European Joint Programme on Radioactive Waste Management

7.3.2 Characterise uncertainties and determine their implications for the outcome of the safety assessment (Treatment of uncertainty)

Domain Insight

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Overview

Uncertainties arise in all phases of the implementation of a radioactive waste disposal programme. They can be due to a lack of knowledge about processes and data (epistemic uncertainties) or to random influences (aleatory uncertainties). This distinction is not always unique, and many uncertainties contain components of both types that are sometimes hard to separate from each other, but in practice there is a difference in their handling: epistemic uncertainties are considered to be principally reducible by further research, while aleatory uncertainties are inherent to the system and are associated with, for example, unpredictable natural events. Consequently, epistemic uncertainties are mainly handled by generating knowledge, while aleatory uncertainties are handled by mitigating their influence on system safety.

While some uncertainties occur and can be handled during the pre-closure phases of a disposal facility, others become relevant in the long term after closure and could, in principle, affect the safety of the system or the validity of its assessment. These latter uncertainties can be grouped into scenario uncertainties, model uncertainties and data uncertainties. The final safety statement resulting from the safety case for a disposal facility, however, should be as certain as possible, and this can be achieved through a combination of measures and assumptions that aim either at avoiding the uncertainty, reducing it, or mitigating its influence. Appropriate strategies have to be defined to handle each kind of uncertainty.

Keywords

Uncertainties, uncertainty management, uncertainty quantification, uncertainty assessment, expert judgement, probabilistic approach, Monte-Carlo methods.

Key Acronyms

Acronyms used in this report are explained where they occur for the first time.

1. Typical overall goals and activities in the domain of *Treatment of uncertainty*

This section provides the overall goal for this domain, extracted from the EURAD Roadmap goals breakdown structure (GBS). This is supplemented by typical activities, according to phase of implementation, needed to achieve the domain goal. Activities are generic and are common to most geological disposal programmes.

The domain is assigned to Theme 7 (Safety Case) and Sub-Theme 7.3 (Safety Assessment and Tools) but as uncertainties occur everywhere, it has a more general character and is therefore presented in broader sense.

<table>
<tr><th colspan="2">Domain Goal</th></tr>
<tr><td colspan="2">7.3.2 Characterise uncertainties and determine their implications for the outcome of the safety assessment (Treatment of uncertainty).</td></tr>
<tr><td colspan="2">Domain Activities</td></tr>
<tr><td>Phase 1: Programme Initiation</td><td>Identification and quantification of relevant general uncertainties that are associated with the disposal programme but independent of the site (amount of waste, fuel burn-up, interim storage time, etc.).</td></tr>
<tr><td>Phase 2: DGR (Deep Geological Repository) Site Identification</td><td>Identification and quantification of site-specific uncertainties for each candidate site, identification of uncertainty management options for different sites, assessment and comparison of manageability of uncertainties, uncertainty analysis in orienting performance assessments.</td></tr>
<tr><td>Phase 3: DGR Site Characterisation</td><td>Compilation and quantification of all relevant uncertainties specific to the selected site. The list should be as complete as possible. Uncertainties should be assessed verbally, but individual uncertainties should only be excluded if there is strong evidence for their non-relevance. Performance assessments should include uncertainty analysis. Options and strategies for managing the uncertainties have to be developed.</td></tr>
<tr><td>Phase 4: DGR Construction</td><td rowspan="2">Continuous critical assessment and re-evaluation of previously identified uncertainties. Newly arising uncertainties, due to unforeseeable events, changes in the construction or operation plans, political decisions etc. have to be identified and appropriate management strategies have to be developed.</td></tr>
<tr><td>Phase 5: DGR Operation and Closure</td></tr>
</table>

2. Contribution to generic safety functions and implementation goals

The safety function of a disposal system is provided by a combination of components, each contributing to the safety requirements in its specific manner. The EURAD Roadmap Generic Safety and Implementation Goals (see, Domain 7.1.1 - Safety requirements) should be fulfilled. The system components, however, are subject to various influences, which themselves are more or less uncertain. During the implementation of a disposal programme, it is essential to identify and, where possible, quantify all relevant uncertainties and manage them in an appropriate manner, so that the fulfillment of the safety goals is adequately ensured and not jeopardised in the long term. Although the focuses of uncertainty treatment may, to some extent, differ between the different safety and implementation goals, the general approach is the same and is described in the following in a generic manner.

Uncertainties result from a lack of knowledge. To capture them correctly, it is necessary to keep in mind that we do not always know what we know or do not know. There are three categories of non-knowledge that should be taken into account:

- *Known unknowns:* Things we know we do not know. For instance, the numerical values of physical parameters that are needed to describe relevant effects or phenomena but are unknown or uncertain for the situation under investigation.
- *Unknown/ignored knowns:* Things we principally know but we are not aware of being potentially relevant or we ignore, for whatever reason, intentionally.
- *Unknown unknowns:* Things we do not know we do not know. That means influences we are not aware of even existing or unforeseeable events. This is crucial as the uncertainty itself is uncertain and therefore hard to capture.

In a practical study like a repository safety case, one might tend to consider only the first of these categories, as it is the most obvious and manageable one, but one should never lose sight of the fact that the range of uncertainties is always larger than that.

Uncertainties arise in all phases of the implementation of a disposal programme and can concern scientific, technical and operational aspects as well as societal and financial ones. The phase in which an uncertainty arises is not necessarily the one with the highest relevance for safety. Uncertainties which are relevant only during the pre-closure phases allow a direct reaction to unforeseen developments or events, so that they are less likely to affect long-term safety. Nevertheless, the safety statement about the repository system will be subject to some uncertainty, and it is important to quantify this uncertainty as accurately as possible. In principle, throughout the implementation phases, the uncertainty of the safety statement should never increase, but if it does, this is a sign of false uncertainty estimation at an earlier stage, either because a known unknown was not well captured, because some relevant influence was ignored or because a previously unknown unknown has come to light. It is therefore important to thoroughly assess all uncertainties, their safety relevance and their interactions in a clear traceable and reliable manner, and keep the assessment updated over the entire programme.

There are various options to treat and manage uncertainties. Appropriate management strategies should be developed for all uncertainties, once they have been identified and, as far as possible, quantified. Such strategies may aim at:

- *Reducing* the uncertainty by measures to improve knowledge about bandwidths of safety-relevant influences, e. g. by research and development (R&D), field investigations, and site exploration, but also by quality control of materials and installations;
- *Mitigating* the effects of the uncertainty by conceptual measures that reduce the general relevance of an uncertainty, which could be reached by arranging for additional barriers or shifting parts of the safety function to less uncertain components of the system;
- *Avoiding* uncertainty by completely excluding the uncertain component from the system, where possible.

Some possible elements of strategies are listed below (this is not a complete list).

Conceptual measures. Potentially problematic uncertainties that probably cannot be significantly reduced should be identified early in the programme and, if possible, mitigated by conceptual measures that remove parts of the safety function from the problematic component.

FEP analysis. The future development of a repository system is influenced by a number of factors like climate, geological evolution, seismic events etc., which are rather uncertain. Analysing and combining FEPs (Features, Events, Processes) is an established means to build and assess scenarios of system evolution and to manage scenario uncertainties.

Research and development programmes. Many uncertainties result from a lack of knowledge about some processes. R&D programmes contribute to deepening the understanding of uncertain processes and determining reliable data for parameters that represent them. Such programmes can comprise, for instance, measurements, laboratory experiments on different scales, in-situ investigations, process modelling or development of techniques and materials. Generally, the uncertainty about processes and data is reduced by such investigations. One should not lose sight, however, of the relevance of the investigated uncertainty for repository safety. R&D should predominantly focus on the most relevant uncertainties.

Natural analogues. Evaluating natural analogues of barrier performance can, in specific cases, provide a valuable contribution to reducing uncertainty. Analogues can be considered as natural long-term experiments.

Conservatism. If it is not possible to reduce an uncertainty, one can consider accounting for its influence on the overall safety statement by using conservative assumptions or data. Such assumptions may deviate from the realistically expected conditions, being intentionally shifted towards worst-case conditions, so that some additional safety margin is present in the safety assessment. The problems with this approach are twofold. Firstly, due to the nonlinear behaviour of complex coupled systems, an uncertain parameter can have a non-monotonic effect on safety, so that identifying a uniquely conservative assumption about its value is difficult or even impossible. For example, a conservative assumption could be made about the temperature induced at the surface of a metal container, with an assumed high temperature giving the highest possible corrosion rate. However, high temperature could imply local desaturation leading to reduced water availability for corrosion and a reduced container corrosion rate. Identifying the most conservative conditions whilst ensuring a credible and consistent overall treatment of uncertainty may not be straightforward.

The second potential problem is that conservatism generally reduces the safety margin, possibly resulting in loss of confidence in the investigation. In extreme cases, over-conservatism can even lead to unacceptable results. Therefore, conservatism should always be applied with care.

Quality assurance. Requirements for system components and applied materials to be checked after production are proven means to reduce uncertainties. Components not complying with the specifications are rejected. This can be done either by checking each individual part of a kind, e.g. each individual waste canister, or on a statistical basis by checking only a test or representative sample. Strong quality assurance leads to effective uncertainty reduction but can cause high costs. Also, for numerical models and codes that are used to assess barrier performance or future consequences of radionuclide releases, quality assurance is necessary to reduce the probability of incorrect results.

Benchmarking. The uncertainty of assessment results can be reduced by comparing them with other, independently obtained results for comparable situations. Benchmarking of approaches and tools between different teams is a valuable means of uncertainty management.

Probabilistic approach. In long-term safety investigations on the basis of numerical simulations, specific sets of data are used. Each model input parameter has its own uncertainty. To take all the parameter uncertainties into account, the probabilistic approach is an approved means. Each parameter is assigned a statistical distribution representing its uncertainty. Interdependencies between different parameters are incorporated by appropriate methods to obtain a multi-parameter distribution. Then a number of parameter value sets are generated by some appropriate sampling method from this multi-parameter distribution and the numerical model is evaluated many times according to the sets of parameter values. From the results, statistical statements about the model output as well as parameter sensitivities can be derived (Swiler et al., 2021), which help to better quantify the significance of uncertainties. However, an essential precondition for probabilistic approaches to yield significant results is that the initial parameter distributions are correctly quantified to represent the actual non-knowledge about the parameter values.

3. International examples of *Treatment of uncertainty*

Uncertainties occur in all geological disposal programmes and need to be addressed in an appropriate manner when developing safety cases. In the different countries with their differently developed programmes, there exist different regulatory requirements and practices of addressing uncertainty. In the following sections, three examples of key issues and approaches to handling uncertainties are described briefly, referring to an early-stage programme (Germany), a more developed programme (Switzerland) and an advanced programme (Finland).

Germany: The German regulations require that the radioactive wastes have to be safely enclosed passively in a maintenance-free, robust system of barriers. As the main barrier a specifically qualified region of the host rock - the containment-providing rock zone - is planned to be identified, if that is possible. In crystalline formations containing networks of inter-connected permeable fractures, however, it is unlikely that a sufficiently large rock zone will be found that provides isolation and containment by itself, so in this case the containment may be provided by technical and geotechnical barriers (EndlSiAnfV 2020).

This concept is an approach to mitigate uncertainties related to the release and migration of radionuclides that may occur during the operational and post-operational phases. As it assigns the main retention function to one specific natural or technical barrier, uncertainties about retention occurring in other parts of the disposal system may be assumed to be less important.

The German site selection act (StandAG, 2017) requires the identification of those regions that, according to specific criteria, provide suitable conditions for safe containment of radioactive waste. For each of these regions, preliminary safety investigations have to be performed (EndlSiUntV, 2020). These include the assessment of uncertainties existing at the time of the investigation. Uncertainties, including their connections and interactions, have to be systematically identified and characterised, and it has to be assessed how they might affect the results of the preliminary safety investigations.

Uncertainty assessment in the context of a preliminary safety investigation will start with a general overview and categorisation of the unknown influences, including aleatory as well as epistemic uncertainties. In a first step, these uncertainties should be screened by verbal argumentation. For each uncertainty considered relevant, management options should be identified and justified. Such options could be, for instance, reducing uncertainty by R&D or by quality assurance, or mitigating uncertainty by conservative assumptions. Some uncertainties, however, will have to be accepted as they are. These should be quantified as properly as possible and their effects on the uncertainty of the preliminary safety investigation should be assessed. Probabilistic approaches to uncertainty and sensitivity analysis are an approved means for such assessment (Swiler et al., 2021).

Switzerland[1]: The guideline of the Swiss regulator, Eidgenössisches Nuklearsicherheitsinspektorat, ENSI-G03 states the need to minimise uncertainty, whilst also acknowledging the inevitability of uncertainty and the need to understand its influence on safety assessments. It states, in particular, that the safety case shall provide information on the reliability of the claims made and on the safety relevance of uncertainties, and that uncertainties shall be reduced, as far as necessary and possible, by research and data collection. As highlighted by the regulator, the focus of uncertainty management at Nagra, the Swiss National Cooperative for the Disposal of Radioactive Waste, is to quantify uncertainties and to identify the uncertainties that may be safety relevant.

The Repository programme aims to quantify and minimise the uncertainties in the evidence, knowledge, assessment tools, and methodologies forming the assessment basis. Parameter uncertainty relating to collected data, whether the source is experiments, field observations, literature, or expert elicitation, is quantified by assigning bounding values or probability density functions (PDFs) where possible. If available data and the associated uncertainty are deemed relevant to safety, the associated parameter uncertainty is reduced, if possible, through R&D studies, etc. In all instances independent review

[1] This text was kindly provided by Li Xiaoshuo, Nagra, Switzerland

processes and good documentation practices ensure both the credibility and traceability of the collected data and the treatment of uncertainty, such as through derived bounding values and PDFs.

In the framework of Nagra's overall uncertainty management strategy, a range of standard practices is implemented to reduce model uncertainties. Examples of such practices are comparison of available models, validation of the models against experimental/analytical data and benchmarking the results of the modelling studies against other models. Robust quality assurance procedures, independent review processes and good documentation practices supplement the uncertainty management programme at Nagra. For modelling studies carried out for performance assessment and analysis of radiological consequences, additional methods to bound the uncertainty of the model outputs are implemented. Use of simplification in the abstraction of the model where justified, use of conservatism and global uncertainty analysis using deterministic and probabilistic approaches are among the methods implemented.

Additionally, the impact of highly pessimistic cases or extremely uncertain events in the distant future are characterised by analysing 'what-if?' cases and stylised scenarios, respectively. Although the completeness of an uncertainty management programme cannot be guaranteed, measures such as using FEP databases and interactions with the wider and international communities support the aim of achieving completeness.

Finally, the quality control and quality assurance practices implemented at Nagra lead to the minimisation of human error in every stage of the project.

Finland[2]: In Finland, uncertainties are directly handled within the safety case of the ONKALO final repository. The safety case is a key document within Posiva's operating license application for the spent nuclear fuel repository, submitted to the Finnish Radiation and Nuclear Safety Authority (STUK) in December 2021. The safety case is continuously updated based on new knowledge and requirements from the authorities. The safety case includes numerically "demonstrating the potential generation of radiation doses to the environment in the event of failure of one or more engineered release barriers and release of radioactive substances from the repository to the living environment. […] The safety case also addresses uncertainties related to the behaviour of the disposal solution and to the assessment of various possible events and developments. The risk assessment takes into account the likelihood of events". (Posiva, 2023a). Uncertainties are handled in a numeric way with mathematical models for the required one million years of repository evolution. Posiva's Operating License Application is public. (Posiva, 2023b).

Posiva's safety case methodology defines in Step 4 to define the "scenarios based on the evolution, analysis of the performance and remaining uncertainties" and these uncertainties are tied to the design requirements as well as design loads and conditions of the expected repository environment, as defined in previous steps. (Posiva, 2023c). There is also the defined Step 6 of developing "complimentary considerations in parallel to the safety analysis to enhance overall understanding and provide context to the residual uncertainties" (Posiva, 2023c). Within the Performance Assessment and Formulation of Scenarios (PAFOS), these "scenarios are formulated based on uncertainties or deviations identified throughout the safety case assessment iterations".

Posiva's safety case shall adhere to the STUK Guide YVL D.5 (STUK, 2018a), which describes the main features that must be demonstrated as safe. The repository safety case must be in compliance with Regulation STUK Y/4/2018 (STUK, 2018b), for instance with clause 36 (addressing uncertainties) that states:

"The safety case and the methods, data and models used in it shall be based on high-quality research data and expert judgement, and they shall be documented in a traceable manner. The data and models shall be appropriate and correspond to the anticipated conditions at the disposal site and system during each assessment period.

[2] This text was kindly provided by Erika Holt, VTT, Finland and is based directly on publicly available text

The basis for calculational analyses shall be that the actual amounts of radioactive substances released and the actual radiation exposure shall be, with a high degree of certainty, lower than the results received from the safety analyses. The safety case shall separately assess the uncertainties included in the data, models and analyses and their significance."

4. Critical background information

Some specifically critical aspects and challenges of *Treatment of uncertainty* are highlighted in the following.

Identification of uncertainties. Although it is important to identify all relevant uncertainties that might occur, familiar uncertainties can be forgotten or underestimated, or the uncertainty analysis may concentrate on uncertainties that can be managed by established methods.

Subjective bias. We often tend to concentrate on things we have a good command of while neglecting those where we are less proficient, regardless of their relevance. For instance, when a numerical model is used to calculate future radiation exposure, a lot of effort is often put into numerical uncertainty and sensitivity analysis, possibly applying sophisticated mathematical methods, but one must not lose sight of the fact that this does not analyse the uncertainties of the real system but those of the model. Whether or to what extent the model is adequate to represent the real situation has to be assessed independently and this can be much more relevant than the influence of a specific model parameter.

Unknown unknowns. During the implementation of a repository programme and the post-closure phase, events or uncertainties might occur that no one has thought of.

Quantification of identified uncertainties. The uncertainty of the final safety statement can only be specified if the primary uncertainties are quantified as reliably as possible. It makes little sense, for instance, to perform detailed probabilistic uncertainty analysis with parameter distributions that were roughly estimated based on very limited information or knowledge. Proper quantification of numerical uncertainties is an important issue.

Treatment of non-quantifiable uncertainties. Some uncertainties are principally non-quantifiable. They should be handled by showing that they do not have significant influence on overall safety, regardless of their characteristics.

4.1 Integrated information, data or knowledge (from other domains) that impacts understanding of the *Treatment of uncertainty*

Uncertainties occur in every phase of the repository implementation process and every domain defined in the GBS, each requiring specific management approaches. A central part of the safety case is the assessment of risks to future generations (sub-theme 7.3), including the domain described in this document (7.3.2). Treatment of uncertainty, however, is a higher-level issue that is relevant in all themes and domains of the GBS, becoming increasingly relevant as soon as predictions about repository performance in the future are being made, which is mainly the case in themes 6 - Siting and Licensing and 7 - Safety Case. Uncertainty management strategies are essential components of processes dealing with establishing data and undertaking long-term safety assessments.

During the site selection phase, it is necessary to investigate candidate sites and to present long-term safety assessments for each of them in order to create a decision basis (sub-theme 6.2). Uncertainties in this phase will be rather high, however, as one can put only limited effort in site investigation and data establishment for a larger number of sites. Therefore, proper estimation of uncertainties and their consequences to the safety statement is essential in this phase. For a site to remain in the candidate list, it is necessary to prove that safety will not be jeopardised by uncertainties, including those that might only become obvious during detailed investigations after selection of the respective site. Uncertainty management strategies in this phase might aim at generally mitigating many kinds of uncertainty by introducing strong requirements on safety-relevant system components whose uncertainty is considered to be assessable and manageable, such as requirements for a thick and tight host rock layer or a specifically qualified overburden.

Once the site has been identified, a comprehensive safety case (Theme 7) has to be made. Relationships to treatment of uncertainty exist predominantly with establishing safety and performance indicators (domain 7.1.2), information, data and knowledge management (7.2.2), performance assessment (7.3.1) and scenario development / FEP analysis (7.3.3). All these domains require thorough identification and quantification of uncertainties (Brendler et al., 2023). These comprise the classical categories of scenario, model and data uncertainties.

5. Maturity of knowledge and technology

Different kinds of uncertainty require different strategies and approaches for their handling. EURAD WP 10 “Uncertainty management multi-actor network” (UMAN) as a strategic study aimed at developing a common understanding among different actors, identifying contributions of past and on-going R&D projects as well as identifying remaining issues and needs associated with uncertainty management. UMAN deliverables provide an overview of the state of the art under different aspects.

For the safety case, three categories of uncertainties are of specific relevance:

Scenario uncertainties: The FEP approach is a well-developed means of systematically identifying and categorising scenarios and their uncertainties (NEA 2019).

Model uncertainties: There is no systematic approach to assessing model uncertainties. To some extent this can be done by model validation, but this is problematic for models of long-term repository performance.

Parameter uncertainties: The challenge with this kind of uncertainty is twofold: firstly, the uncertainties of the parameters have to be correctly quantified (as a statistical distribution) to reflect the actual uncertainty as well as possible. Secondly, the effects of parameter uncertainties on safety assessment results have to be calculated. While for the second task the probabilistic approach provides a well-established, mathematically elaborated means, the first task requires a combination of expert judgement, quality assessment and mathematical tools and there is still no well-established approach to this.

5.1 Past and ongoing (RD&D) projects

Past (RD&D) Projects:

- EU PAMINA: (2006 – 2009): Performance assessment methodologies in application to guide the development of the safety case (see links [1] and [2]).

Ongoing (RD&D) Projects:

- EURAD WP10: UMAN – Uncertainty Management Multi-Actor Network (see link [6]).
- EURAD WP 4: DONUT – Development and Improvement of Numerical Methods and Tools for Modelling Coupled Processes (see link [7]).

6. Methodological uncertainties

The issue of uncertainty treatment itself is subject to a variety of uncertainties, including completeness of identified uncertainties, unknown unknowns, quantification of numerical uncertainties, assessment of expert judgment and more. Such meta-uncertainties contribute to the overall uncertainty of the safety case and must also be addressed in the uncertainty assessment.

7. Further reading, external links and references

7.1 Further reading

EURAD WP10 (Uncertainty Management multi-Actor Network – UMAN) deals with uncertainties, their identification, quantification and management options. UMAN deliverables provide a comprehensive overview of the state of the art. The following deliverables are specifically recommended for orientation:

EURAD D10.2: UMAN – Generic strategies for managing uncertainties (Hicks et al, 2022).

EURAD D10.3: UMAN – Uncertainty identification, classification and quantification (Brendler et al., 2023).

EURAD D10.11: UMAN - Study on management options for different types of uncertainties and programme phases (Kaempfer et al., 2023).

7.2 External links

[1] https://cordis.europa.eu/project/id/36404

[2] https://igdtp.eu/activity/pamina-performance-assessment-methodologies-in-application-to-guide-the-development-of-the-safety-case/

[3] https://cms.posiva.fi/

[4] https://www.posiva.fi/en/index/finaldisposal/long-termsafety.html

[5] https://cms.posiva.fi/posivas-safety-case-introduction/common-introduction-to-safety-case

[6] https://www.ejp-eurad.eu/implementation/wp10-understanding-uncertainty-risk-and-safety-uman

[7] https://www.ejp-eurad.eu/implementation/development-and-improvement-numerical-methods-and-tools-modelling-coupled-processes

7.3 References

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EndlSiUntV (2020): Endlagersicherheitsuntersuchungsverordnung vom 6. Oktober 2020 (BGBl. I S. 2094, 2103)

ENSI (2020): Geologische Tiefenlager, Ausgabe Dezember 2020, Richtlinie für die schweizerischen Kernanlagen, ENSI G03/d

Hicks et al. (2022): UMAN – Strategies for managing uncertainties. EURAD Deliverable D10.2

Kaempfer et al. (2023): UMAN – Study on management options for different types of uncertainties and programme phases. EURAD Deliverable D10.11

Nagra (2024), NTB 24-19: Methodologies for assessing repository performance and safety in support of the general licence application (in preparation)

NEA (2019): International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste, Version 3.0, NEA/RWM/R(2019)1

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Posiva (2023b): Safety Case for the Operating License Application (SC-OLA), Posiva Oy. 2023. Access rights available at link [3]

Posiva (2023c) Posiva. Common Introduction to Safety Case, link [5], accessed November 2023.

StandAG (2017): Standortauswahlgesetz vom 5. Mai 2017 (BGBl. I S. 1074), das zuletzt durch Artikel 8 des Gesetzes vom 22. März 2023 (BGBl. 2023 I Nr. 88) geändert worden ist

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STUK (2018b): Regulation STUK Y/4/2018. Radiation and Nuclear Safety Authority Regulation on the Safety of Disposal of Nuclear Waste. 2018, Helsinki, 17 p. available at https://www.stuklex.fi/en/maarays/stuk-y-4-2018

Swiler, L. P. et al.: Sensitivity Analysis Comparisons on Geologic Case Studies: An International Collaboration (Volume 1). SAND2021-11053, 2021.

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