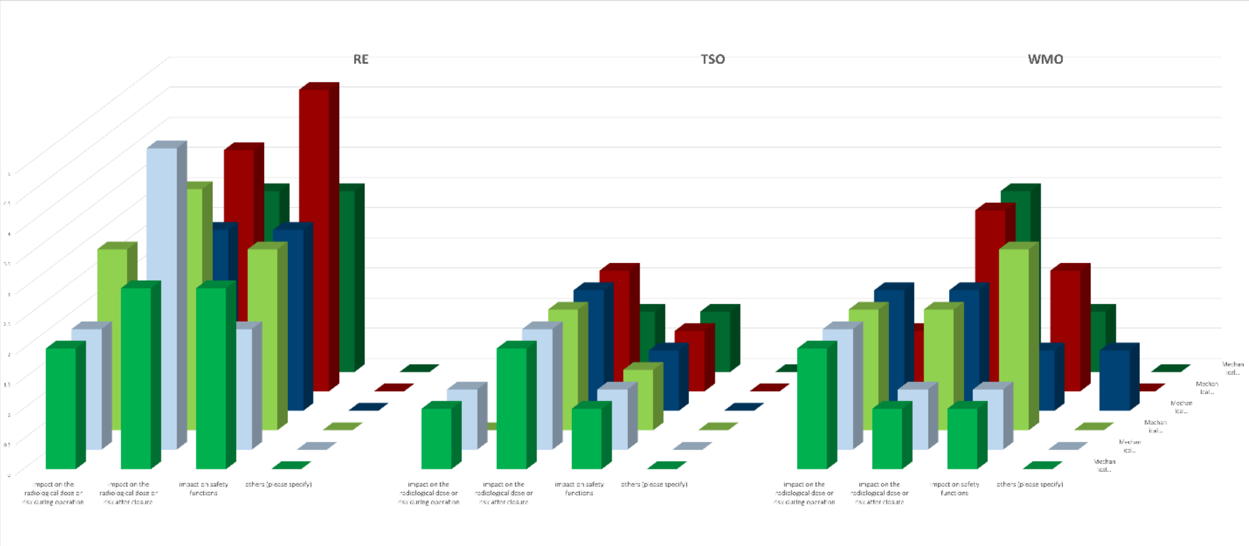

Figure 35. Actors views on impact for safety-significant uncertainties (topics 1-6, related to mechanical properties of the barriers) on radiological dose/ risk during operation, on radiological dose/risk after closure, on safety functions or on other potential impact(s)

3.4.2 Uncertainties characterisation

Methods mostly used in the EDZ and bentonite uncertainties characterisation by all actors are: modelling, use of the accuracy and detection limits, statistical methods and quantification by expert judgement (see

Figure). No general trend for preferences of individual actors could be identified, except maybe that REs often indicated expert judgement; however; this might be a consequence of the relative low number of replies to the characterisation methods questions.

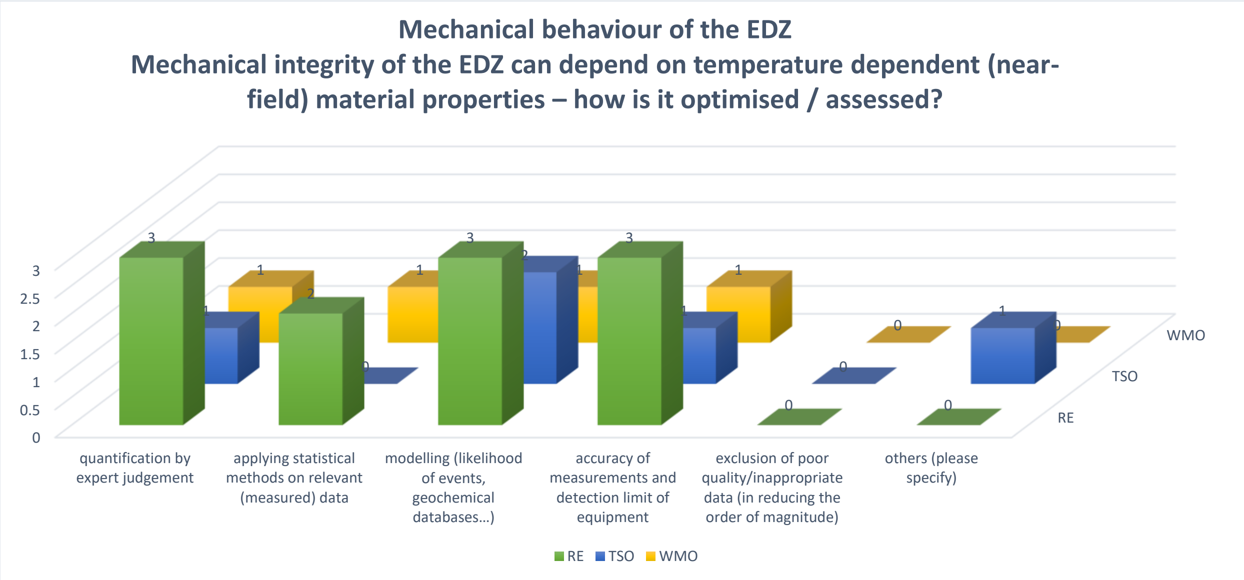

Figure 36. Actors' preferences in the characterisation of uncertainties associated with mechanical properties of the barriers – topic 1

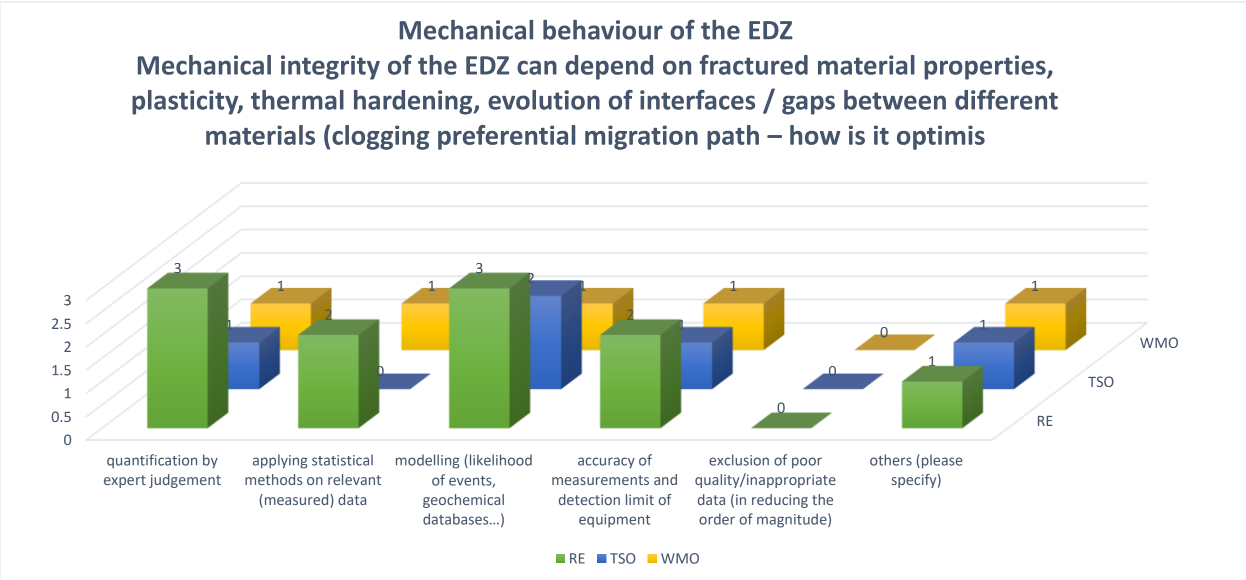

Figure 37. Actors' preferences in the characterisation of uncertainties associated with mechanical properties of the barriers – topic 2

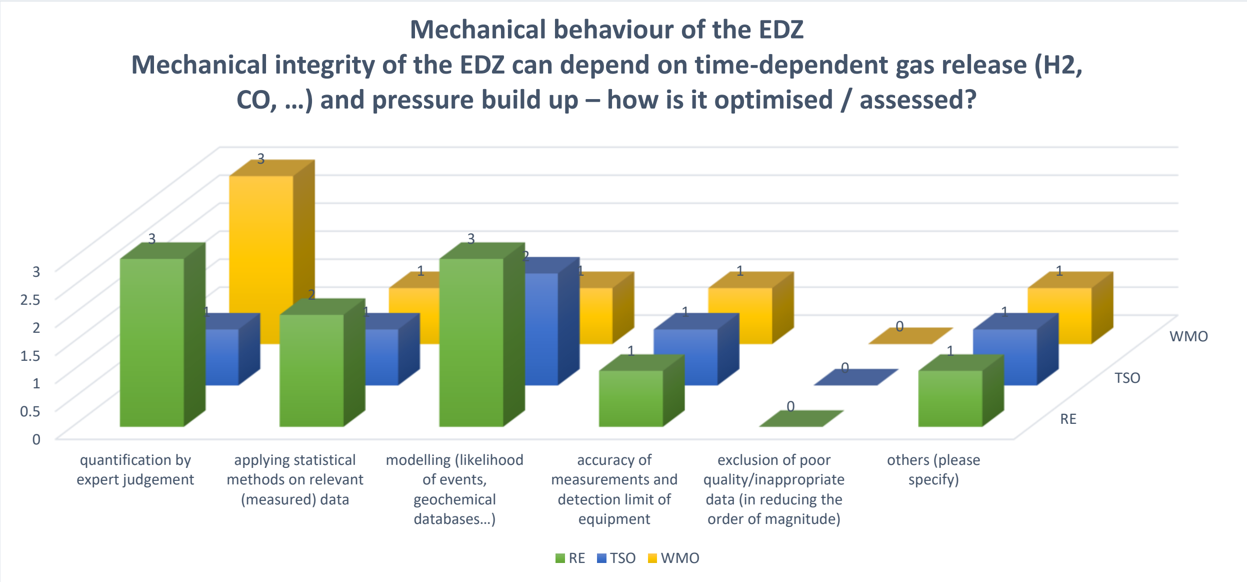

Figure 38. *Actors' preferences in the characterisation of uncertainties associated with mechanical properties of the barriers – topic 3*

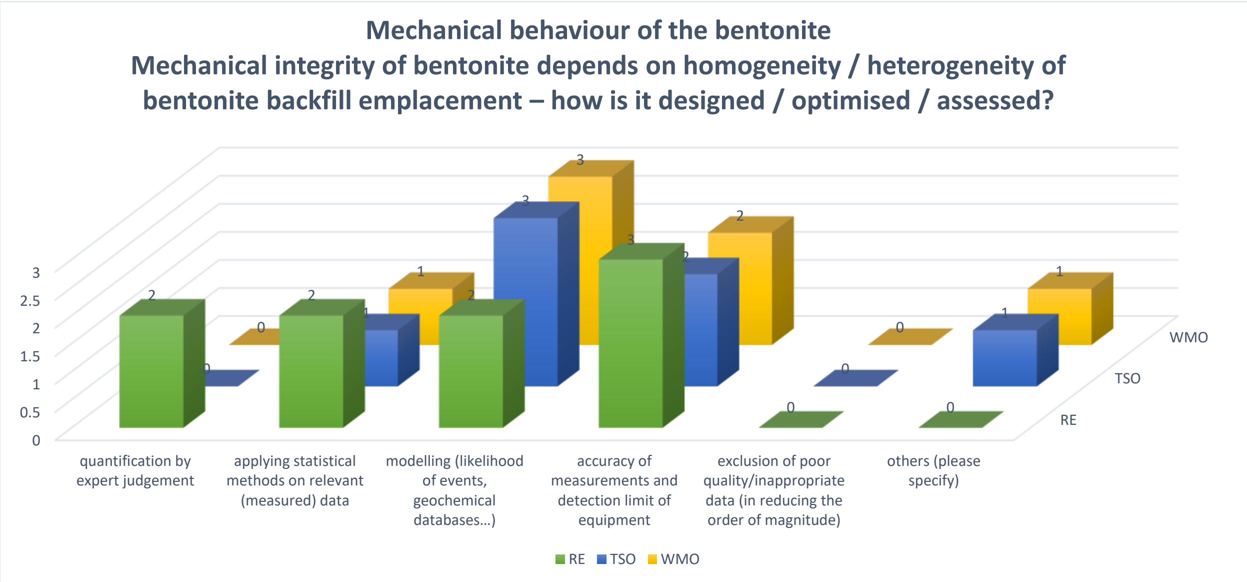

Figure 39. Actors' preferences in the characterisation of uncertainties associated with mechanical properties of the barriers – topic 4

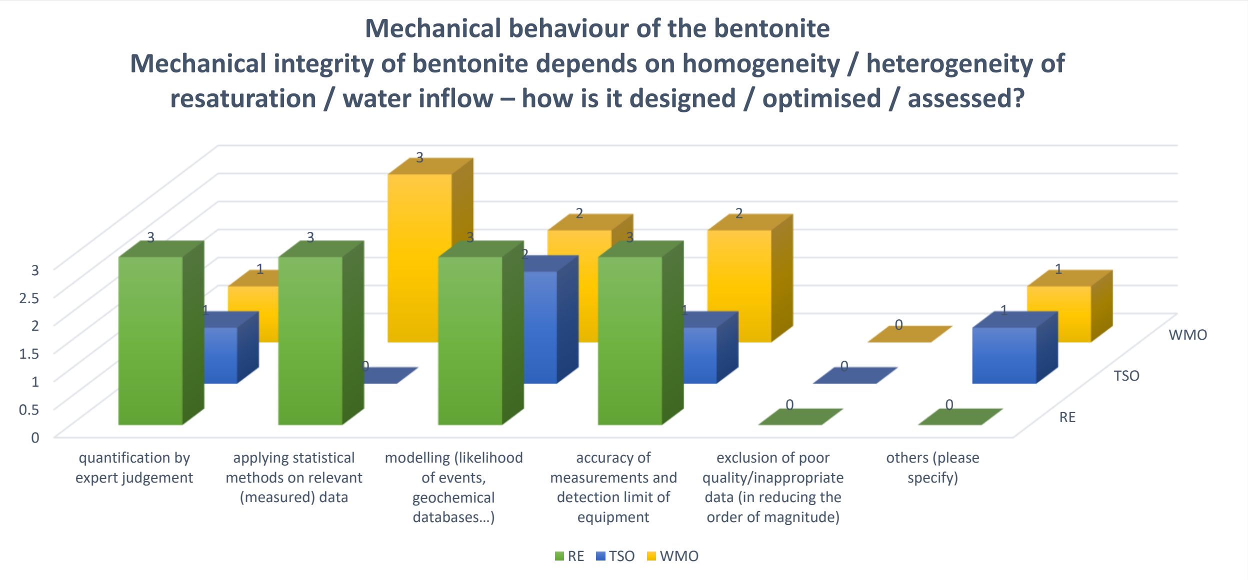

Figure 40. Actors' preferences in the characterisation of uncertainties associated with mechanical properties of the barriers – topic 5

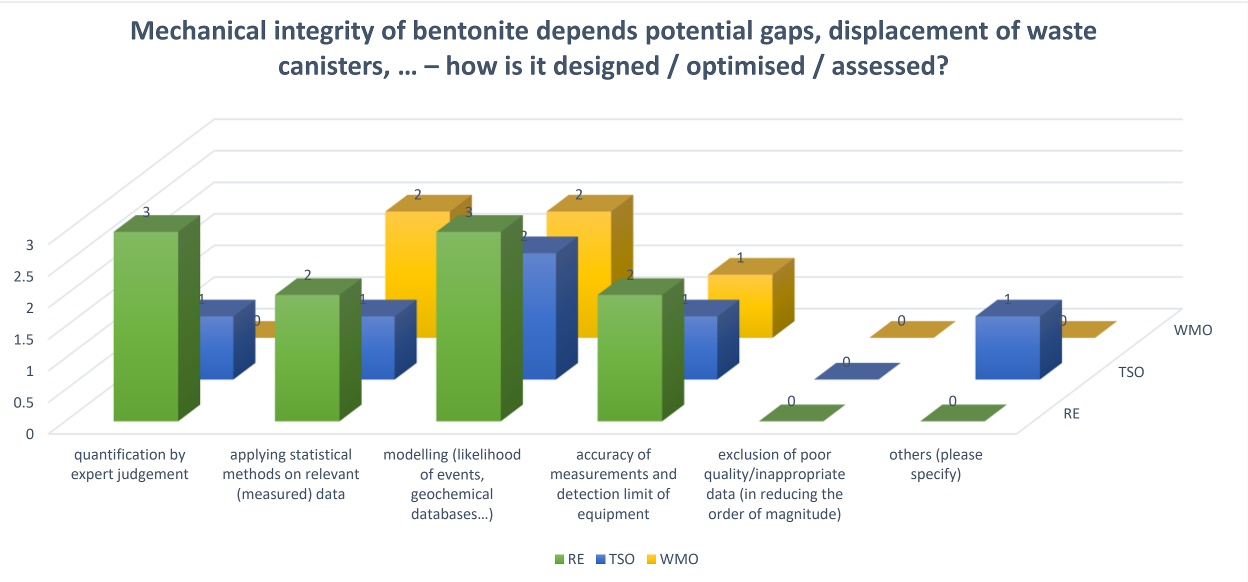

Figure 41. Actors' preferences in the characterisation of uncertainties associated with mechanical properties of the barriers – topic 6

3.4.3 Uncertainty evolution in time

The overall evolution of the uncertainties associated with processes related to mechanical properties of the barriers with time/programme phase does not show a clear trend (*Figure 43*); there are high significance uncertainties for each of the 3 phases considered. For some topics such as "mechanical integrity of bentonite”, the uncertainties seem to decrease (more green from top to bottom, for others such as “mechanical behaviour of the EDZ” or “mechanical behaviour of the bentonite”, it is the opposite – more red from top to bottom (*Figure 43*). Also here, replies are predominantly from actors being in the phase of site evaluation and near-field uncertainties are not looked in detail yet.

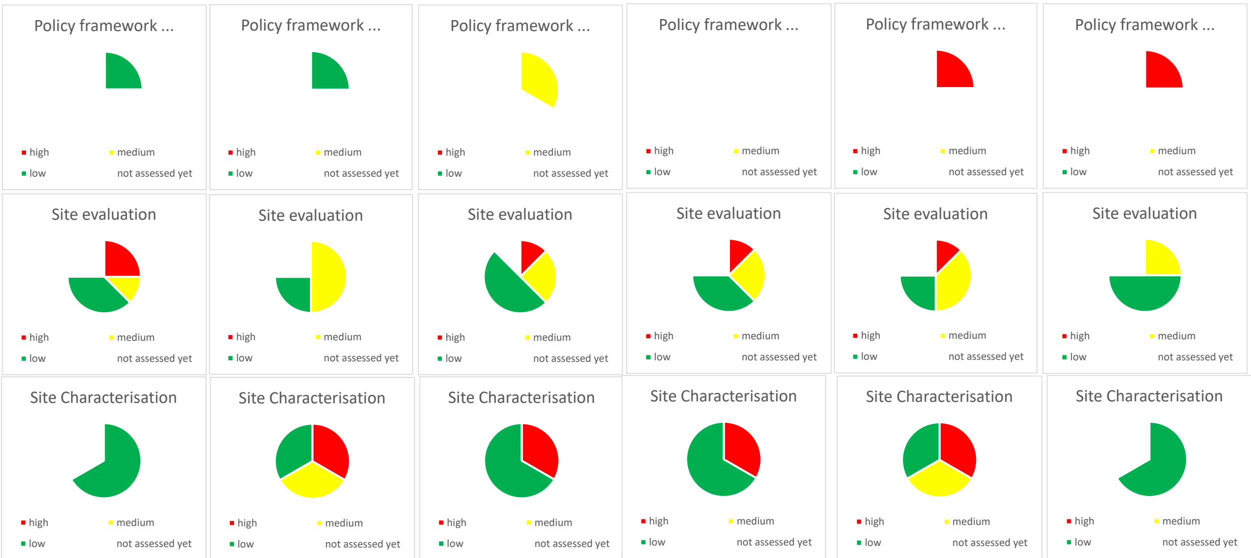

Figure 42. Actors' views on the evolution of uncertainties with time / programme phase associated to mechanical properties of the barriers (for uncertainties see Figure 35 and Table 5 from left to right)

4. Uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers (II)

The concept for waste package and technical barriers is influenced by the waste type, the type of host rock and the depth of the repository. Different waste types, Spent Fuel or vitrified waste may need different container materials or thicknesses for different host rocks due to unwanted canister degradation, gas production and/or canister lifetime requirements for different host rocks. First group of uncertainties (chapters 3.1 to 3.4) are associated with the extension of an EDZ during excavation (excavation method, speed…) and during operation, depending on the ambient air conditions (moisture, temperature) resulting from the ventilation and on the conception of retaining walls. Here, uncertainties are addressed with respect to different concepts of waste packages and technical barriers and their interplay (3rd questionnaire), which are listed below as a reminder and for a better identification of the in detail explained topics within the figures, where they are nearly not readable:

- Metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different barriers (waste package, liners…). Lifetime, gas generation and pressure build-up, other degradation processes, pH-, Eh-evolution, pit corrosion, colloid formation (continuous or step functions?).
- Interface processes may occur at different time scales and with varying spatial extension. Pore clogging and no further gas transport might be a serious problem in tight host rocks (clays), at bentonite-crystalline, or cement-bentonite interfaces. How is the influence on RN transport conceptualised? How are specific designs optimised to prevent unwanted processes? How are the remaining uncertainties assessed/limited? Clogging – pressure build-up – may induce integrity problems. Matrix sealing may induce reduced RN retardation. …
- Extent of EDZ, geometry and opening of fractures - These parameters are influenced by the operation conditions (moisture, temperature of ambient air)
- Concrete parameters and associated processes used in near-field conceptualisation - Carbonation processes during operational phase and re-saturation phase could have an impact on mechanical parameters
- Alternative conceptual models of solute diffusion in the near-field:
    - The single interlayer-porosity Donnan equilibrium model
    - The electrochemical model based on the Nernst-Planck Eq.
    - The multiple porosity (interlayer, double layer, free) model.
    - The use of different effective diffusion coefficients for each chemical species while preserving charge balance.
    - Fracture-matrix or equivalent porous medium?
    - Conceptual diffusion models i-v yield different De, with different uncertainties. Which concept for RN transport and/or major ion transport (near-field evolution)? Which concept is the less uncertain? Consistent concepts?
- Coupling influences - In performance assessment, near-field evolution calculations and RN transport calculations are not coupled. For RN transport calculations, stepwise (spatial, temporal) constant transport parameters are assumed. Is this concept valid? Which uncertainties are accompanied /neglected/? Is it valid to choose “conservative values” in case of non-linearly coupled processes and long time scales?
- Monitoring influences - uncertainties associated with installation of monitoring equipment and potentially induced pathways

4.1.1 Significance for safety

The significance of uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers shows two different patterns related to the significance identified by the different actors.

For the first 3 topics REs, TSOs and WMOs identified the significance decreasing with series of actors, while the second significance pattern for topics 4 to 7 shows highest significance for REs, lowest significance for TSOs and high significance for WMOs (*Figure 44* and *Table 6*), where REs indicated always the highest significance among all actors and the topic “metallic material behaviour” yield the highest uncertainty by all actors. Only for the topic “concrete parameters and associated processes used in near-field conceptualisation - Carbonation processes during operational phase and re-saturation phase could have an impact on mechanical parameters”, WMOs rated with the highest significance among all actors; for all other topics REs indicated highest significance. There seems to be no correlation of uncertainty significance with type of host rock.

In addition to the quantification of significance given by the different actors, their specific concerns are as follows:

REs noted that

… more dedicated experimental work using proxies or industrial analogues could help reducing the uncertainties and better constrain the modelling of interfacial processes in the future.

… this is important especially for mechanistically describing how solute diffusive properties can evolve over time due to coupled processes. It is on the other hand not so important for 'static' predictions with a fixed value, since the different conceptual models will be fitted prior to their use with the same experimental data to predict similar diffusive fluxes, with some exceptions

… reducing uncertainties in these coupling influences could be quite relevant to reduce conservatism and optimize repository design to comply with low dose requirements. At the moment, there are a lot of uncertainties in this field related to interfacial processes, role of sustained unsaturated conditions on diffusion of RNs, temperature dependent transport properties, coupling RN transport with chemical conditions and evolution of near-field

TSOs noted that

… life time of canister affects the release rate

… instant release strongly affects the transport

… improved knowledge on copper corrosion and hydrogen impact to canister properties (linked with sulphur interaction). Expect improving with time (testing, modelling, material science).

… potential transport pathways are present in EDZ and carbonization could lead to creation of potential transport pathways.

… transport pathways in models are affected

… realistic models shall be used in relevant measure for transport evaluation

… verification of estimated transport pathways is necessary

… remember that final repository safety should not rely on active monitoring requirement, thus this is insignificant

MWOs noted that

… metallic behaviour has a direct impact on the time at which RN release in the disposal system starts

… transient H_2 pressure is important and initial EDZ (extension, connectivity) is likely to contribute to its evolution.

… concrete recipes must be defined in order to minimise geochemical perturbations

… safety function of the concrete buffer protecting the containment function of the canister by ensuring favourable chemical conditions is important

… coupling influences such as temperature dependence are important. Coupling processes such as osmosis or thermo-diffusion are known to have very low influence

… monitoring programme not developed yet. However, the regulatory authority requires that operations and activities in the context of monitoring should in no case compromise the performance of the disposal system. These uncertainties will therefore be avoided and/or minimized at all phases.

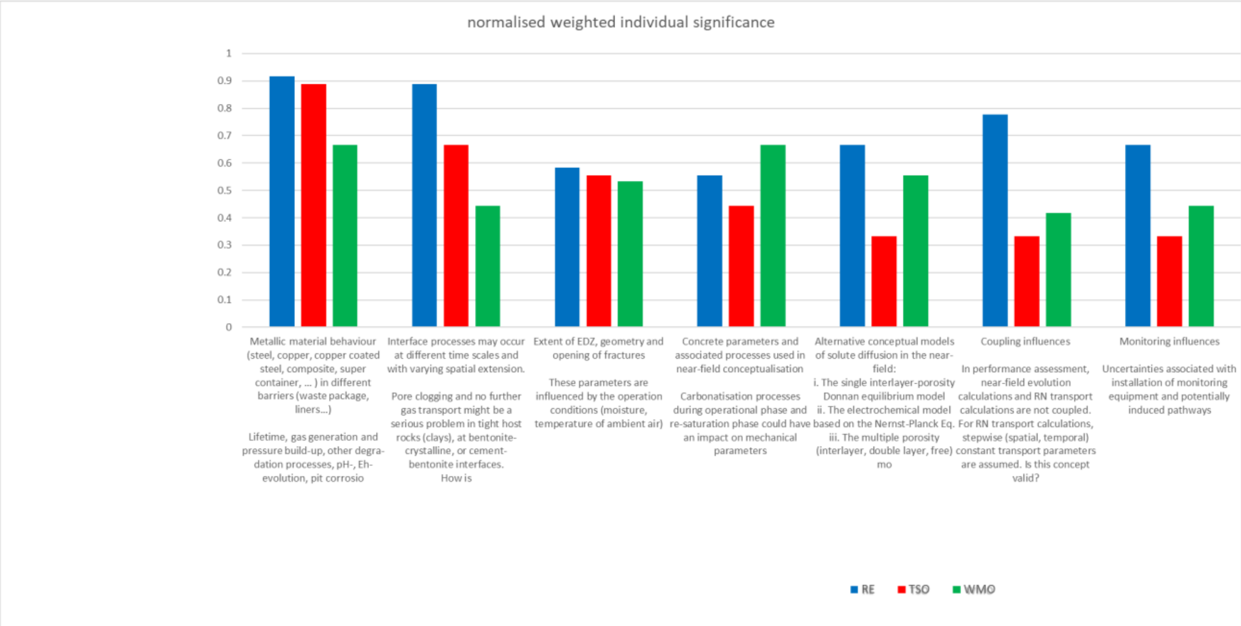

Figure 43. Significance for safety of uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

Table 6. Synopsis of the actors' views on uncertainties related to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
		REs		TSOs		WMOs	Operational dose/risk	Post-closure dose/risk	Safety functions
Metallic material behaviour (steel, copper, copper coated steel, composite, super container, ...) in different barriers (waste package, liners...) Lifetime, gas generation and pressure build-up, other degradation processes, pH-, Eh-evolution, pit corrosion, colloid formation (continuous or step functions?)	0.73	3h; 1m; 1n	0.67	2h; 1m; 1n	0.46	2h; 1m; 2l; 2n	5	10	9
Interface processes may occur at different time scales and with varying spatial extension.	0.53	2h; 1m; 2n	0.33	1h; 1l; 2n	0.19	1m; 2l; 4n	3	7	4

Pore clogging and no further gas transport might be a serious problem in tight host rocks (clays), at bentonite-crystalline, or cement-bentonite interfaces. How is the influence on RN transport conceptualised? How are specific designs optimised to prevent unwanted processes? How are the remaining uncertainties assessed/limited? Clogging – pressure build-up – may induce integrity problems. Matrix sealing may induce reduced RN retardation. …									
Extent of EDZ, geometry and opening of fractures These parameters are influenced by the operation conditions (moisture, temperature of ambient air)	0.46	3m; 1l; 2n	0.41	2m; 1l; 1n	0.38	1h, 1m; 3l;2n	6	6	5
Concrete parameters and associated processes used in near-field conceptualisation Carbonation processes during operational phase and re-saturation phase could have an impact on mechanical parameters	0.33	2m; 1l; 2n	0.33	1m; 2l; 1n	0.28	2m; 2l; 3n	5	4	3
Alternative conceptual models of solute diffusion in the near-field: i. The single interlayer-porosity Donnan equilibrium model ii. The electrochemical model based on the Nernst-Planck Eq. iii. The multiple porosity (interlayer, double layer, free) model. iv. The use of different effective diffusion coefficients for each chemical species while preserving charge balance. v. Fracture-matrix or equivalent porous medium?	0.4	1h; 1m; 1l; 2n	0.16	2l; 2n	0.23	1h; 2l;4n	3	6	4

Conceptual diffusion models i-v yield different De, with different uncertainties. Which concept for RN transport and/or major ion transport (near-field evolution)? Which concept is the less uncertain? Consistent concepts?									
Coupling influences In performance assessment, near-field evolution calculations and RN transport calculations are not coupled. For RN transport calculations, stepwise (spatial, temporal) constant transport parameters are assumed. Is this concept valid? Which uncertainties are accompanied /neglected/? Is it valid to choose "conservative values" in case of non-linearly coupled processes and long time scales?	0.4	1h; 1m; 1l;2n	0.16	2l; 2n	0.19	1m; 2l; 4n	4	8	2
Monitoring influences Uncertainties associated with installation of monitoring equipment and potentially induced pathways	0.50	4n; 2m; 2l	0.67	1h; 1n; 1l	0.73	3h, 2l;2n	3	4	2

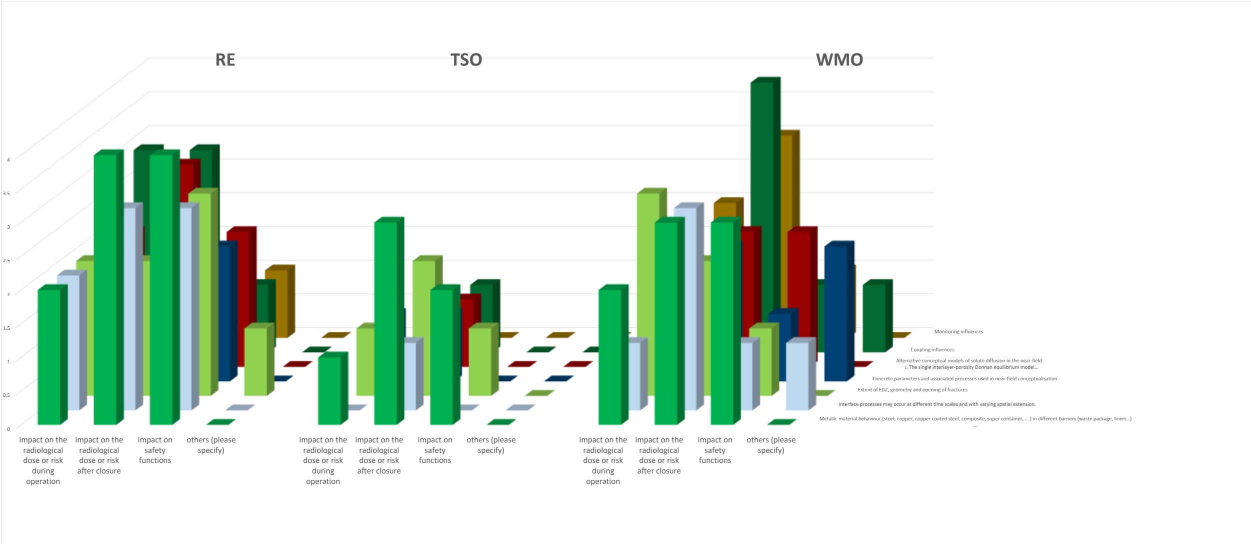

Figure 44. Actors' views on impact for safety-significant uncertainties (topics 1-7, related to conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers) on radiological

dose/ risk during operation, on radiological dose/risk after closure, on safety functions or on other potential impact(s)

The actors views on impact of safety-significant uncertainties associated with conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers is shown in Figure 45. Generally, there is an increasing impact depending on the actual implementation phase of the individual replier from "during operation" to "after closure" and then staying at high level with respect to impact on "safety functions", a trend, which is the same for all actors.

4.1.2 Uncertainties characterisation

No preferred method for characterisation of uncertainties related to conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers can be identified (*Figures 46 - 52*). Modelling seems to be slightly ahead of other methods and exclusion of poor data is at the end of characterisation methods of the different actors.

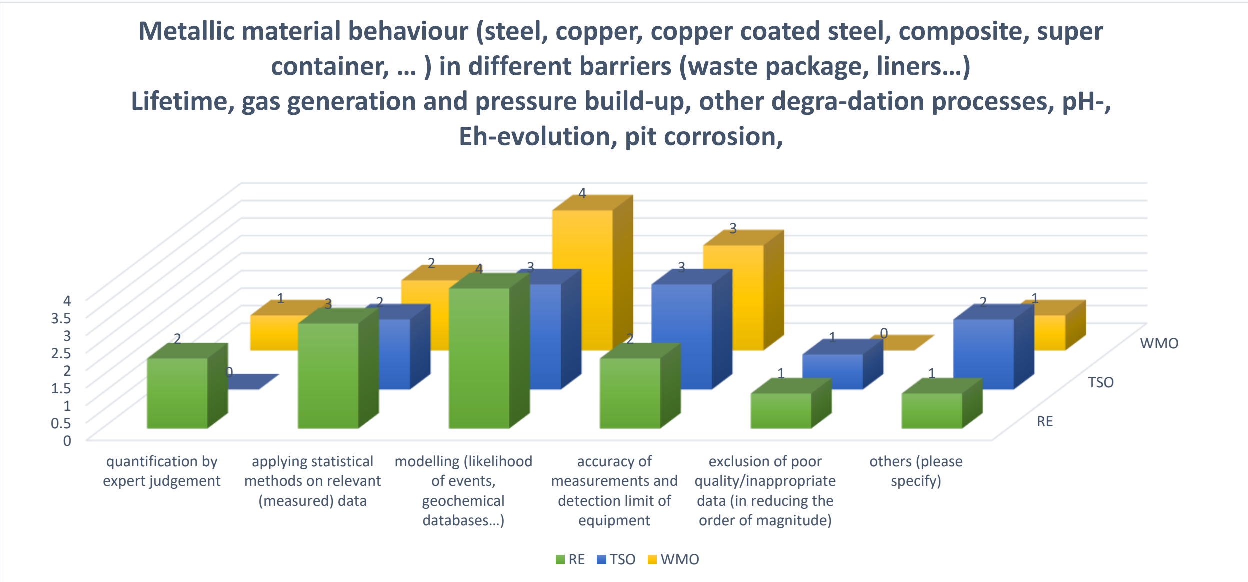

Figure 45. Actors' preferences in the characterisation of uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

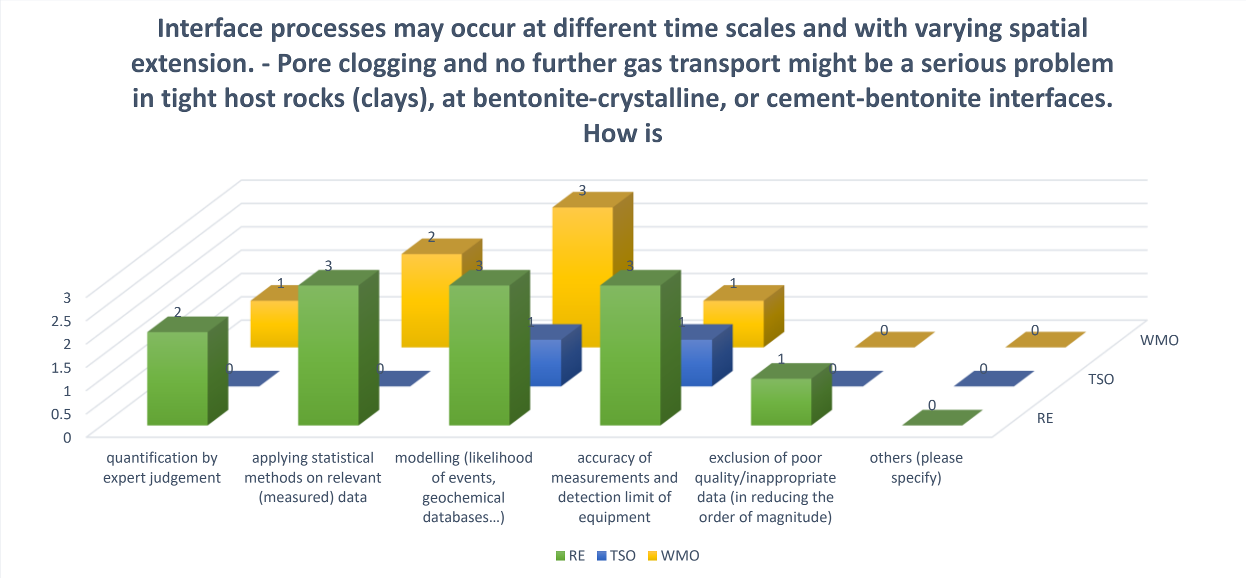

Figure 46. Actors' preferences in the characterisation of uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

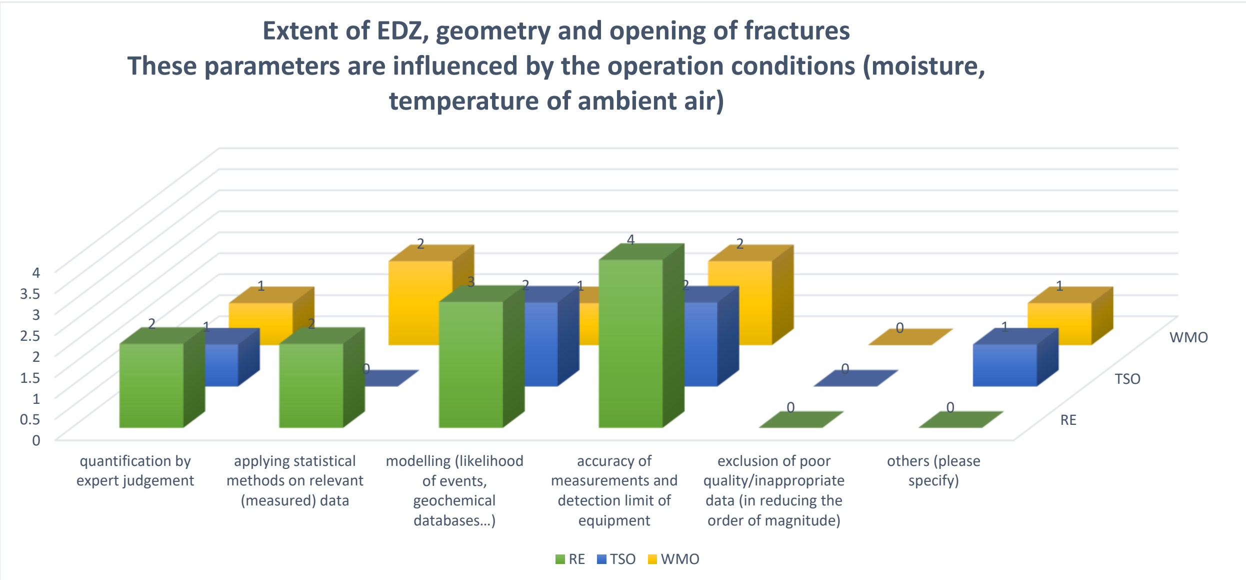

Figure 47. Actors' preferences in the characterisation of uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

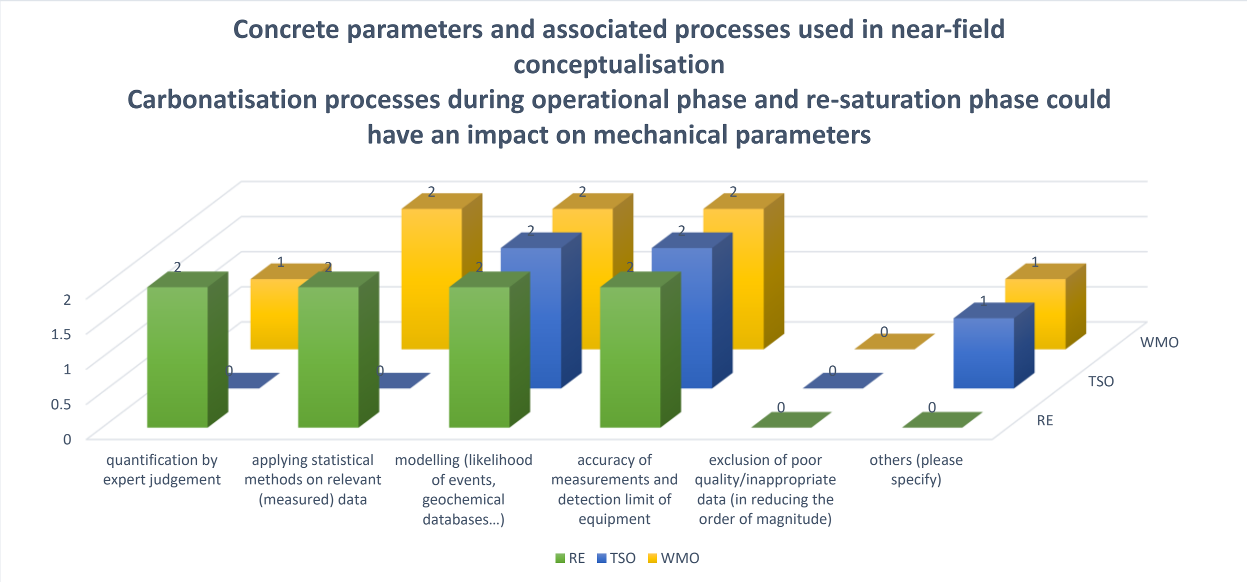

Figure 48. Actors' preferences in the characterisation of uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

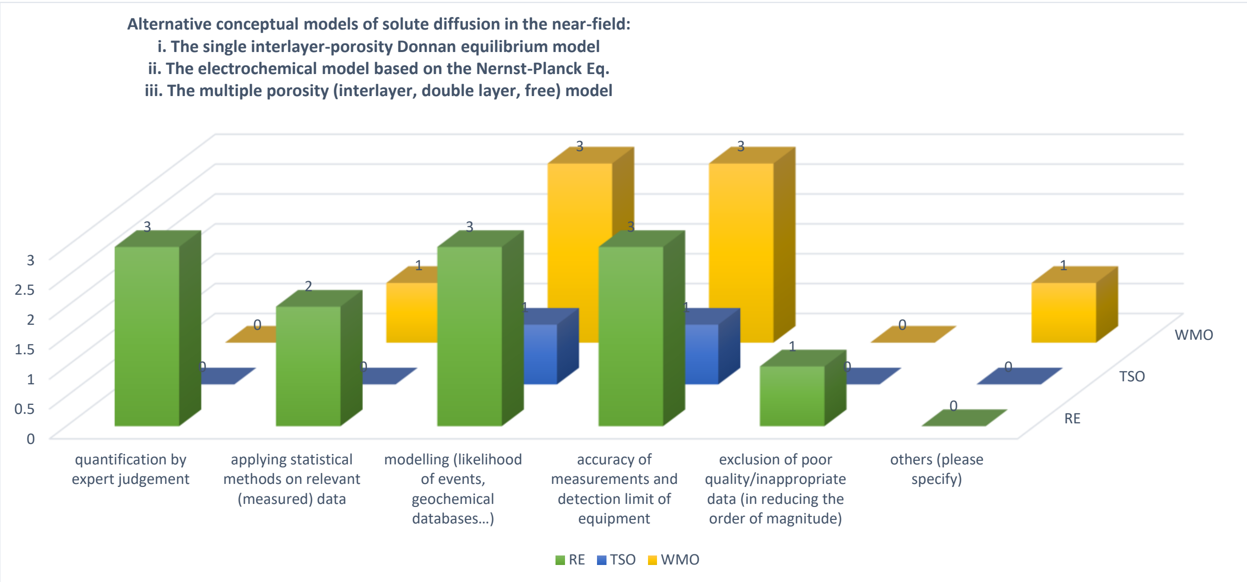

Figure 49. Actors' preferences in the characterisation of uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

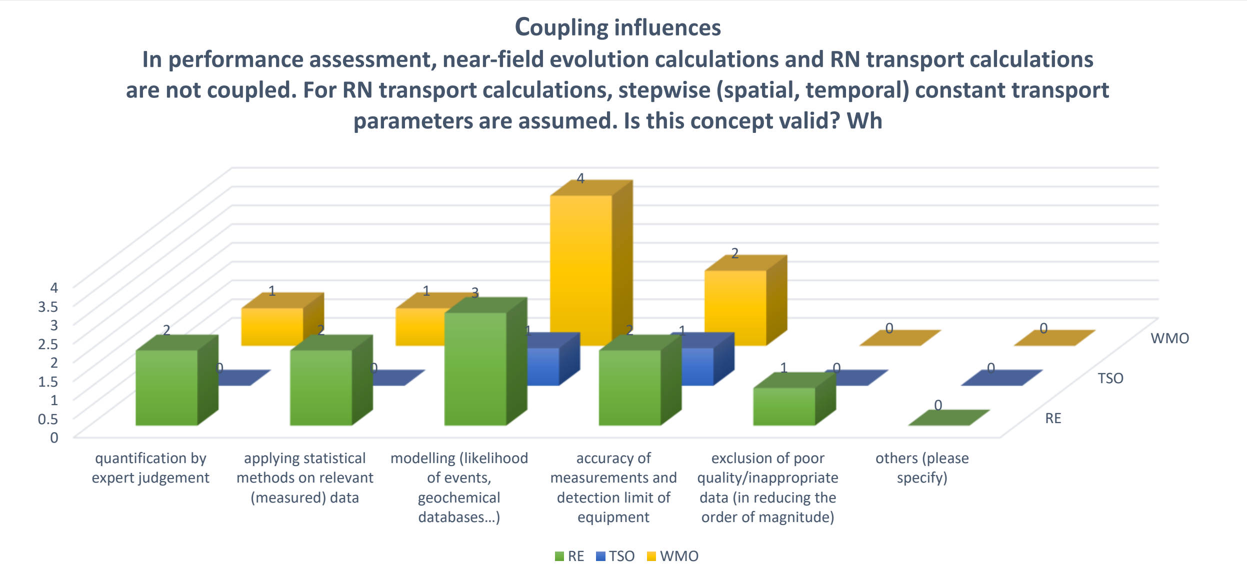

Figure 50. Actors' preferences in the characterisation of uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

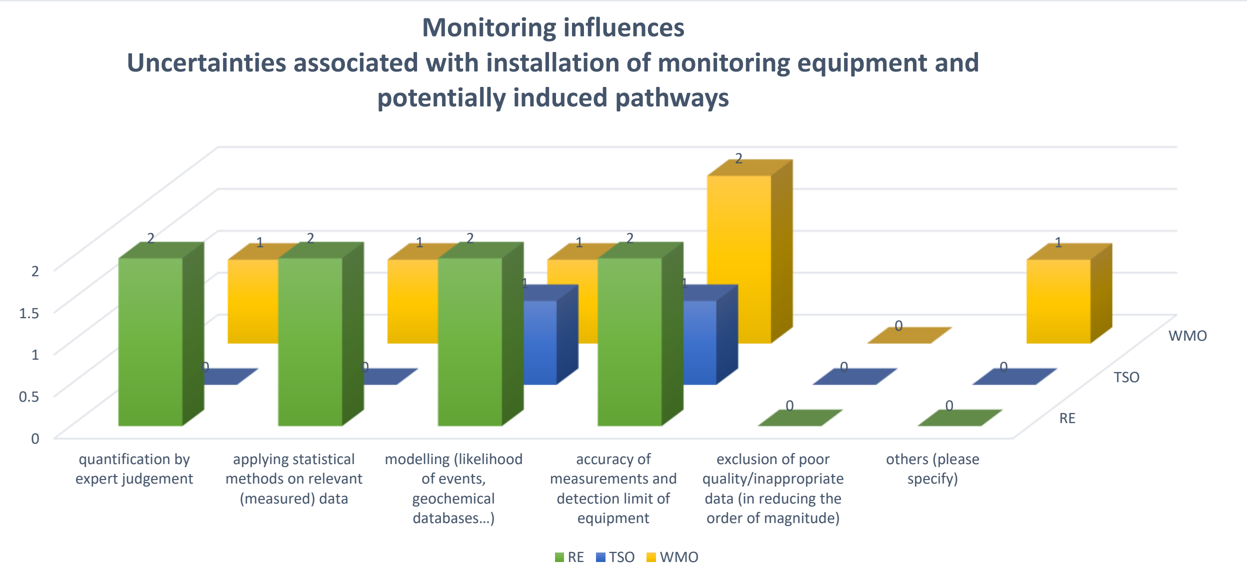

Figure 51. Actors' preferences in the characterisation of uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

4.1.3 Uncertainty evolution in time

The overall evolution of significance of uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers with time/programme phase does not show a clear trend (*Figure 53*); there are again high significance uncertainties for each of the 3 phases considered. For topics like “metallic material behaviour …”, “extent of EDZ …” or “ concrete parameters …”, the uncertainties seem to decrease (more green from top to bottom, whereas for “interface processes …” and “coupling influences …”, it is the opposite – more red/yellow from top to bottom (*Figure 53*). Also here, replies are predominantly from actors being in the site evaluation phase and near-field uncertainties are not looked at in detail yet.

Figure 52. Global uncertainties evolution related to conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers along the disposal programme phases (for uncertainties see Figure 44 and Table 6 from left to right)

5. Uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems (III)

The description of the heterogeneous near-field with respect to materials, hydraulics, mechanics, chemistry, microbes and radiation needs a lot of equations describing all the processes in such a system. Several of these processes are strongly coupled due to nonlinear dependence on parameters influenced by different processes. The processes might be dominating at different time scales, e.g., temperature during the first 1000 years, re-saturation up to 10000 years or more, chemical degradation/ reaction fronts up to more than 100000 years. Also, the extent, duration and importance of each of these processes (taken individually even without accounting for their influence on each other) are also subject to uncertainty. A decoupled description of processes induces uncertainties on a correct system description with respect to evolution of the near-field and evolution of transport parameters in the near-field. Another issue is the model description with reduced dimensionality – 1D instead of 3D spatial distribution – together with constant or partly constant parameters with time due to the lack of sufficient computer performance.

In more detail, the evolution of the accessible porosity, which will change due to reactive transport processes and the strong (geo-) chemical gradients between barrier and host rock porewater compositions, has an influence on the RN flux. Similarly, the evolution of diffusion coefficient De, which will change due to temperature evolution, porosity changes (mineral reactions). Also, the evolution of partition coefficient Kd, which will change due to porosity changes (mineral reactions) degradation/reaction fronts (canister corrosion) changes of mineral surface areas and/or changes in pH, Eh, together with competitive sorption reactions among RN and other degradation products, e.g., from canister corrosion, influence RN migration and include uncertainties, which should be quantified. Temperature has an influence on dissolution and precipitation of mineral phases (thermodynamic and materials data) and influences transport parameters evolution in the near-field.

The often used 1D RN transport modelling/prediction in performance assessment analyses includes a lot of assumptions / uncertainties – would there be a reduction of uncertainties by using 4D simulations? Here a direct comparison is difficult to perform because of long computational times in 4D, however, how can these simplifications be confirmed? In addition, near-field evolution and RN transport are often separated in performance assessment analyses, i.e., near-field evolution is used for (stepwise) constant transport parameters used for separate RN migration calculations, not taking into account competitive sorption reactions. This could be a source for large uncertainty.

Multiphase flow is a further complex coupled process in the near-field as for example the complex porosity structure of the bentonite which requires the use of dual or triple continuum models includes already model uncertainty, whereas parameter uncertainty comes along with retention curves of bentonite (and other buffer materials and host rock) having different gas entry pressure, hysteresis and temperature dependence.

So far, there is no preference/necessity for coupled description of near-field processes, also there is no favourable ranking/importance of T+H+M+C+B+R processes. Often “conservative assumptions” are used for decoupling and simplifications without assessing related uncertainties and there seems to be a need for transient phase description to justify these assumptions. Also, geochemical-mechanical coupling is often excluded, but high pH liner/construction material with bentonite interaction may weaken mechanical and retardation properties of bentonite – parameter uncertainty is still large and should be reduced especially with respect to design optimisation of a repository.

5.1.1 Significance for safety

Uncertainties related to THMCBR processes dominating at different time scales as well as with gas migration in near-field systems seem to have quite different significance for safety for the three categories of actors. REs indicate about a factor of two more significance then TSOs and WMOs, except for the question of 4D versus 1D modelling, where WMOs indicated a slightly higher significance (*Figure* 53, *Table 7*). Nevertheless, the number of replies to these topics with “not known/assessed yet” is the lowest compared to all other topics, which may explain these large differences among the different actors’ views. Their additional comments are given below:

REs noted that

… Kd is a key parameter in radionuclide migration and as result affects radiological impact

… the increase of the system temperature might imply for some radionuclides a modification of the solid phase likely to control the solubility of a given radionuclide. This in turn might imply a solubility increase and thus an increase of their aqueous concentration in the near-field

… more accurate experimental characterization techniques would be needed to overcome and reduce these uncertainties, which depend on investing in improved experimental techniques

TSOs noted that

… there might be a possible effect on length of transport pathway, and transport velocity

… there might be a possible effect on the rate of processes

… partition coefficient strongly affects radionuclides transport and concentration, and their time dependence

… partition coefficient of some important radionuclides are dependent on temperature

… calculated transport conditions are dependent on the near field description (evolution)

WMOs noted that

… limited effect on RN transport at the scale of the disposal system - uncertainty in thermal effects on De is limited

… possible effects of alkaline plume are limited and taken into account in the models associated with the radionuclide sorption - neglecting competitive sorption not assessed yet

… uncertainty on systems understanding remains; it is not deemed safety relevant.

… the safety concept aims to avoid the release of RN during the thermal phase to mitigate these uncertainties (TC coupling) - minor irreversible effects are expected

… 1D/2D approach followed in the radionuclide sorption will have low impact of induced uncertainties on final result for a concept in poorly indurated clay where disposal gallery length is significantly greater than host rock thickness. 3D models might also be needed in the future to investigate specific processes/scenarios.

… the relevance of each of the processes depends on the evolution of the boundary conditions. Remaining uncertainty is however expected not to have safety relevance

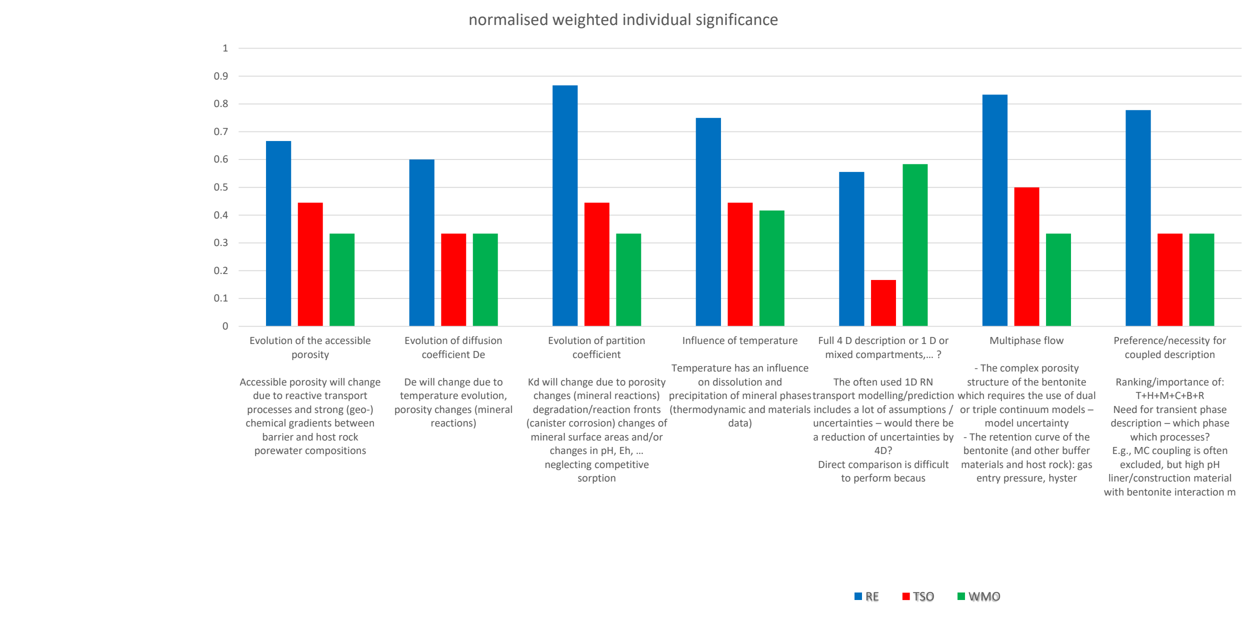

Figure 53. Significance for safety of uncertainties related to uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems

Table 7. Synopsis of the actors' views on uncertainties related to uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
		REs		TSOs		WMOs	Operational dose/risk	Post-closure dose/risk	Safety functions
Evolution of the accessible porosity Accessible porosity will change due to reactive transport processes and strong (geo-) chemical gradients between barrier and host rock porewater compositions	0.75	2h;1m; 1l; 1n;	0.33	3l; 1n	0.33	3l; 4n	3	8	5
Evolution of diffusion coefficient De De will change due to temperature evolution, porosity changes (mineral reactions)	0.67	4m; 1n;	0.56	1h; 2l; 1n	0.41	1m; 3l; 3n	3	7	4

Evolution of partition coefficient Kd will change due to porosity changes (mineral reactions) degradation/reaction fronts (canister corrosion) changes of mineral surface areas and/or changes in pH, Eh, … neglecting competitive sorption	0.67	1h; 2m; 1l; 1n;	0.56	1h; 2l; 1n;	0.4	1m; 4l; 2n	3	8	4
Influence of temperature Temperature has an influence on dissolution and precipitation of mineral phases (thermodynamic and materials data)	0.67	1h; 2m; 1l; 1n;	0.56	1h; 2l; 1n	0.33	3l; 4n	3	5	3
Full 4 D description or 1 D or mixed compartments, ? The often used 1D RN transport modelling/prediction includes a lot of assumptions / uncertainties – would there be a reduction of uncertainties by 4D? Direct comparison is difficult to perform because of long computational times in 4D Confirmation of simplification - a large uncertainty?	0.80	2h; 3m;	056	1h; 2l;1n	0.44	1m; 2l; 4n	3	6	4
Multiphase flow - The complex porosity structure of the bentonite which requires the use of dual or triple continuum models – model uncertainty - The retention curve of the bentonite (and other buffer materials and host rock): gas	0.75	1h; 2m; 2l;	0.33	2l; 2n	0.33	3l; 4n	3	5	3

entry pressure, hysteresis and temperature dependence (several models) – parameter uncertainty									
Preference/necessity for coupled description Ranking/importance of: T+H+M+C+B+R Need for transient phase description – which phase which processes? E.g., MC coupling is often excluded, but high pH liner/construction material with bentonite interaction may weaken mechanical and retardation properties of bentonite .	0.50	1h; 1m; 4l; 2n;	0.67	1h; 1m; 1l;	0.53	1h; 3l; 1m; 2n	x	xxxx	xx

Near-field processes have a large impact on radiological dose/risk after closure and on safety functions, especially in the view of REs (*Figure 55*). As the transient phase of a resaturating near-field could be very long, uncertainty will not decrease with time. It is just the opposite, uncertainty will increase with time due to the highly nonlinearly coupled processes in the near-field. Uncertainties that are not so relevant for short-term near-field evolution will increase in the long term.

In the **REs** view, impact of uncertainties increase after repository closure with impact also on safety function according to the actual implementation phase of the individual replier. Whereas some **TSOs** indicate less influence on safety function than on after closure impact, same as for **WMO** views.

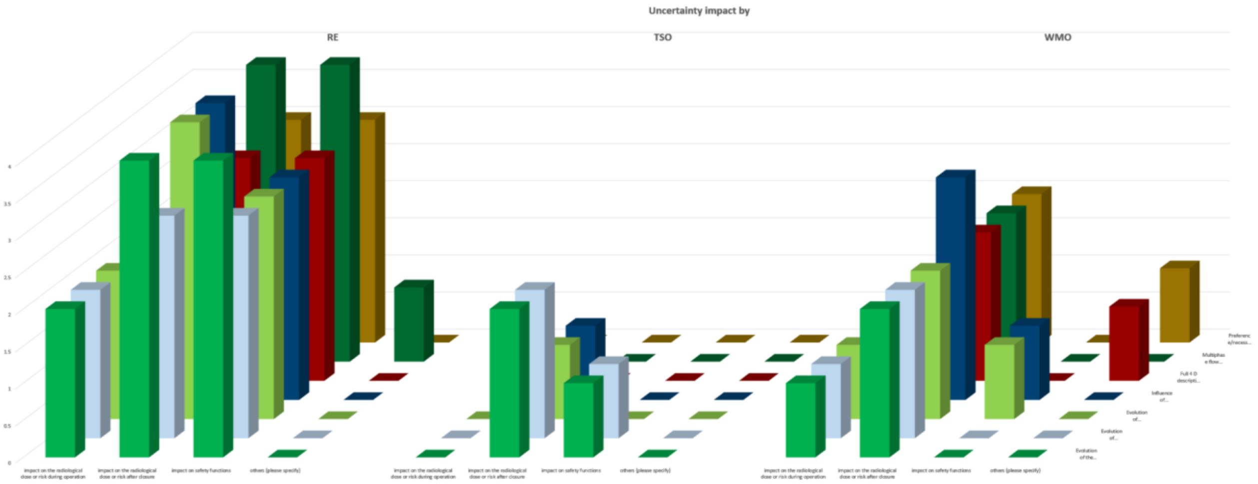

Figure 54. Actors views on impact for safety-significant uncertainties (topics 1-7, related to THMCBR processes dominating at different time scales as well as with gas migration in near-field systems) on radiological dose/ risk during operation, on radiological dose/risk after closure, on safety functions or on other potential impact(s)

5.1.2 Uncertainties characterisation

Overall, modelling seems to be the preferred method used by all actors in the characterisation of THMCBR processes dominating at different time scales as well as with gas migration in near-field systems (*Figure 61* - 62. Different preferences for different actors are not clear, also due to the low number of replies to these topics and the large number of “not known/assessed yet”.

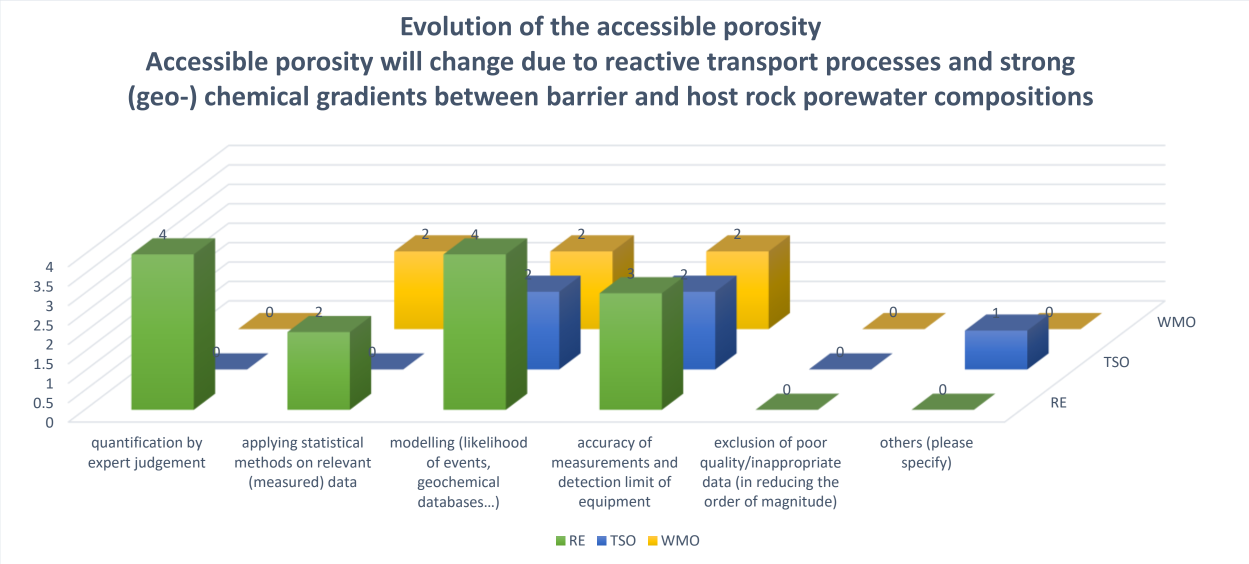

Figure 55. Actors' preferences in the characterisation of uncertainties related to THMCBR processes dominating at different time scales as well as with gas migration in near-field systems – porossity

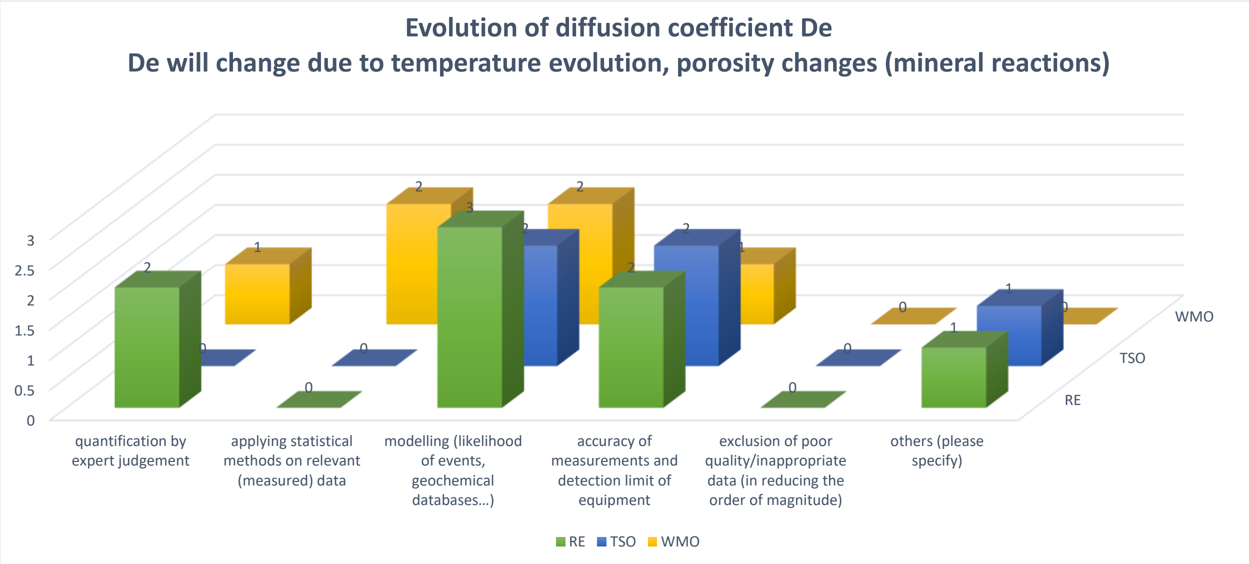

Figure 56. Actors' preferences in the characterisation of uncertainties related to THMCBR processes dominating at different time scales as well as with gas migration in near-field systems – diffusion coefficient

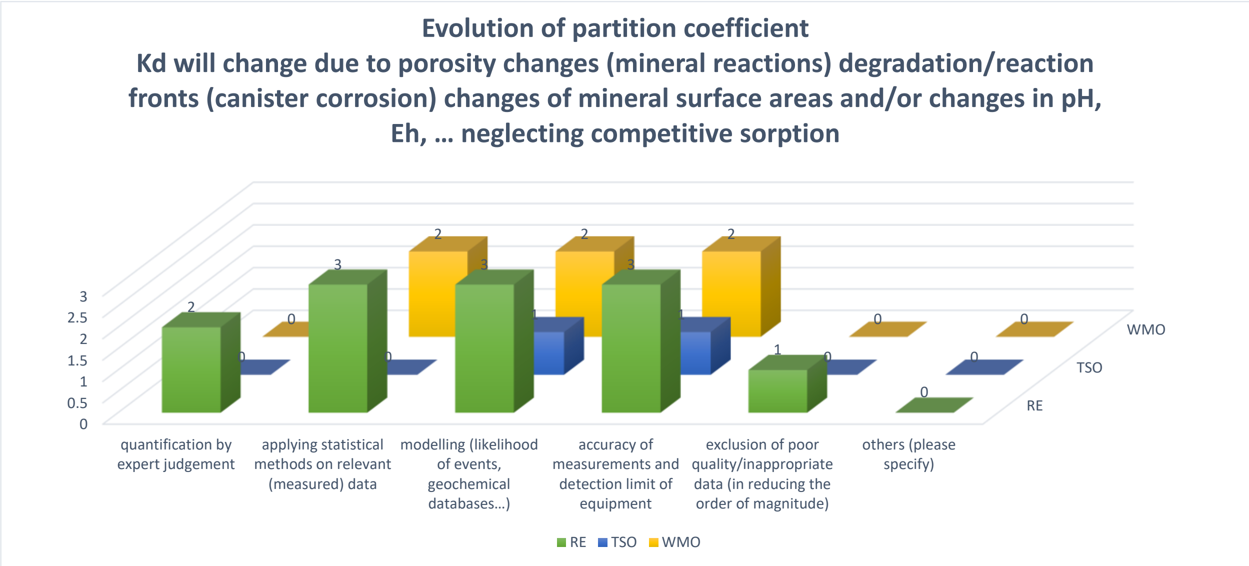

Figure 57. Actors' preferences in the characterisation of uncertainties related to THMCBR processes dominating at different time scales as well as with gas migration in near-field systems – partition coefficient

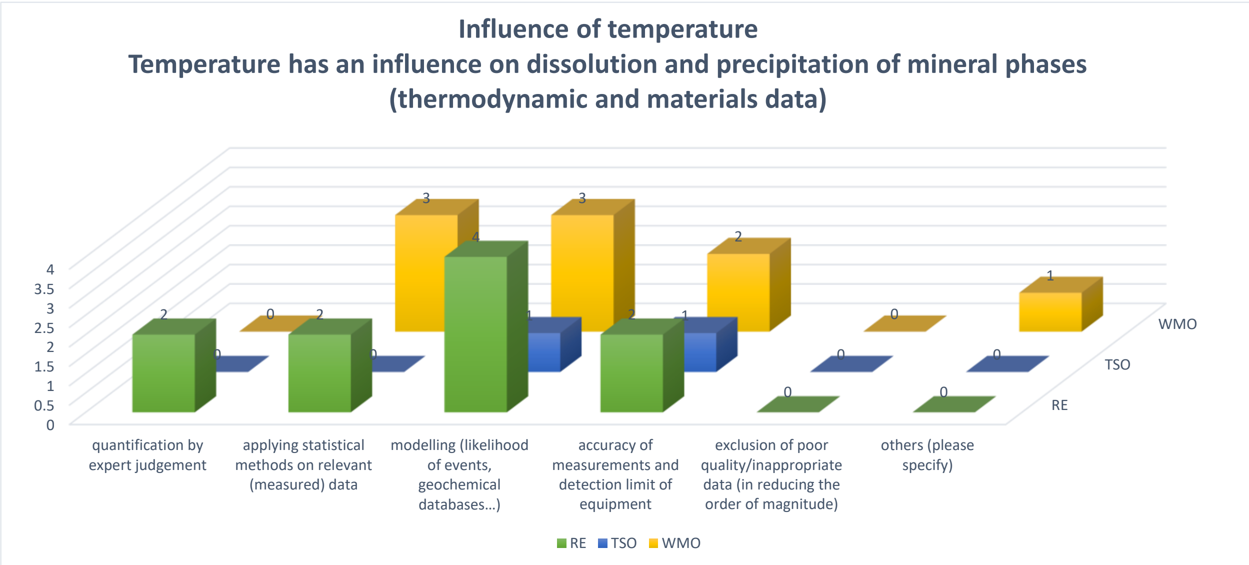

Figure 58. Actors' preferences in the characterisation of uncertainties related to THMCBR processes dominating at different time scales as well as with gas migration in near-field systems – influence of temperature

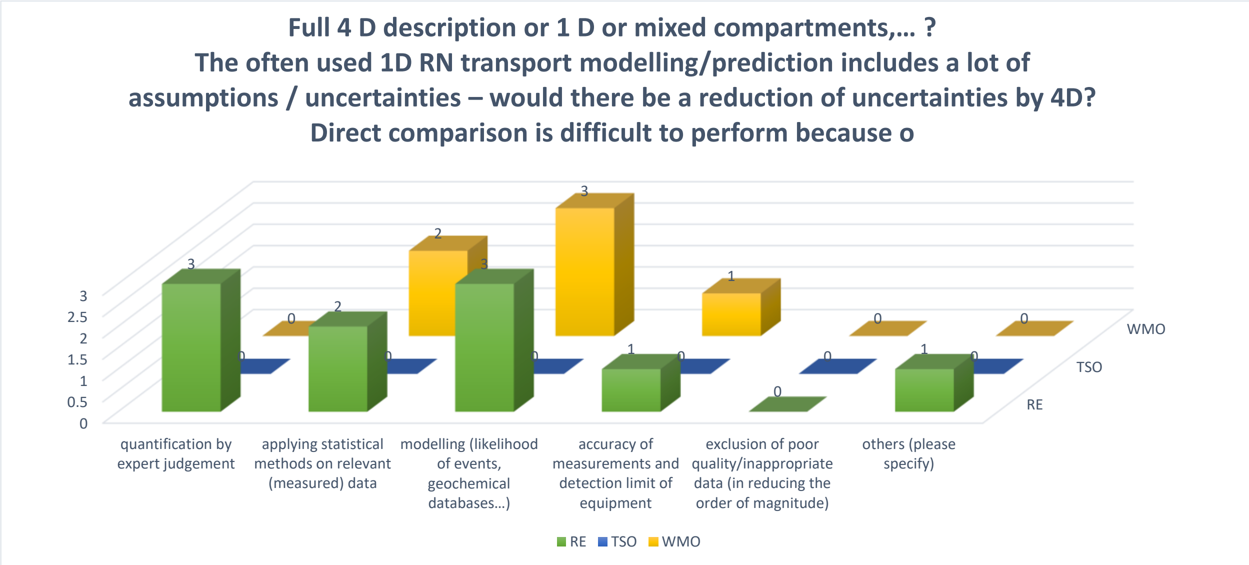

Figure 59. Actors' preferences in the characterisation of uncertainties related to THMCBR processes dominating at different time scales as well as with gas migration in near-field systems – 4D versus 1D

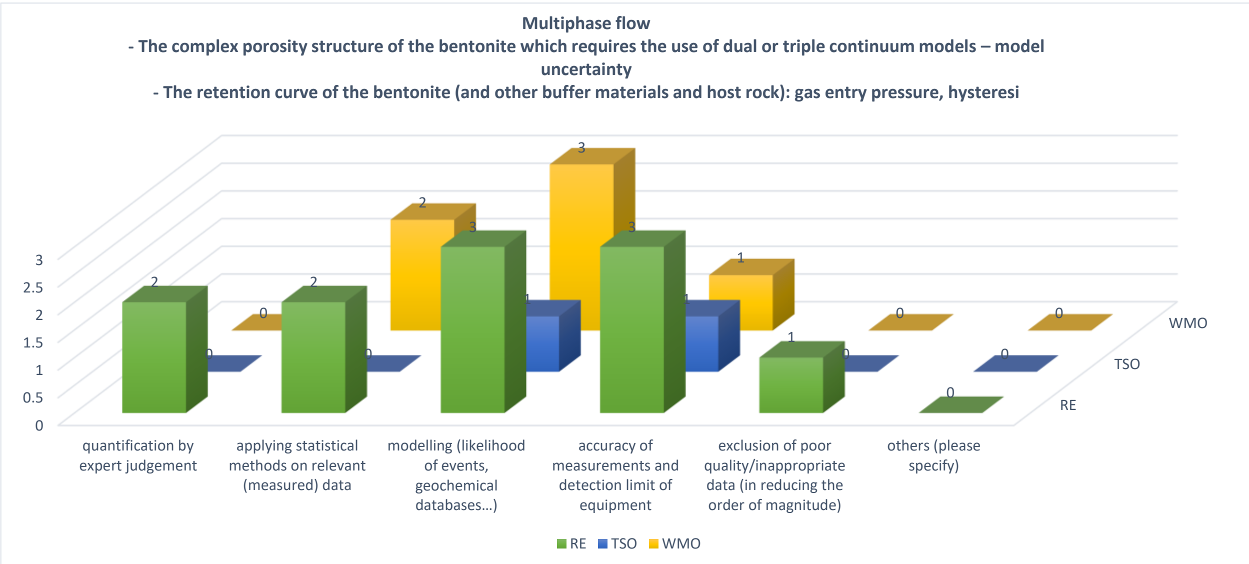

Figure 60. Actors' preferences in the characterisation of uncertainties related to THMCBR processes dominating at different time scales as well as with gas migration in near-field systems – multi phase flow

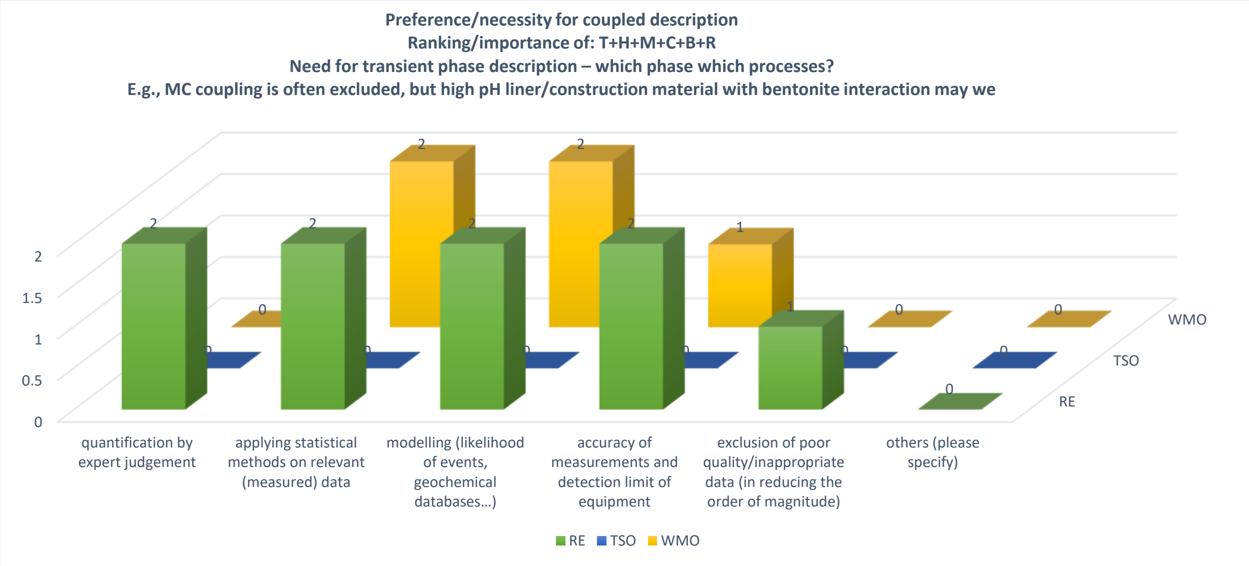

Figure 61. Actors' preferences in the characterisation of uncertainties related to *THMCBR processes dominating at different time scales as well as with gas migration in near-field systems – Preferences for THMCBR couplings*

5.1.3 Uncertainty evolution in time

The overall evolution of significance of uncertainties related to THMCBR processes dominating at different time scales as well as with gas migration in near-field systems with time/programme phase does not show a clear trend (*Figure 63*); there are again high significance uncertainties for each topic except for "evolution of De". However, for some topics (evolution of partition coefficient, evolution of temperature) the uncertainties seem to decrease (more green from top to bottom, for others (evolution of accessible porosity, full 4D) it is the opposite – more red/yellow from top to bottom. Also here, replies are predominantly from actors being in the site evaluation phase and near-field uncertainties are not looked at in detail yet.

Figure 62. Global uncertainties evolution along the disposal programme phases (for uncertainties see Figure 54 and Table 7 from left to right)

6. Additional input from the Workshop on near-field uncertainties

This deliverable includes also the results of Task 3.6 Workshop held at RATEN, Romania 24-25 November 2022, which has been performed in hybrid form and where the replies to the near-field questionnaire and the SotAs of CONCORD [1] and MAGIC [2]have been presented and discussed. During the Workshop, the three groups of actors (**RE, TSO, WMO**) organised themselves also in hybrid form to discuss and identify the most relevant uncertainties in order to be further discussed in tasks 4 (management options) and 5 (discussion with CS).

From **REs** discussion group (participants RE: LEI, RATEN, TUS, PSI, SCK-CEN online, GRS online**)** the proposed topics to be further discussed as input for task 4 and 5 were:

- uncertainties on Kd – models, parameter and evolution are of highest interest (however, sorption has been topic in subtask 3.3 already)
- re-saturation – heterogeneous, chemical reaction, mechanical integrity of bentonite, concrete (MAGIC), seals – coupled processes, multiphase flow, evolution of the accessible porosity
- material properties, interactions canister with near-field (CONCORD)

From **TSOs** discussion group (participants: SURO online, VTT online, IRSN, BelV online) the proposed topics to be further discussed as input for task 4 and 5 were:

- mechanical behaviour of bentonite (homogeneity, re-saturation,
- metallic material behaviour

- during WS and post WS discussion: Full 4D description or 1D, preferences for coupled description

From **WMOs** discussion group (participants NAGRA, SURAO, BGE online, ONDRAF/NIRAS) the proposed topics to be further discussed as input for task 4 and 5 were:

- parameter uncertainty (e.g. transport parameter)
- uncertainty in canister lifetime
- uncertainties related to coupled/interdependent processes / parameters: Specific couplings ? E.g. MC coupling in concrete (MAGIC), TC coupling (HITEC)

7. Recommendations for future EURAD activities

As shown in the uncertainty management approach, jointly developed under the WP UMAN by all involved actors [7], there are different types of actions which can be applied to reduce uncertainties, or to avoid or mitigate their impact on disposal safety. In addition, there are different dominating uncertainties influencing safety for different repositories designs, host rocks and waste types so that different countries may have different foci on uncertainties related to near-field uncertainties.

R&D activities related to bentonite (homogeneous) re-saturation started within the Beacon project, taking not into account geochemical reactions and gas transport. However, these processes have influence on both bentonite as a barrier or with a sealing function and should be investigated further by extended modelling and benchmarking and using long-term experimental data into consideration, e.g., FE experimental data from the Mont Terri URL.

Uncertainties related to metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different barriers (waste package, liners…) seems to be another hot topic especially in the Seminar 5 together with CS, where container lifetime was identified as an important property of a safety function in several repository concept, Especially the long-term durability of the containers might be difficult to assess in a complex heterogeneous near-field environment with strong hydraulic, mechanical, temperature and geochemical gradients as driving forces for a lot of non-linearly coupled processes. Interface processes on several scales define finally fluxes across the buffer material interfaces; e.g., clogging with positive and negative effects on safety functions.

How to model these non-linearly coupled processes, 1D, 2D, 3D spatial geometry with which processes coupled on which scale using which data was identified predominantly from the REs as a third R&D direction including the development of digital twins with different complexity for different purposes. These advanced numerical tools enable transparent sensitivity analysis to identify most dominating processes and related significant uncertainties for safety, allowing design optimisation and visualisation of coupled processes to achieve a better process understanding even for CS. It includes coupled modelling of complex near-field processes within a statistical framework supported by surrogate models to assure good statistics for dominant (significant) parameter identification or parameter optimisation in a transparent procedure.

Needs for R&D, strategic studies and knowledge management activities have been identified as part of the Workshop 5 dedicated to management options for near-field uncertainties, where several of them are similar to management options for site and geosphere uncertainties, because of similar processes, which have been formulated as recommendations for future EURAD activities [7]. Workshop 5 and Seminar 5 participants identified a variety of research activities related to the three topics of near-field uncertainties that were chosen for further discussion in WS5 and Sem5 and for which research activities (R&D and/or Strategic Studies) should be performed in the near future.

7.1 R&D Activities needed to reduce uncertainties related to hydraulic properties of the bentonite

Workshop 5 and Seminar 5 discussion showed that further research on

- Experimental data from re-saturation and swelling pressure evaluation under different boundary conditions (temperature, pH, microbes, gas production) should be used for model validation
- THMC coupling approaches applied to complex defined lab experiments but also to large scale experiments, using e.g. monitoring data (FE experiment), to get a better understanding by performing experiments (short term ~20 years), sophisticated modelling of these experiments, and later on predicting on repository scales (spatial and time) with special focus on the transients of re-saturation, mechanical (swelling pressure) and hydraulic properties, temperature including heterogeneous bentonite initial distribution, heterogeneous re-saturation, and related consequences for the safety function of the technical barrier
- Development of digital (virtual) twins for re-saturation phase including model validation and benchmarking
- Heterogeneous re-saturation of bentonite in an environment with strong thermal, hydraulic mechanic and geochemical gradient inducing interface processes on different scales

This would allow to better understanding:

* Bentonite buffer performance as a pillar of the safety function. Re-saturation and swelling pressure evolution "as expected"

and will guarantee

* mechanical integrity of the near-field,
* heat transfer from HLW/SF through the buffer into the host rock – temperature limit for bentonite to guarantee sorption capacity of bentonite (design dependent)

This would contribute to answer questions of CS formulated at the Seminar 5:

- What level of uncertainty is acceptable to license bentonite for example? How is the decision made?
- What to do if bentonite does not behave as expected? If breach in the safety envelop, what happen? How is this decision made?
- What are the conditions for closure? What level of certainty is needed? How is the decision made?
- Which are the remaining unreducible uncertainties: key component of the closure discussion?

7.2 R&D activities needed to reduce uncertainties related to metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different barriers (waste package, liners…)

Workshop 5 and Seminar 5 discussion showed that further research is needed on:

- Alternative material sources, use of suitable materials to reduce gas generation and corrosion processes is still an ongoing process in many countries, e.g. to improve canister performance for long term with respect to reduce uncertainties related to:
    - corrosion, understanding of stress corrosion cracking, strength resistance, heat resistance, radiation resistance,
- several design measures reducing corrosion rates are investigated by experiments and modelling, e.g., overpack (choice of carbon steel, high pH conditions provided by a cementitious buffer), copper coating of steel containers (reduction of H_2 production and build-up of counter pressure, and related material alteration with changing near-field geochemistry, temperature, …
- determining the time at which RN start to migrate in the disposal system

Therefore, further R&D activities should investigate re-saturation process of the near-field after repository closure including geochemical and microbial processes (BEACON-II):

* Degradation products have an influence on cation sorption (RN sorption competition with Fe, Ni, Mn, …). These sorption competition effects have to be quantified in more detail
* Increase system understanding including canister – near-field interaction and identify dominating processes with respect to canister lifetime – partly investigated in CONCORD. Also, because “metallic behaviour” includes interface processes, for which a specific, high spatial resolution in modelling is necessary – often not taken into account for modelling – just mm/y as “corrosion rate” and related material/gas production - upscaling of processes is needed
• Test different canister concepts / or “flexible design” are indications that there is still uncertainty on canister lifetime, which is large
• Modelling corrosion of non(low)-porous materials (electrochemical vs geochemical, moving boundaries, effect of corrosion products on near-field geochemistry/clogging etc…), which is still a challenge
* Better understanding of interface processes is necessary including experiments related to geochemical and microbial influences on degradation/corrosion products and rates and related modelling

7.3 R&D activities needed to reduce uncertainties related to THMCBRG modelling incl. benchmarking

Workshop 5 and Seminar 5 discussion showed that further research on THMCBRG modelling, coupled processes incl. benchmarking is necessary to achieve more realistic safety assessments, reduce over conservatism, performing complex sensitivity analysis …. Using new improved modelling tools, AI and ML in science as well as in communication with the CS/public ([8-15].

- Global sensitivity analysis of coupled modelling to identify dominant parameter uncertainties Uncertainty analysis and optimisation with respect to experimental data and their safety relevance, Heterogeneous near-field requests investigation of complex THMCBR processes – experimentally and by modelling. Without modelling parameter uncertainty is difficult to access.

- Benchmarking of coupled codes, model benchmarking (i.e. comparison of results obtained with different codes simulating the same conditions. Model validation (i.e. comparison of modelling results with real data – large scale URL experiments (FE at Mont Terri)

Multiscale modelling, upscaling using PBM and DDM. Better understanding of interface processes is necessary including experiments related to geochemical and microbial influences on degradation/corrosion products/speed and related modelling

* Large uncertainty at interfaces with respect to "material fluxes" due to "mixing volumes" in performance assessment: RN leaching from canister into a small volume of water around the canister yield RN concentrations as a source term for the barrier/buffer; also RN input from barrier/buffer into host rock and later on again input into geosphere with mixing volume of aquifer assumption
* No modelling of near-field evolution and RN transport calculations at the same time – why not? Take into account the coupling of near-field evolution and RN transport (safety case assessment) in the modelling, reduce expert opinions and "conservative assumptions" to be more realistic in modelling the near-field evolution. Use 4D, multiscale, multi-physics and coupled modelling. Create virtual twins on repository scale for different purposes: detailed modelling on scientific level, maybe also on safety case – or performance assessment scale, and on "public/CS scale" for better understanding and acceptance reasons

- Improved visualisation tools
- Digital twin development
- Mechanistic description of chemical and physical perturbations on RN behaviour
- Exchanges on the substantiation that models used in the safety assessments are fit for their purpose, considering the viewpoint and expectations of different actors (regulators, civil society, REs,…) and on how to reach a common understanding of model purposes and the meaning/significance of modelling results in the context of the safety case
- Civil Society involvement to understand the general conditions for closure (technical and societal aspects)

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

8. Conclusions

The UMAN Deliverable 10.18 provides information on the views of three categories of actors (REs, TSOs and WMOs) related to:

- the significance for safety of uncertainties related to the near-field,
- the preferences in uncertainties characterisation
- the uncertainties evolution along the disposal programme implementation

to be used in:

- selection of the uncertainties with a significant relevance for safety as input to Task 4.3 and Workshop 5: Management options and preferences of different actors regarding near-field related uncertainties, organized by Subtask 4.3, and in
- preparation of the dialogue with Civil Society foreseen for Seminar 5, organized under Task 5

The deliverable analyses the views of the three categories of actors collected via the new and final UMAN Questionnaire survey on **near-field uncertainties**, launched on April 5, 2022. It also includes the results of Task 3.6 Workshop held at RATEN, Romania 24-25 November 2022, where the replies to the questionnaire and the SotAs of CONCORD and MAGIC have been presented and discussed.

The questionnaire grouped the uncertainties related to near-field into 6 topics, gathering in total 37 parameters and processes considered by the UMAN experts' group to have a potential significance for safety. The 6 topics, have been structured in three main categories:

I. Uncertainties associated with the processes governing or altering radionuclide migration and the performance of disposal system components
II. Uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers
III. Uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems

The analysis performed is based on the 18 replies received from 17 organisations, representing 5 REs, 4 TSOs and 8 WMOs (one with two replies), which address all the disposal concept of geological disposal (DGD), one reply is related to salt host rock, which has been not considered here. The disposal concepts for near surface (NSD) and sub-surface (SSD), as well as salt as host rock for GDG were not under the scope of near-field uncertainties analysis. A detailed description on the significance for safety, characterization and evolution was provided only for the uncertainties evaluated as having a relevant impact on the disposal safety, by majority of actors.

Answers compilation revealed that there was no group of uncertainties scored with medium and high significance by all categories of actors, which was abolished by low significance answers, especially by individual advanced WMOs. Ignoring individual WMOs low significance answers, the uncertainties with medium and high significance involved in this survey are those related to:

- partition coefficient Kd: Kd values are the result of assumptions associated with the conceptual model (i.e., linear kinetics for sorption / desorption process) and could depend on redox conditions, and could be affected by the near-field evolution)

- metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different barriers (waste package, liners…), lifetime, gas generation and pressure build-up, other degradation processes, pH-, Eh-evolution, pit corrosion, colloid formation (continuous or step functions?)
- uncertainties related the diffusion coefficient De: values for the neutral elements, cations and anions …

- hydraulic properties of the bentonite: effects of re-saturation and swelling pressure evolution (bentonite re-saturation is considered to be homogenous, to the expected swelling pressure, but preferential flow paths could develop).

- permeability – associated to two-phase flow: barriers are considered homogeneous in terms of permeability, while anisotropy given by e.g., preferential flow paths, fractures/pores, … can lead to increased flow.

A lower significance for safety has been indicated for uncertainties associated with:

- evolution of diffusion coefficient De: De will change due to temperature evolution, porosity changes (mineral reactions)

- concrete parameters and associated processes used in near-field conceptualisation: carbonation processes during operational phase and re-saturation phase could have an impact on mechanical parameters

- permeability measurement methods (for– two phase flow): permeability has very low values and depends on the accuracy of the measurement method.

As a result of the replies to the questionnaire, the SotA presentations of CONCORD and MAGIC, and the dedicated workshop discussions, the uncertainties with high impact for safety proposed for a more detailed analysis at this stage are:

- uncertainty related to metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different barriers (waste package, liners…)
- uncertainty related to hydraulic properties of the bentonite
- uncertainty related to modelling of radionuclide transport: full 4 D description or 1 D or mixed compartment.

As a general observation, there are differences between the importance given by the three categories of actors to the same group of uncertainties, with WMOs and REs generally giving more significance to uncertainties and their impact on safety than TSOs.

By far the largest difference for safety significance between the different categories of actors is associated with the topics related to uncertainties on THMCBR processes dominating at different time scales as well as with gas migration in near-field systems. REs give generally a much higher (twice as high) significance than TSOs and WMOs, where several replies to these topics indicate uncertainty not assessed or not known, especially from less advanced or early stage programme countries.

For all other topics REs and WMOs rate the importance of uncertainties similarly, REs mostly slightly higher than WMOs.

Each category of actors uses in the uncertainties' characterisations a diversity of methods, adequate to the uncertainty type (parametric, scenario, conceptual, etc.), which complement each other, with the aim to reduce the uncertainty level. A general trend is not obvious.

In contrary to the actors views on site and geosphere uncertainties, where generally all actors' opinions converge on the fact that uncertainty will decrease along the programme phases, as the knowledge of the site and scientific accumulations evolve until a certain level, for near-field uncertainties, such convergence is missing. For some uncertainties it is just the opposite. A reason might be, that site and geosphere uncertainties have to be reduced during the site selection and site characterisation phase, otherwise there will be no site selected, whereas for near-field uncertainties there is still some time during design optimisation and construction to reduce near-field uncertainties. Also, there was no difference in the replies when considering the views of actors from advanced and respectively less advanced programmes.

When taking into account the pluralistic discussion of all EURAD colleges (MWO, TSO, RE) and CS in Seminar 5, the topic of transparency in accessing uncertainties dominated discussions. Questions like, why these models, codes, data, couplings, … were raised by CS representatives.

Also CS participation in the process of uncertainty assessment was requested and uncertainty about the continuity, availability and integrity of a governance framework (governing institutions and associated expertise) has been stressed.

Tools like digital twins were very much appreciated, especially for cases were data, processes and uncertainties of data have been visualised in 4D animations for an easier understanding of results shown.

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10. Attachment 1: Questionnaire on near-filed uncertainties

Introduction to the "Questionnaire on Near-Field Uncertainties"

Within EURAD UMAN Task 3 – Characterisation and significance of uncertainties for different categories of actors - the objective of the subtask 3.6 (EURAD 2nd wave extension) is to synthesize the existing knowledge and views of different kinds of actors on the identification, classification, characterisation and significance of uncertainties associated with the near-field, and to formulate recommendations for future EURAD R&D, KM and strategic study activities. A questionnaire related to uncertainties on waste inventory and on the impact of predisposal steps (subtask 3.2), uncertainties related to site and geosphere (subtask 3.3), uncertainties related to human aspects (subtask 3.4) and uncertainties related to spent fuel (subtask 3.5) has been distributed in 2020. This questionnaire is related to the missing topic of the different categories of uncertainties, i.e., near-field uncertainties. The uncertainties investigated under this subtask cover the main types of host rocks: sedimentary and crystalline.

The expert group carrying out this activity is composed by representatives of RE, TSO and WMO, bringing in the views of different actors, major contributors to national disposal programmes.

From all uncertainties related the near-field, this subtask focuses on:

- uncertainties related to the processes governing or altering radionuclide migration and the performance of disposal system components in the near field;
- uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers;
- uncertainties associated with thermal, hydraulic, mechanical, chemical, biological and radiation conditions and processes (THMCBR) dominating at different time scales (except those already taken into account in subtask 3.2 on the waste inventory and subtask 3.3 on geosphere and sites related uncertainties) as well as with gas migration in near-field systems.

The first step in the subtask implementation was to draft a preliminary list of uncertainties starting from the existing knowledge and experience of the expert group, using as well as information available in public reports related to safety cases/safety assessments from other countries. The second step is this questionnaire, which should be used to collect the opinions of different actors on the uncertainties related to the near-field. Information collected via this questionnaire will be as well used as input for subtask 4.2 – Compilation and review of available information on possible uncertainty management options having as main objective *"to develop a comprehensive overview about different approaches and uncertainty management options to assess and where relevant to reduce risks and optimise safety"*.

GENERAL INFORMATION

Affiliation (not mandatory):

Country (mandatory):

Is your organisation a (single answer, please tick the corresponding box):

☐ RE (Research Entity)

☐ WMO (Waste Management Organisation)

☐ TSO (Technical Support Organisation)

☐ Civil Society Organisation (please specify): Click or tap here to enter text.

PROGRAMME INFORMATION

Please answer the following questions, choosing the appropriate item in each dropdown list.

B. In which disposal programme are you involved? Which type of host rock is considered? What is the current phase of the programme

Deep geological disposal in: Rock type Choose an item. Current phase of the programme Choose an item.

For further clarifications, please contact: Pfingsten Wilfried (PSI) at wilfried.pfingsten@psi.ch

I. Uncertainties associated with the processes governing or altering radionuclide migration and the performance of disposal system components

The processes governing or altering the evolution of the near-field of disposal systems are key to assessing the performance of their components and the release of radionuclide from the canisters or waste packages into the environment. Uncertainties related to the near-field constitute the "missing link" in current UMAN WP activities focusing on uncertainties related to the source term (spent fuel and other wastes), human aspects as well as to some aspects of the site and geosphere. (This missing link makes it difficult to gain the overall picture of safety-significant uncertainties. For instance, the relevance for safety and management options of uncertainties on the thermal output produced by spent fuel cannot be investigated without addressing the influence of temperature on the near-field and its safety significance.)

Starting with the waste/waste matrix and surrounding waste container, the near-field is the third technical barrier for radionuclides before they may enter the natural barrier, which is the host rock. The near-field is the area with the largest material heterogeneity (metal, bentonite, clay or crystalline rock and concrete). There are the largest temperature, hydraulic and stress gradients (related to the materials properties), and also the largest chemical gradients between different porewater compositions (e.g., cement – clay). Therefore, a complex evolution of the near-field has to be expected, which needs to keep its barrier functionality for radionuclides in the very long term. In the safety case and safety assessment, each safety-related aspect of the near-field has to be considered, analysed, understood and integrated, together with their associated uncertainty [7-12].

The main remaining uncertainties related to conceptualisation of the technical barriers in scenario and model development selected by the expert group of subtask 3.6 relate to the evolution of the near-field as expected with focus on:

- transport properties for each RN within the near-field
- temperature evolution
- re-saturation and swelling pressure evolution,

5. (bentonite) mechanical evolution

- Evolution at interfaces and seals of the different materials (clogging preferential migration paths)

A. Uncertainties associated with the transport properties for major ions and RN within the considered barrier medium	C1. Safety signify-cance	C2. For safety-significant uncertainty (high or medium), what is the potential implications for safety and why?	C3. Methods used for uncertainty characterization		C4. Where possible, for each of the uncertainties you rated high or medium, how do you think that it will evolve over time?
			a) quantification by expert judgement b) applying statistical methods on relevant (measured) data c) modelling (likelihood of events, geochemical databases…) d) accuracy of measurements and detection limit of equipment e) exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) f) others (please specify)	Where possible, for each uncertainty you rated high or medium, could you provide further information (methods, references, comments…) regarding its characterization?	
Accessible porosity In numerical models, accessible porosity is generally deduced from the measured total porosity in an arbitrary manner	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	a ☐ b ☐ c ☐ d ☐ e ☐ f please specify	please specify	please specify
Diffusion coefficient *De* Values for the neutral elements, the cations and anions in numerical models are generally those obtained experimentally	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s)	a ☐ b ☐ c ☐ d ☐	please specify	please specify

for most representative RN and extrapolated for the other elements.		Please specify	e ☐ f please specify		
Partition coefficient *Kd* *Kd* values are the result of assumptions associated with the conceptual model (i.e., linear kinetics for sorption / desorption process). *Kd* could depend on redox conditions, and could be affected by the near-field evolution.	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	a ☐ b ☐ c ☐ d ☐ e ☐ f please specify	please specify	please specify
Solubility limit Values for each element in numerical models are typically deduced from lab measurements for very few elements and are extrapolated for the other elements. Due to strong chemical gradients within the near-field, precipitation / dissolution fronts will develop in the near-field influencing solubility limits of elements	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Time evolution of transport properties Reactions caused by the diffusion of reactants from	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…)	please specify	please specify

different sources (container, backfill, liner) can alter rock diffusivity		Please specify which safety functions ☐ Other potential impact(s) Please specify	☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify		
Microbiology Microbiological processes can impact the pH, Eh, speciation and transport behaviour of elements	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Seals evolution Seals specific uncertainties include chemical and hydraulic transients due to contact with concrete, aggressive ground-waters / re-saturation kinetics … They could influence bentonite swelling properties, homogeneous swelling / fingering, dry zones, preferential migration paths (gas flow / pressure build up, …) – which	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	

related transport parameter uncertainty is acceptable?					

B. Uncertainties associated with heat transport properties of barriers	**C1. Safety signify-cance**	**C2. For safety-significant uncertainty (high or medium), what is the potential implications for safety and why?**	**C3. Uncertainty characterisation**		**C4. Where possible, for each of the uncertainties you rated high or medium, how do you think that it will evolve over time?**
Variation of thermal conductivity, specific heat capacity, bulk density, … due to re-saturation Heat transport is influenced by re-saturation and or gap evolution with consequences for maximum temperature at the canister surface and mechanical properties of materials in the near-field	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Variation of thermal conductivity, specific heat capacity, bulk density, …due to the chemical conditions Heat transport is influenced by chemical reactions due to	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s)	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty)	please specify	please specify

changing material and transport properties in the near-field		Please specify	☐others please specify		
Duration of the "thermal pulse"	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify

C. Uncertainties associated with flow properties through barriers	C1. Safety signify-cance	C2. For safety-significant uncertainty (high or medium), what is the potential implications for safety and why?	C3. Uncertainty characterisation		C4. Where possible, for each of the uncertainties you rated high or medium, how do you think that it will evolve over time?
Kinematic porosity – Kinematic porosity is generally deduced in an arbitrary manner (a half, the quarter…) from experimental measurements of total porosity	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Permeability – two phase flow	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…)	please specify	please specify

Barriers are considered homogeneous in terms of permeability, while anisotropy given by e.g., preferential flow paths, fractures/pores, … can lead to increased flow.		☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify		
Permeability measurement methods (for– two phase flow) Permeability has very low values and depends on the accuracy of the measurement method.	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Hydraulic head gradient Numerous measurements in well distributed boreholes around the site would be necessary to have a constrained hydrogeological near-field model. Vertical hydraulic gradient from aquifers above and below may not be realistic.	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Hydraulic properties of EDZ (conductivity, storativity, …)	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…)	please specify	please specify

Due to the repository construction (excavation), excavation damaged zones (EDZ) may have different horizontal and vertical extensions, different hydraulic properties and long term evolutions – different for different host rocks.		Please specify which safety functions ☐ Other potential impact(s) Please specify	☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify		
Hydraulic properties of the bentonite (effects of re-saturation and swelling pressure evolution) Bentonite re-saturation is considered to be homogenous, to the expected swelling pressure, but preferential flow paths could develop.	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Seals evolution Seals specific uncertainties include chemical and hydraulic transients due to contact with concrete, aggressive ground-waters / re-saturation kinetics … They could influence bentonite swelling properties, homogeneous swelling / fingering, dry zones, preferential migration paths (gas flow / pressure build up, …) – which	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	

related hydraulic parameter uncertainty is acceptable?					

D. Uncertainties associated with mechanical properties of the barriers	**C1. Safety signify-cance**	**C2. For safety-significant uncertainty (high or medium), what is the potential implications for safety and why?**	**C3. Uncertainty characterisation**		**C4. Where possible, for each of the uncertainties you rated high or medium, how do you think that it will evolve over time?**
Mechanical behaviour of the EDZ Mechanical integrity of the EDZ can depend on temperature dependent (near-field) material properties – how is it optimised / assessed?	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Mechanical behaviour of the EDZ Mechanical integrity of the EDZ can depend on fractured material properties, plasticity, thermal hardening, evolution of interfaces / gaps between different materials (clogging preferential migration path – how is it optimised / assessed?	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify

Mechanical behaviour of the EDZ Mechanical integrity of the EDZ can depend on time-dependent gas release (H2, CO, …) and pressure build up – how is it optimised / assessed?	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Mechanical behaviour of the bentonite Mechanical integrity of bentonite depends on homogeneity / heterogeneity of bentonite backfill emplacement – how is it designed / optimised / assessed?	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Mechanical behaviour of the bentonite Mechanical integrity of bentonite depends on homogeneity / heterogeneity of re-saturation / water inflow – how is it designed / optimised / assessed?	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Mechanical behaviour of the bentonite	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…)	please specify	please specify

Mechanical integrity of bentonite depends potential gaps, displacement of waste canisters, … – how is it designed / optimised / assessed?		☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify		

II Uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

The concept for waste package and technical barriers is influenced by the waste type, the type of host rock and the depth of the repository. Different waste types, SF or vitrified waste may need different container materials or thicknesses for different host rocks due to unwanted canister degradation, gas production and/or canister lifetime requirements for different host rocks. Uncertainties in I. are associated with the behaviour of the host rock during excavation (excavation method, speed...) and during operation, depending on the ambient air conditions (moisture, temperature) resulting from the ventilation and on the conception of retaining walls. Here, uncertainties are addressed with respect to different concepts of waste packages and technical barriers and their interplay.

A. Uncertainties associated with ...	C1. Safety signify-cance	C2. For safety-significant uncertainty (high or medium), what is the potential implications for safety and why?	C3. Uncertainty characterisation		C4. Where possible, for each of the uncertainties you rated high or medium, how do you think that it will evolve over time?
			Methods used for uncertainty characterization	Where possible, for each uncertainty you rated high or medium, please provide further information (methods, references, comments...) regarding its characterization?	
Metallic material behaviour (steel, copper, copper coated steel, composite, super container, ...) in different barriers (waste package, liners...) Lifetime, gas generation and pressure build-up, other	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases...) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify

degradation processes, pH-, Eh-evolution, pit corrosion, colloid formation (continuous or step functions?)					
Interface processes may occur at different time scales and with varying spatial extension. Pore clogging and no further gas transport might be a serious problem in tight host rocks (clays), at bentonite-crystalline, or cement-bentonite interfaces. How is the influence on RN transport conceptualised? How are specific designs optimised to prevent unwanted processes? How are the remaining uncertainties assessed/limited? Clogging – pressure build-up – may induce integrity problems. Matrix sealing may induce reduced RN retardation. ...	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Extent of EDZ, geometry and opening of fractures	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…)	please specify	please specify

These parameters are influenced by the operation conditions (moisture, temperature of ambient air)		☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify		
Concrete parameters and associated processes used in near-field conceptualisation Carbonatisation processes during operational phase and re-saturation phase could have an impact on mechanical parameters	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Alternative conceptual models of solute diffusion in the near-field: i. The single interlayer-porosity Donnan equilibrium model ii. The electrochemical model based on the Nernst-Planck Eq. iii. The multiple porosity (interlayer, double layer, free) model. iv. The use of different effective diffusion coefficients for each chemical species while preserving charge balance.	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify

v. Fracture-matrix or equivalent porous medium? Conceptual diffusion models i-v yield different De, with different uncertainties. Which concept for RN transport and/or major ion transport (near-field evolution)? Which concept is the less uncertain? Consistent concepts?					
Coupling influences In performance assessment, near-field evolution calculations and RN transport calculations are not coupled. For RN transport calculations, stepwise (spatial, temporal) constant transport parameters are assumed. Is this concept valid? Which uncertainties are accompanied /neglected/? Is it valid to choose "conservative values" in case of non-linearly coupled processes and long time scales?	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Monitoring influences Uncertainties associated with installation of monitoring equipment and potentially induced pathways	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s)	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment	please specify	please specify

		Please specify	☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify		

III Uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems

The description of the heterogeneous near-field with respect to materials, hydraulics, mechanics, chemistry, microbes and radiation needs a lot of equations describing all the processes in such a system. Several of these processes are strongly coupled due to nonlinear dependence on parameters influenced by different processes. The processes might be dominating at different time scales, e.g., temperature during the first 1 000 years, re-saturation up to 10 000 years or more, chemical degradation/ reaction fronts up to 100 000 and more years. Also, the extent, duration and importance of each of these processes (taken individually even without accounting for their influence on each other) are also subject to uncertainty. A decoupled description of processes induces uncertainties on a correct system description with respect to evolution of the near-field and evolution of transport parameters in the near-field.

Performing statistical/sensitivity analysis for such coupled systems to identify the most important parameters, e.g., for radionuclide transport, and optimise the technical barrier system accordingly is computationally very expensive and currently hardly possible with the current computer performance.. Nevertheless, uncertainties of processes, their parameters and their couplings have to be identified for a robust safety analysis.

			C3. Uncertainty characterisation	

A. Uncertainties associated with …	C1. Safety signify-cance	C2. For safety-significant uncertainty (high or medium), what is the potential implications for safety and why?	Methods used for uncertainty characterization	Where possible, for each uncertainty you rated high or medium, please provide further information (methods, references, comments…) regarding its characterization?	C4. Where possible, for each of the uncertainties you rated high or medium, how do you think that it will evolve over time?
Evolution of the accessible porosity Accessible porosity will change due to reactive transport processes and strong (geo-) chemical gradients between barrier and host rock porewater compositions	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Evolution of diffusion coefficient *De* *De* will change due to temperature evolution, porosity changes (mineral reactions)	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Evolution of partition coefficient	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data	please specify	please specify

Kd will change due to porosity changes (mineral reactions) degradation/reaction fronts (canister corrosion) changes of mineral surface areas and/or changes in pH, Eh, … neglecting competitive sorption		Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify		
Influence of temperature Temperature has an influence on dissolution and precipitation of mineral phases (thermodynamic and materials data)	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Full 4 D description or 1 D or mixed compartments,… ? The often used 1D RN transport modelling/prediction includes a lot of assumptions / uncertainties – would there be a reduction of uncertainties by 4D? Direct comparison is difficult to perform because of long computational times in 4D Confirmation of simplification - a large uncertainty?	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify
Multiphase flow	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data	please specify	please specify

- The complex porosity structure of the bentonite which requires the use of dual or triple continuum models – model uncertainty - The retention curve of the bentonite (and other buffer materials and host rock): gas entry pressure, hysteresis and temperature dependence (several models) – parameter uncertainty		Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify		
Preference/necessity for coupled description Ranking/importance of: T+H+M+C+B+R Need for transient phase description – which phase which processes? E.g., MC coupling is often excluded, but high pH liner/construction material with bentonite interaction may weaken mechanical and retardation properties of bentonite .	Choose an item.	☐Impact on radiological dose/ risk during operation Why? Click or tap here to enter text ☐Impact on radiological dose/risk after closure Why? Click or tap here to enter text ☐ Impact on safety functions Please specify which safety functions ☐ Other potential impact(s) Please specify	☐quantification by expert judgement ☐applying statistical methods on relevant (measured) data ☐ modelling (likelihood of events, geochemical databases…) ☐ accuracy of measurements and detection limit of equipment ☐exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) ☐others please specify	please specify	please specify

11. Attachment 2: Preliminary list of uncertainties from UMAN Subtask 3.6

Milestone MS 261:

Preliminary list of uncertainties from UMAN Subtask 3.6 as input to Subtask 4.2 and questionnaire

Work Package 10 - UMAN

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	By	Date
Delivered (Lead Beneficiary)	Wilfried Pfingsten (PSI)	29 November 2021
Verified (WP Leader)	Frank Lemy (Bel V)	
Reviewed (Reviewers)	-	-

Executive Summary

Uncertainties related to near-field treated under sub-task 3.6 focus mainly on:

- uncertainties related to the processes governing or altering radionuclide migration and the performance of disposal system components in the near-field;
- uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers;
- uncertainties associated with thermal, hydraulic, mechanical, chemical, biological and radiation conditions and processes (THMCBR) dominating at different time scales (except those already taken into account in subtask 3.2 on the waste inventory and subtask 3.3 on geosphere and sites related uncertainties) as well as with gas migration in near-field systems.

As a first step, a preliminary list of uncertainties has been proposed by the expert group on near-field aspects as input for the sub-task 4.2, based on the existing experience of the contributing organisations, existing approaches in contributing countries, as well as on some publicly available reports on different safety cases:

- Geological disposal in clay rock in France (IRSN);
- Geological disposal in clay rock in Swiss (PSI);
- Spent Fuel Disposal in granite in Czech Republic (SURAO);
- Geological disposal in clay rock in Belgium (SCK-CEN);
- State of The Art (SoTA) reports from EURAD projects ACED, DONUT, FUTURE, GAS, HITEC, (MAGIC (MS262) and CONCORD (MS252) maybe not available until November 2021)
- HORIZON-2020 BEACON project (Bentonite Mechanics)

The uncertainties included in the preliminary list address uncertainties related to the near-field of HLW/SF disposal facilities in the context of two different host rocks (crystalline and clay):

Table of content

List of Tables

Appendix A. Introduction

The objective of the sub-task 3.6 is to synthesize the existing knowledge and views of different kinds of actors on the identification, classification, characterisation and significance of uncertainties associated with the near-field, and to formulate recommendations for future EURAD R&D, KM and strategic study activities.

As mentioned in the description of the work, the uncertainties investigated under this sub-task should cover the main types of host rocks: sedimentary and crystalline.

The expert group carrying out this activity is composed by representatives of RE, TSO and WMO, bringing in the views of different actors, major contributors to national disposal programmes.

From all uncertainties related the near-field, this sub-task focuses on:

- uncertainties related to the processes governing or altering radionuclide migration and the performance of disposal system components in the near field;
- uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers;
- uncertainties associated with thermal, hydraulic, mechanical, chemical, biological and radiation conditions and processes (THMCBR) dominating at different time scales (except those already taken into account in subtask 3.2 on the waste inventory and subtask 3.3 on geosphere and sites related uncertainties) as well as with gas migration in near-field systems.

The first step in the sub-task implementation was to draft a preliminary list of uncertainties starting from the existing knowledge and experience of the expert group, using as well as information available in public reports related to safety cases/safety assessments from other countries.

This preliminary list has two objectives:

- to provide input for sub-task 4.2 – Compilation and review of available information on possible uncertainty management options having as main objective *“to develop a comprehensive overview about different approaches and uncertainty management options to assess and where relevant to reduce risks and optimise safety”.*
- to use it as a starting point in the elaboration of the questionnaire and in the discussions with other actors in order to consolidate the list based on which the characterisation and significance of site and geosphere uncertainties will be further elaborated.

Appendix B. Methodology for uncertainty selection

The preliminary list of near-field related uncertainties was elaborated by the expert group representing the three main categories of actors involved in EURAD and in disposal programme development and implementation: REs, WMOs and TSOs, from both less and more advanced programmes:

- IRSN (TSO - France)
- PSI (RE - Switzerland)
- SURAO (WMO – Czech Republic)
- SCK-CEN (RE – Belgium)

The preliminary list was built up based on the own experts' experience and information from national programmes represented in the subtask as well as from the information available from other advanced programmes and international organisations reports, all reported in the References section.

The following national Safety Cases / Safety Assessments have been considered in the analysis of the remaining uncertainties on near-field:

- CIGEO geological repository in clay rock in France;
- Geological disposal in clay rock in Belgium and Switzerland;
- Geological disposal repository in granite in Czech Republic;

Input provided by each expert has been discussed finally in the WP UMAN Task 3.6 meeting (November 29, 2021) and further compiled based on the received feedback and recommendations.

Appendix C. List of Uncertainties and their justification

Radioactive waste disposal programs raise a number of unique scientific, technical and societal issues, especially because of the very large time scale to be considered.

A general feature of waste disposal systems is that their long-term performance is subject to uncertainty [1-3]. These uncertainties fall into two broad classes:

- uncertainties that can be quantified and expressed as such as part of the evaluation results;
- uncertainties that cannot be quantified, for example, because they represent the divergence of the informed vision or because they are inherent to our abilities of human beings [4].

In any case, exploring, analysing and discussing existing uncertainties can provide an extra degree of confidence in the ability of a disposal system to provide the required level of safety.

The main causes of uncertainty in assessing the safety of a disposal facility include:

- the incomplete knowledge of natural systems, such as the geological environment, due to the inherent variability of the properties of these systems and the complexity of the processes that take place within them; and,
- the unpredictable aspects of human behaviour and the evolution of the site, the repository itself and its environment, once the institutional controls have come to an end.

The temporal and/or spatial variation of some properties of natural systems (for example, groundwater flow, rock stresses, geochemical conditions, distribution of soil types, percolation of rainwater) can be measured and quantified to some extent. However, uncertainty will always persist.

In addition, attempts beyond a certain point to improve knowledge about the geological environment of a repository (“no Swiss cheese”, …) may cause unacceptable disruptions to the behaviour of the respective environment and, consequently, to the performance of the disposal system as a whole.

The analysis of the second cause of uncertainties should be approached in a different way, because it is not possible to "predict" the future, so as to provide a convincing set of arguments regarding the safety of the disposal system in all possible future circumstances.

Perceived knowledge gap

Processes governing or altering radionuclide migration and the performance of disposal system components in the near-field are usually strongly coupled. These couplings are often treated in safety assessment models using conservative approaches whereby processes are decoupled and the near-field is conceptualized in a simplified manner. However, in such de-coupled systems, it is difficult to estimate the uncertainty of individual parameters governed by non-linear coupled processes. Specific methods are also necessary to identify parameter uncertainties that are most relevant for safety [5, 6].

Several past and on-going R&D projects were or are aimed at reducing or treating uncertainties associated with near-field systems and components. At the same time, various approaches have been or are being developed in national programmes and safety cases to treat, reduce, mitigate or even avoid safety-significant uncertainties. It is felt necessary to identify and exchange on possible management options and the contribution of these R&D projects to the overall management of these uncertainties. This would contribute to the identification of the remaining and emerging issues and needs associated with the management of these uncertainties.

1.1. Uncertainties related to the processes governing or altering radionuclide migration and the performance of disposal system components in the near-field

The processes governing or altering the evolution of the near-field of disposal systems are key to assessing the performance of their components and the release of radionuclide from the canisters or waste packages into the environment. Uncertainties related to the near-field constitute the "missing link" in current UMAN WP activities focusing on uncertainties related to the source term (spent fuel and other wastes), human aspects as well as to some aspects of the site and geosphere. (This missing link makes it difficult to gain the overall picture of safety-significant uncertainties. For instance, the relevance for safety and management options of uncertainties on the thermal output produced by spent fuel cannot be investigated without addressing the influence of temperature on the near-field and its safety significance.)

The near-field is – after the waste/waste matrix and the waste container- the third and last technical barrier just before the host rock. It is the area with the largest material heterogeneity (metal, bentonite, clay or crystalline rock and concrete), with the steepest temperature gradients, hydraulic and stress gradients and, related to the materials, chemical gradients initially, allowing for a complex near-field evolution, and keeping its barrier functionality for radionuclides in the very long term. In the safety case and safety assessment, each safety-related aspect of the near-field has to be considered, analysed, understood and integrated, together with their associated uncertainty [7-12].

The main remaining uncertainties related to conceptualisation of the technical barriers in scenario and model development selected by the expert group of sub-task 3.6 relate to the evolution of the near-field as expected with respect to:

- temperature evolution
- re-saturation and swelling pressure evolution,
- (bentonite) mechanical evolution

6. transport properties for each RN within the near-field

- Evolution at interfaces of the different materials (clogging preferential migration path)

1.2. Uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers

The concept for waste package and technical barriers is influenced by the waste type, the type of host rock and the depth of the repository. Different waste types, SF or vitrified waste may need different container materials or thicknesses for different host rocks due to unwanted canister degradation, gas production and/or canister life time requirements for different host rocks. Other uncertainties are associated with the behaviour of the host rock in the near-field when excavated (excavation method, speed…) and during operation, depending on the ambient air conditions (moisture, temperature) resulting from the ventilation and on the conception of retaining walls.

1.3. Uncertainties associated with thermal, hydraulic, mechanical, chemical, biological and radiation conditions and processes (THMCBR) dominating at different time scales*

* except those already taken into account in subtask 3.2 on the waste inventory and subtask 3.3 on geosphere and sites related uncertainties) as well as with gas migration in near-field systems.

The description of the heterogeneous near-field with respect to materials, hydraulics, mechanics, chemistry, microbes and radiation needs a lot of equations describing all the processes in such a system. Several of these processes are strongly coupled due to nonlinear dependence on parameters influenced by different processes. The processes might be dominating at different time scales, e.g. temperature during the first 1 000 years, re-saturation up to 10 000 years and more, chemical degradation/ reaction fronts up to 100 000 and more years. Also, the extent, duration and importance of each of these processes (taken individually even without accounting for their influence on each other) are also subject to uncertainty. A decoupled description of processes induces uncertainties on a correct system description with respect to evolution of the near-field and evolution of transport parameters in the near-field.

Performing statistical/sensitivity analysis for such coupled systems to identify the most important parameters, e.g. for radionuclide transport, and optimise the technical barrier system accordingly is computationally very expensive when possible at all at the moment. Nevertheless, uncertainties of processes, their parameters and their couplings have to be identified for a robust safety analysis.

1.4. List of near-field uncertainties relevant to the safety of radioactive waste disposal

Based on the analysis of the above mentioned categories of uncertainties by the expert group, a preliminary list of near-field uncertainties considered as being relevant for the safety of radioactive waste disposal was drafted. Table 1 presents and describes these uncertainties together with justifications for their selection.

Table 1. List of near-field uncertainties relevant to the safety of a radioactive waste disposal

Topic	**Uncertainty**	**Description/Justification**	**References**
1- Processes governing or altering radionuclide migration and the performance of disposal system components			
1.1- Transport properties for major ions and RN within the considered barrier medium	accessible porosity	Considered accessible porosity values in numerical models are generally deduced from the measured total porosity in an arbitrary manner	[13]
	diffusion coefficient *De*	Considered values of diffusion coefficient for the neutral elements, the cations and anions in numerical models are generally obtained experimentally for most representative RN and extrapolated for the other elements.	[13-17]
	partition coefficient *Kd* (already a conceptual model)	Kd is one of the most sensitive parameters in the transport models. Some assumptions associated with the conceptual model of Kd deserve to be verified (for each solute, is the relation between sorption and its concentration linear, is it the same relation in case of desorption…), and thus uncertainties are actually associated with the use of the Kd model.	[13, 18, 19]
	solubility limit	Considered values of solubility limit for each element in numerical models are typically deduced from lab measurements for very few elements and are extrapolated for the other elements. Due to strong chemical gradients within the near-field precipitation/dissolution fronts will develop in the near-field influencing solubility limits of elements	[20, 21]
	Evolution through time of transport properties	Reactions caused by the diffusion of reactants from different sources can alter rock diffusivity	[13, 21]
	ILW disposal zone	Saline plume (NaNO3 and NaSO4) : impact on RN behaviour	

	Microbiology	Impact on pH, Eh, speciation and transport behaviour of elements	[13, 22, 23]
1.2-Heat	Direct and indirect effects of temperature on RN migration	influence on re-saturation, chemical reactions material properties transport parameters, … and the maximum temperature at the canister due evolving cooling properties of materials in the near-field	
1.3-Flow properties	kinematic porosity	Values of kinematic porosity are generally deduced from the experimental total porosity in an arbitrary manner (a half, the quarter…).	[23]
	permeability - 2 phase flow	Is the host rock homogeneous in terms of permeability? For the concepts in clayey host rocks: - anisotropic effect on permeability - given the very low values of permeability in clayey rocks, what is the remaining uncertainty on its measurement (variability from a method to another (in-situ, laboratory))?	[24]
	hydraulic head gradient	Numerous measurements in well distributed boreholes around the site would be necessary to have a constrained hydrogeological near-field model. In addition, the vertical hydraulic gradient in the host rock is deduced from the measurements of hydraulic heads in the aquifers located above and below, when available, but may not be realistic	[13-], 16-18, 25-33]
	Uncertainty on the hydraulic properties of the near-field components	Depending on the host rocks, excavation damaged zones (EDZ) due to the repository construction (excavation) may have different horizontal and vertical extensions, different hydraulic properties and long term evolutions – different for different host rocks	[17, 18]
	Effects of re-saturation and swelling pressure evolution,	Correct swelling pressure achieved, seals as wanted, homogeneity of re-saturation and related pressure build-up	[34]
1.4-Mechanical processes	(bentonite) mechanical effect	Mechanical behaviour of the bentonite depends a.o. on: - homogeneity of bentonite backfill emplacement - homogeneity of re-saturation / water inflow - potential gaps, displacement of waste canisters	[33-39]

	Zone around HLW cells (HITEC)	- Mechanical behaviour influence of the non - linearity of the mechanical behaviour (fractured material properties, plasticity, thermal hardening) and the time - dependent behaviour of the COx (how it affects its response to a thermal load) - The thermal reactivity of the Boom Clay kerogen constitutes a factor of uncertainty. Because the kerogen in the Boom Clay is thermally immature, significant amounts of CO_2 and organic acids will be released during heating. This release may affect the mobility of radionuclides by complexation, while the dissolution of CO_2 in water, leading to pH reduction, may modify the near-field chemistry of the clay. - The different relationships between relative permeability and water saturation, or the retention curves, implemented in different THM codes, led to a wide range of buffer re-saturation times.	[40]
	transport properties for each major elements and RN within the near-field	Solute and gas transport parameters are temperature dependent and phase dependent. Both develop from initially dry and hot conditions to wet and cold conditions…	[40]
	interfaces of the different materials (clogging preferential migration path)	Extension , thickness , and consequences for RN and gas transport	[41]
2- Uncertainties to be taken into consideration when conceptualizing waste packages, technical barriers and adjacent EDZ of natural barriers	Metallic material behaviour (steel, copper, copper coated steel, composite, super container, …) in different barriers (waste package, liners…)	Lifetime, gas generation and pressure build-up, other degradation processes pH-, Eh-evolution, pit corrosion, colloid formation In performance assessment, near-field evolution calculations and radionuclide transport calculations are not coupled. For RN transport calculations stepwise (spatial and temporal) constant transport parameters are assumed. This approximation is not that easy to assess.	
	interface processes at which time scale and spatial extension	Pore clogging and no further gas transport might be a serious problem in tight host rocks (clays)	

	fully 4 D description or 1 D or mixed compartments, …	Direct comparison difficult to perform because of long computational times in 4D	
	bentonite-crystalline interface	Study of transport at the bentonite-EDZ interface, a key area for determining RN transport in the near-field	
	Multiphase flow (DONUT SoTA)	a. The complex porosity structure of the bentonite which requires the use of dual and triple continuum models (Marcelo Sanchez and Olivella, 2005, 2012, 2016) b. The retention curve of the bentonite (and other buffer materials and host rock) : gas entry pressure, hysteresis and temperature dependence	[42-44]
	Extent of EDZ, geometry and opening of fractures	Depends on - the hydro-mechanical properties of the host rock - the excavation method, its speed as well as the speed and nature of the retaining walls - the operational conditions, notably ventilation (moisture, temperature of ambient air)	
	Concrete	Carbonatisation processes during operational phase and re-saturation phase > mechanical impact?	
3- **Uncertainties associated with THMCBR processes dominating at different time scales as well as with gas migration in near-field systems**			

DONUT SoTA: Amongst others example of the remaining uncertainties of the coupled THMC models of the EBS that need further research include:	Reactive solute transport (DONUT SoTA)	a. Relevance of reactive gases such as CO2(g) and O2(g) b. Solute diffusion from the EBS into the host rock c. Alternative conceptual models of solute diffusion in the EBS: i. The single interlayer-porosity Donnan equilibrium model (Birgersson, 2017) ii. The electrochemical model based on the Nernst-Planck equation (Idiart and Pkekala, 2016) iii. The multiple porosity (interlayer, double layer and free) model (Samper et al., 2008; Zheng and Samper, 2015). iv. The use of different effective diffusion coefficients for each chemical species while preserving charge balance	[45-46] [47-48]
	Geochemistry (DONUT SoTA)	a. Precipitation of the secondary mineral phases at the canister-bentonite interphase such as Fe-phyllosilicates (chlorite, cronstedtite and berthierine); Fe-rich smectites and zeolites such as phillipsite, chabazite and merlionite; b. Precipitation of secondary mineral phases at the concrete-bentonite interphase such as CSH, CASH, zeolites such as phillipsite, chabazite and merlionite, and iron silicates c. Fe reduction in the bentonite d. The uncertainties in the kinetic rate laws, rate constants, reactive surfaces and catalytic effects of kinetic mineral dissolution/precipitation. The dynamic update of the reactive surface areas of the minerals;	[49]
	Coupled effects (DONUT SoTA)	a. Changes in porosity and other transport and chemical parameters caused by mineral precipitation/dissolution reactions b. Simulating canister corrosion in a more realistic manner by adopting a dynamic corrosion front; c. The coupling of the evolution of the bentonite microstructure with the changes in the composition of the exchange complex	[49]
BEACON	Bentonite re-saturation, (BEACON, EARB reports))	Modelling of different bentonite re-saturation experiments (HM modelling): final saturated state can be reproduced in terms of water content and dry densities, however the dynamics of the hydration process remains difficult to predict. Understanding the dynamics of the hydration process is especially important when predicting bentonite hydro-mechanical evolution of bentonite barriers within real repositories.	[34]

		The total pressures and displacements remains difficult to reproduce. The EARB believes that adequate prediction of stresses is important since in some concept swelling pressure is a parameter supporting safety functions. Some analyses have shown the sensitivity of the results to some parameters such as retention curve or swelling pressure dry density relationship. The EARB therefore agrees with the BEACON conclusion identifying the need to determine more precisely a set of basic but essential data for a better representation of the physical processes that develop within bentonites during hydro mechanical solicitations. The EARB thinks that the non-sensitivity of the models to the initial dry densities distribution is contradictory to experimental observations (e.g. EB experiment where zone of low initial dry densities does not reach complete homogenization). The EARB notices the large dispersion in the prediction of both axial and radial stresses between the modelling teams both during the transient and the final state. Adequate prediction of stress is however important since in some concept swelling pressure is a parameter supporting safety functions. Areas for improvement should be identified. Sensitivity of the models to the micro-macro interaction functions, the retention curve and the swelling pressure dry density relationship are quite relevant for further investigations.	
ACED	D2.4 Treatment of chemical evolutions in national programmes	Interface between steel overpack and buffer: These geochemical calculations have been made at 25C since most thermodynamic data are related to this temperature. The influence of temperature on dissolution and precipitation of mineral phases could reduce the uncertainty in the calculated results Chemical evolution post overpack failure: Early canister failure due to aggressive species There is a large uncertainty on the composition of the pore water composition and the composition of the buffer, mainly because the time of failure due to aggressive species is very uncertain Hydraulic gradients:	[50]

		considerable uncertainty exists with respect to the potential development of a gas phase. For compacted waste (CSD-C), hydrogen is produced through the corrosion of caisson reinforcement bars, primary canisters and metals contained in the waste forms. The relative importance of each source term depends on the reactive surface area and corrosion rate in disposal conditions (anaerobic, alkaline). Conceptual Model Uncertainties: The biggest uncertainty in the safety assessment is the representativeness of data and models: For the geochemical evolution of the cementitious materials, more or less scoping calculations have been performed to see what a minimum in the period in time for the alkaline beneficial conditions could be. Precipitation and dissolution of mineral phases have been calculated but changes in porosity as a result of these processes have been excluded i.e. constant values for diffusion of dissolved species has been assumed. Sorption of species has been excluded. The geochemical interaction of the clay host rock with corrosion and degradation products from the EBS were to be assessed in OPERA(2011-2017). Whether concrete interfacing clay is represented by assuming a constant pore water composition is a large normal scenario evolution uncertainty. A large modelling uncertainty is the calculated impact of advective flow i.e. the chlorine concentration is negligible from the clay-concrete till ten metre into the clay. The impact of corrosion gases such as hydrogen has been excluded. The biggest uncertainty in the safety assessment is the representativeness of data and models e.g. instant release of all radionuclides i.e. neglecting the corrosion resistance of Zircaloy	
ACED	D2.5 Experiments and numerical model studies on interfaces	Evidences on the occurrence of pitting corrosion during the post-closure stage can create uncertainty about the performance of the metallic containers.	[51]
ACED	D2.6 Modelling of the steel-clay interface - approaches, first results and model refinements	There are uncertainties in the prediction of the pH of bentonite pore water due to $CO_2(g)$degassing liquid phase which was not taken into account in the model Since there are numerous uncertainties such as lack of defined back-end strategy, thus inventory of the highly active residue of nuclear energy production, availability	[52]

		of suitable host rock formation, appropriate repository area, the main geometry and geological characteristics of the selected host area etc., the disposal concept is going to be revisited before each decision points. These revisions might result the changing of the original design, therefore we are fully committed to exploring new ideas, to improve suitable concept to serve our decision makers.	
ACED	D2.10 HLW: Report describing the selected experiments and the existing/expected experimental results	Solid or interface characterization: Uncertainties associated to the different techniques (SEM, XRD, Tof-SIMS)	[53]
CONCORD, MAGIC	No MS/SoTA available so far		

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