European Joint Programme on Radioactive Waste Management

Deliverable 10.1: UMAN - Training materials

Work Package 10

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°847593.

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

Document information

Project Acronym	**EURAD**
Project Title	**European Joint Programme on Radioactive Waste Management**
Project Type	**European Joint Programme (EJP)**
EC grant agreement No.	**847593**
Project starting / end date	**1st June 2019 – 30 May 2024**
Work Package No.	**10**
Work Package Title	**Uncertainty Management multi-Actor Network**
Work Package Acronym	**UMAN**
Deliverable No.	**10.1**
Deliverable Title	**UMAN - Training materials**
Lead Beneficiary	**Bel V**
Contractual Delivery Date	**May 2023**
Actual Delivery Date	**31 May 2023**
Type	
Dissemination level	**PU**
Authors	**Valéry Detilleux (Bel V), Attila Baksay (TSENERCON), Jeroen Bartol (COVRA), Dirk Alexander Becker (GRS), Vincenz Brendler (HZDR), Chris de Bock (ONDRAF/NIRAS), Julien Dewoghélaëre (NTW), Tim Hicks (GSL), Jeroen Mertens (Bel V), Jitka Miksova (SURO), Klaus-Jürgen Röhlig (TUC), Peter Schillebeeckx (JRC)**

To be cited as:

Detilleux V., Baksay A., Bartol J., Becker D.-A., Brendler V., de Bock C., Dewoghélaëre J., Hicks T., Mertens J., Miksova J., Röhlig K.-J., Schillebeeckx P. (2023): EURAD Uncertainty Management multi-Actor Network - Training materials. Final version as of 31.05.2023 of deliverable D10.1 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

Disclaimer

Acknowledgement

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

Status of deliverable		
	By	Date
Delivered (Lead Beneficiary)	Valéry Detilleux Bel V	26/05/2023
Verified (WP Leader)	Daniela Diaconu RATEN	29/05/2023
Reviewed (Reviewers)	Not applicable	
Approved (PMO)	Elisabeth Salat IRSN	01/06/2023
Submitted to EC (Coordinator)	ANDRA	02/06/2023

Executive Summary

This report contains the aims, the learning outcomes and the description of the training course organised by the Work Package UMAN on February 14-16 2023 at Bel V (Brussels, Belgium). The report also contains abstracts of the lectures, the slides prepared and presented by each lecture, a career summary of these lecturers and the test organised at the end of the training course.

Table of content

1. Introduction

UMAN is a Strategic Study Work Package dedicated to the management of uncertainties potentially relevant to the safety of different radioactive waste management stages and programmes. It includes various activities such as exchanges on views, practices and uncertainty management options and the review of existing strategies, approaches and tools. Interactions between different types of actors including civil society are central to this WP. These interactions are aimed at meeting the shared objective of fostering a mutual understanding of uncertainty management strategies, approaches and preferences. A particular focus is put on uncertainties in direct link with RD&D WPs and with a high (and where relevant medium) priority subdomain of the SRA for which exchanges of information and experiences and strategic studies have been identified as beneficial by the JP actors themselves. The WP considers past and present EU projects on the topics of interest and other initiatives carried out at international level such as IAEA and NEA. The WP allows identifying the contribution of past and on-going RD&D projects to the overall management of uncertainties as well as remaining and emerging issues associated with uncertainty management that could be addressed in subsequent waves or implementation phases of EURAD.

Owing to the nature of a strategic study, it is not foreseen to increase in EURAD the scientific knowledge. Nonetheless, the work carried out in UMAN leads to the development or improvement of strategies, approaches and tools. The knowledge consolidated in UMAN or generated through knowledge/know-how sharing and discussions in UMAN of common challenging issues constitutes a valuable input to knowledge management activities. Therefore, in collaboration with WP13 (Knowledge Management) of EURAD, UMAN has prepared and organised on 14-16 February 2023 (at Bel V, Brussels, Belgium) a training about Uncertainty Management and some important aspects addressed in UMAN. The present deliverable documents the preparation and the organisation of the course.

1.1 Training aims

The main aim of the training is to address the training need “7.3.1 Treatment of uncertainty” identified by EURAD Work Package 13 as one the five most urgent and highest priority topics[1]. The training will also address other urgent and high priority topics such as “7.1 Safety strategy”, “3.1 Confirm wasteform compositions, properties and behaviour under storage and disposal conditions, including impact on the disposal environment (wasteform)” or “‘3.1.1 Spent Nuclear Fuel”.

1.2 Learning outcomes.

Upon successful completion of this training course, participants should be able to:

- Understand and classify the different types of uncertainties that may need to be managed in a RW disposal programme;
- Explain the links between uncertainty management, the safety case and the decision-making process;
- Use the global UMAN scheme of uncertainty management strategies;
- Explain the main strategies and approaches available to manage uncertainties;
- List the approaches available to perform uncertainty and sensitivity analyses and discuss their pros and cons;
- Grasp the views of Civil Society representatives involved in EURAD on uncertainty management;

[1] See EURAD Deliverable 13.10: *Belmans N., Coeck M., (2020): Title. List of training needs from Research, Development and Demonstration and Strategic Studies Work Packages Final version as of 12.04.2021 of deliverable D13.1 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.*

- Understand potentially significant uncertainties related to the waste inventory (with a special focus on problematic wastes, organic-bearing wastes and the radiological characteristics of spent nuclear fuel) and discuss their significance;
- Understand potentially significant uncertainties related to human aspects and discuss their significance;
- Describe and discuss the options available to manage specific examples of uncertainties related to the waste inventory and human-related aspects.

1.3 Training course description

The course is a classroom-based training. The target audience and pre-requisites are the following:

- Participants are required to have a MSc degree;
- The target audience is primarily multidisciplinary (professional) experts (i.e. "generalist experts"). However, the course could also be interesting to more specialized experts;
- Professionals actively involved in waste management programmes;
- Experts involved in the development of safety cases;
- Safety case reviewers (TSOs & regulators).

The schedule of the course organised on 14-16 February 2023 is provided in the table below.

	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
	Day 1: Uncertainty management strategies, methods & tools								
A **Tuesday** **14/02/23**	**A.1 Introduction: Uncertainty management, the safety case & the decision-making process** **A.2 Types of uncertainties** *Valéry Detilleux, Bel V*		**A.3 Uncertainty management strategy and approaches** *Tim Hicks, GSL*	**Lunch**	**A.4 Uncertainty identification and quantification** *Vincenz Brendler, HZDR*		**A.5 Approaches to uncertainty and sensitivity analysis – Overview** *Klaus Röhlig, TUC*		**A6. Approaches to uncertainty and sensitivity analysis – Practical examples from the DONUT project** Dirk Alexander Becker, GRS
	Day 2: Management of uncertainties related to the waste inventory								
B **Wednesday** **15/02/23**	**B.1 Characterization and significance of uncertainties related to the waste inventory** *Attila Baksay, TSENERCON*		**B.2 Uncertainties in the radiological characterization of spent fuel** *Peter Schillebeeckx, JRC*	**Lunch**	**B.3. Uncertainties associated with waste management routes** *Chris de Bock, ONDRAF/NIRAS*		**B.4. Options for the management of uncertainties related to the waste inventory** *Jeroen Mertens, Bel V*		
	Day 3: Views of Civil Society & management of uncertainties related to human aspects								
C **Thursday** **16/02/23**	**C.1 Views of Civil Society on Uncertainty Management** *Julien Dewoghélaëre, NTW*		**C.2 Characterization and significance of uncertainties related to human aspects** *Jeroen Bartol, COVRA*		**C.3 Options for the management of uncertainties related to human aspects (Part 1)** *Jitka Miksova, SURO*	**Lunch**	**C.3 Options for the management of uncertainties related to human aspects (Part 2)** *Jitka Miksova, SURO*	**Test**	**Feedback**

2. Lecture materials

For each lecture of the course this section provides a short synopsis written by the corresponding lecturer. The slides used as support during the lectures are provided in the following 12 appendices.

- Appendix A. Slides of lectures A.1 & A.2
- Appendix B. Slides of lecture A.3
- Appendix C. Slides of lecture A.4
- Appendix D. Slides of lecture A.5
- Appendix E. Slides of lecture A.6
- Appendix F. Slides of lecture B.1
- Appendix G. Slides of lecture B.2
- Appendix H. Slides of lecture B.3
- Appendix I. Slides of lecture B.4
- Appendix J. Slides of lecture C.1
- Appendix K. Slides of lecture C.2
- Appendix L. Slides of lecture C.3

Finally, a short career summary of the lecturers is provided in appendix M and the test organised to verify if the audience has broadly understood the lessons (this was not a "qualification test") is given in appendix N.

- *Day 1 – Uncertainty management strategies, methods & tools*

Slot of time	*9:00 – 9:30*
Lecture	A1. Introduction: Uncertainty management, the safety case & the decision-making process A2. Types of uncertainties
Name	Valéry Detilleux
Affiliation	Bel V
Synopsis	Decisions associated with radioactive waste management programmes are made in the presence of irreducible and reducible uncertainties. In the early phase of a programme, several choices must be made on the basis of limited information and need to be confirmed before or during the construction and operation of the disposal facility. At the end of the process, some uncertainties will inevitably remain and it should be demonstrated that these uncertainties do not undermine safety arguments. Hence, the management of uncertainties is a key issue when developing and reviewing the safety case of waste management facilities and, in particular, of waste disposal facilities due to the long-time scales during which the radiotoxicity of the waste remains significant. This introductory lecture will provide a general framework about uncertainty management based on the work performed within UMAN: key definitions, types of uncertainties, links between the management of uncertainties and the decision making process as well as the safety case.

Transition to next talk	This lecture is an introduction to all next lectures and provide an overview of the whole course structure.
Keywords	Uncertainty, risk, Types of uncertainties, Decision making process, Safety Case, Uncertainty management strategy

Slot of time	*10:30 – 12:00*
Lecture	A3. Uncertainty management strategy and approaches
Name	Tim Hicks
Affiliation	GSL
Synopsis	We need to make choices and decisions through all phases of radioactive waste disposal facility development. There are many uncertainties that we need to be aware of when we make these decisions so that our judgments are as well informed as they can be and we can achieve our desired outcomes. These uncertainties range from those associated with the overall disposal programme and inventory to those associated with the data and models that underpin our safety assessments. By implementing a strategy for managing these uncertainties throughout the lifetime of a disposal facility, we have the best chance of arriving at the optimum solution for the long-term safety of disposal. This lecture discusses the components of an uncertainty management strategy.
Transition to next talk	Any strategy for managing uncertainties will of course include activities to identify, characterise and analyse those uncertainties. The identification and assessment of the safety significance of uncertainties is addressed in A4, A5 and A6.
Keywords	Uncertainty management, radioactive waste disposal, types of uncertainty, treatment of uncertainty.

Slot of time	*13:30 – 14:30*
Lecture	A4. Uncertainty identification and quantification
Name	Vinzenz Brendler
Affiliation	HZDR
Synopsis	Before entering into uncertainty processing it is essential to identify such uncertainties (here only numerical ones are considered), to rank them according to their relevance, to categorize them, elucidate internal dependencies and cross-interactions. These steps are supported by B1-B4. Also suitable methodologies to analyse and illustrate complex uncertainty patterns are required. Finally, transfer of only qualitatively described uncertainties into numerical ones must discussed.
Transition to next talk	Once uncertainties are analysed and categorized, they can be used for uncertainty and sensitivity analyses, which is the link to A5 and A6. Respective management decisions are illustrated in B5
Keywords	Numerical uncertainties: models, methodologies, categorization, characterization, Treatment, evaluation

Slot of time	*14:45 – 15:45*
Lecture	A5. Approaches to uncertainty and sensitivity analysis – Overview
Name	Klaus-Jürgen Röhlig
Affiliation	Clausthal University of Technology (TUC, Germany)
Synopsis	Uncertainty and sensitivity analyses (UA, SA) as addressed in this lecture serve the purpose of quantifying the uncertainty of model simulation results (“indicators”) as well as of the impact input uncertainties have on these output uncertainties. If the input uncertainties are quantified using probability density functions (pdfs, cf. lecture A4), the toolbox of stochastic methods offers a variety of methods for UA and SA. The lecture will focus on stochastic methods which are well-established, but other approaches are also applied.
Transition to next talk	A number of methods introduced in lecture A5 will, by means of example, further be addressed in A6 which will also shed light on technical details.
Keywords	Uncertainty Analysis, Sensitivity Analysis, Probabilistic Methods, Variance-based Methods

Slot of time	*16:00 – 17:00*
Lecture	A6. Approaches to uncertainty and sensitivity analysis – Practical examples from the DONUT project
Name	Dirk Alexander Becker
Affiliation	GRS
Synopsis	An overview of practical application of uncertainty and sensitivity analysis in numerical performance assessment (PA) is given. It is demonstrated how one can derive sensitivity statements about PA models by means of probabilistic investigations, what one can learn from such investigations about the model behaviour how one can use such knowledge in view of uncertainty management. The first part of the lesson deals with general practical advantages and disadvantages of different types of UA/SA approaches as presented in the previous talk. Then a few studies are presented that are being performed in the framework of the DONUT WP or elsewhere. Finally, some recommendations for executing effective and meaningful probabilistic investigations are given.
Transition to next talk	
Keywords	Uncertainty analysis, sensitivity analysis, numerical simulation

- *Day 2 – Management of uncertainties related to the waste inventory*

Slot of time	*9:00 – 10:15*
Lecture	B1. Characterization and significance of uncertainties related to the waste inventory
Name	Attila Baksay
Affiliation	TSENERCON
Synopsis	Steps of radioactive waste management (waste generation, characterization, waste processing, etc.) are introduced with regards to the waste inventory. The sources of uncertainties of waste inventory are discussed. Uncertainties connected to each waste management steps are discussed, focusing on their significance from the safety and optimization point view. Possibilities of characterization of uncertainties are presented based on the results of EURAD UMAN work package.
Transition to next talk	A general introduction to next lectures, in particular to B.3 and B.5.
Keywords	Radioactive waste management, Sources of uncertainties of radioactive waste inventory, Significance of uncertainties in waste inventory

Slot of time	*10:45 – 12:15*
Lecture	B2. Uncertainties in the radiological characterization of spent fuel
Name	Peter Schillebeeckx
Affiliation	JRC
Synopsis	The basic principles of uncertainty evaluation and propagation including the production of covariance matrices are reveiwed. The production of radiological quantities such as the decay power and neutron emission in spent nuclear fuel is discussed. The basics behind the theoretical estimation of these quantities together with a realistic uncertainty evaluation is explained. In addition, non-destructive methods to validate the theoretical calculations are presented.
Transition to next talk	
Keywords	Bias, uncertainty propagation, measurement error, systematic effects, covariance matrix, depletion codes, decay heat, neutron emission, nuclear data, disposal

Slot of time	*13:30 – 14:30*
Lecture	B3. Uncertainties associated with waste management routes
Name	Chris de Bock

Affiliation	ONDRAF/NIRAS
Synopsis	Challenging wastes are wastes for which it is difficult to define an appropriate management route. ROUTES has identified 11 wastes types that are generally considered to be challenging wastes. Main blocking points for defining a management route are: (1) lack of disposal route, (2) characterization issues, (3) treatment or conditioning issues. Characterization uncertainties are the root cause of the issues around legacy waste. Legacy waste risks being entrapped in a double vicious circle around characterization. The absence of an established disposal route is the root cause of the early or delayed conditioning dilemma. Sharing solutions between countries may have substantial benefits, particularly for SIMS. Sharing solutions makes needed infrastructure available, know-how is exchanged and costs are shared. However, prerequisite is a common safety culture and a level playing field between participating countries.
Transition to next talk	Possible management options for uncertainties addressed in this lecture will be presented in lecture B5.
Keywords	Waste management, Characterization, Disposal routes, Legacy waste, Treatment and conditioning, Shared solutions

Slot of time	*14:45 – 16:15*
Lecture	B4. Options for the management of uncertainties related to the waste inventory
Name	Jeroen Mertens
Affiliation	Bel V
Synopsis	Present the results of the survey on the importance of the different types of uncertainties related to inventory. Present the uncertainties investigated under the 4.2 UMAN task. Highlight methods to deal with those uncertainties. Give some practical examples of uncertainty management.
Transition to next talk	
Keywords	Uncertainty related to waste inventory, radionuclide inventory, chemical composition, physicochemical conditions in storage or disposal

- *Day 3 (16/02/23) – Views of Civil Society & management of uncertainties related to human aspects*

Slot of time	*9:00 – 9:45*
Lecture	C1. Views of Civil Society on Uncertainty Management
Name	Julien Dewoghélaëre
Affiliation	NTW
Synopsis	Based on work carried out by UMAN Task 5 and the organisation of pluralistic seminars, the lecture will provide elements on Civil Society views regarding uncertainty management with a focus on human aspects. The lecture will present: Model of civil society involvement in EURAD research and in UMAN project, results on seminars related to CS views on uncertainty management (global picture), results related to uncertainties on human aspects, identified methodologies as a way to enable pluralistic management of uncertainties.
Transition to next talk	This lecture will provide a global framework to grasp the lecture C.2.
Keywords	Pluralistic assessment and methodologies, civil society concerns,

Slot of time	*10:00 – 11:15*
Lecture	C2. Characterization and significance of uncertainties related to human aspects
Name	Jeroen Bartol
Affiliation	COVRA
Synopsis	In this lecture we will present the methods used, lessons learnt and the final results of UMAN Subtask n°3.4 – Characterization and significance of uncertainties for different categories of actors – Uncertainties related to human aspects. It will focus on the ten main uncertainties associated with the following topics and considered as of high-priority for further investigation i.e.: • Process for the identification of a workable set of repository requirements • Continuity of the waste management policy along political changes • Robustness of the presently considered safety requirements with regard to the long term • Public acceptance of the repository at potentially suitable or projected location • Schedule to be considered for implementing the different phases of the disposal programme • Robustness of the safety case vis-à-vis sociotechnical factors • New knowledge • Adequacy of safety-related activities safety provisions • Robustness of safety vis-à-vis possible cyber-attacks or programming errors • Availability of well-educated human resources, and relevant experts in radioactive waste management along the repository lifetime until closure.

	Other uncertainties with a lower priority will also be discussed but in less detail. Lastly, some recommendations for potential future actions to address human related issues within the radioactive waste management programmes that still have the greatest uncertainties will be given.
Transition to next talk	The next talk will provide information about how such uncertainties could be managed.
Keywords	Uncertainties related to human aspects, UMAN Subtask n°3.4

Slot of time	*11:45 – 12:30 & 14:00 – 14:45*
Lecture	C3. Options for the management of uncertainties related to human aspects
Name	Jitka Mikšová
Affiliation	SURO
Synopsis	The lecture is presenting uncertainties related to human aspects and their possible management based on the findings which has been identified and discussed within UMAN tasks work. Four different uncertainties were chosen as seen of a high importance by main actors in the RWM participating in EURAD, i.e. WMO, TSO and RE, completed with CS view. First part of the lecture will be dedicated to the Programme uncertainties, especially to Public acceptance and Schedule of the disposal programme implementation. The second part of the lecture will discuss uncertainties related to a facility construction and the uncertainty related to "new knowledge" which can occur during a long lasting disposal programme.
Transition to next talk	
Keywords	Human aspects, programme uncertainties, public acceptance, schedule, new knowledge

Appendix A. Slides of lectures A.1 & A.2

A.1 Introduction: Uncertainty management, the safety case & the decision-making process

A.2 Types of uncertainties

Prepared by Valéry Detilleux, Bel V

eurad
European Joint Programme on Radioactive Waste Management

INTRODUCTION: Uncertainty management, the safety case & the decision-making process (A1) Types of uncertainties (A2)

EURAD Training on Uncertainty Management, A1 & A2

Valéry Detilleux • Bel V

This project has received funding from the European Union's Horizon 2020 research and innovation programme 2014-2018 under grant agreement N°847593

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 1

KEY WORDS

- Uncertainty, risk
- Types of uncertainties
- Decision making process
- Safety Case
- Uncertainty management strategy

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process eurad 2

CONTENT

- Introduction
  - What is UMAN ?
  - Objective and agenda of the course
  - Learning outcomes
  - Go around the table
- Uncertainty management, the safety case & the decision-making process
  - Definitions (uncertainty, risk)
  - Uncertainty and the decision making process
  - Uncertainty and the safety case
  - Types and classification of uncertainties
  - Elements of an uncertainty management strategy
- Summary and conclusions

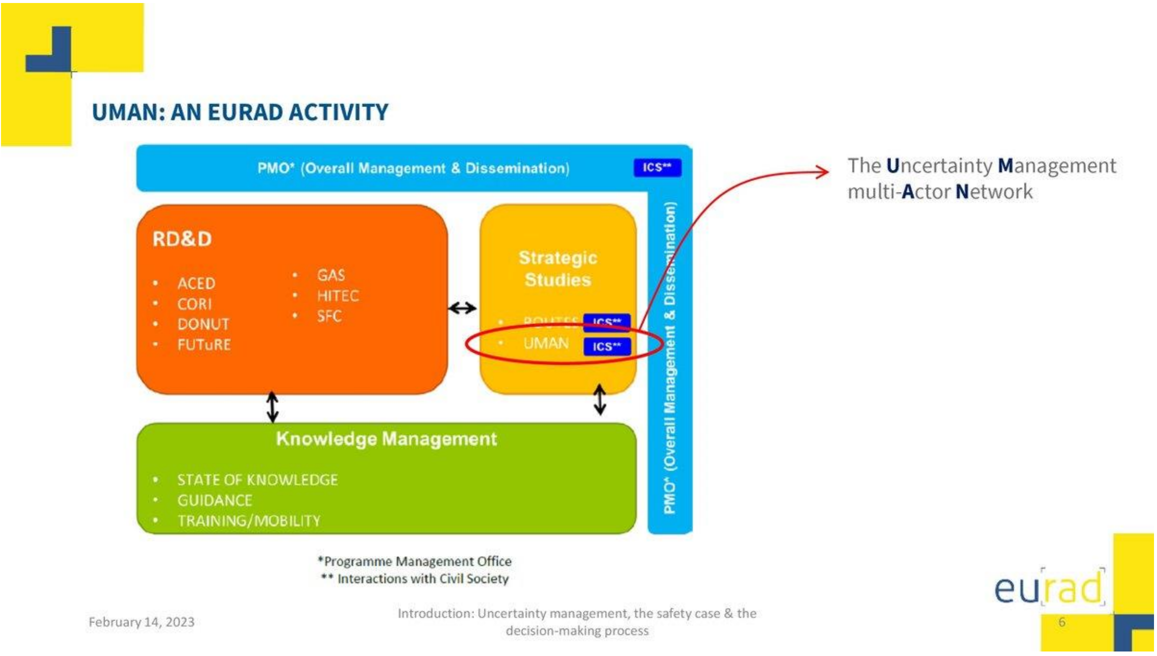
February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 3

INTRODUCTION

- What is UMAN ?
- Objective and agenda of the course
- Learning outcomes
- Roundtable

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 4


EURAD JOINT PROGRAMME VISION
A step change in European collaboration towards safe radioactive waste management (RWM) through the development of a robust and sustained science, technology and knowledge management programme that supports timely implementation of RWM activities and serves to foster mutual understanding and trust between participants
https://www.ejp-eurad.eu
February 14, 2023
Introduction: Uncertainty management, the safety case & the decision-making process
eurad
5


UMAN: AN EURAD ACTIVITY
PMO* (Overall Management & Dissemination)
ICS**
RD&D
ACED
CORI
DONUT
FUTuRE
GAS
HITEC
SFC
Strategic Studies
ICS**
UMAN
ICS**
Knowledge Management
STATE OF KNOWLEDGE
GUIDANCE
TRAINING/MOBILITY
PMO* (Overall Management & Dissemination)
The Uncertainty Management multi-Actor Network
*Programme Management Office
** Interactions with Civil Society
February 14, 2023
Introduction: Uncertainty management, the safety case & the decision-making process
eurad
6

UMAN: RATIONALE

- Decisions associated with RWM programmes are made in the presence of irreducible and reducible uncertainties
- Several choices made on the basis of limited information in early programme phases may have to be confirmed before or during the construction and operation of the facility
- The Council Directive 2011/70/EURATOM requires that transparency be provided by ensuring effective public information and opportunities for all stakeholders concerned to participate in the decision-making process
- At the end of the process, uncertainties will inevitably remain and it should be demonstrated that these uncertainties do not undermine safety arguments
- Hence, the management of uncertainties is a key element of successful programme planning and of the safety case of waste management facilities and…
- …in particular, of waste disposal facilities due to the long time scales during which the radiotoxicity of the waste remains significant

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 7

UMAN: OBJECTIVES

- Develop a common understanding among different categories of actors (WMOs, TSOs, REs & Civil Society) on uncertainty management and how it relates to risk & safety
- In cases where a common understanding is beyond reach, to achieve mutual understanding on why views on uncertainties and their management are different for various actors
- Share knowledge/know-how and discuss common methodological/strategical challenging issues
- Identify the contribution of past & on-going R&D projects to the overall management of uncertainties
- Identify remaining and emerging issues and needs

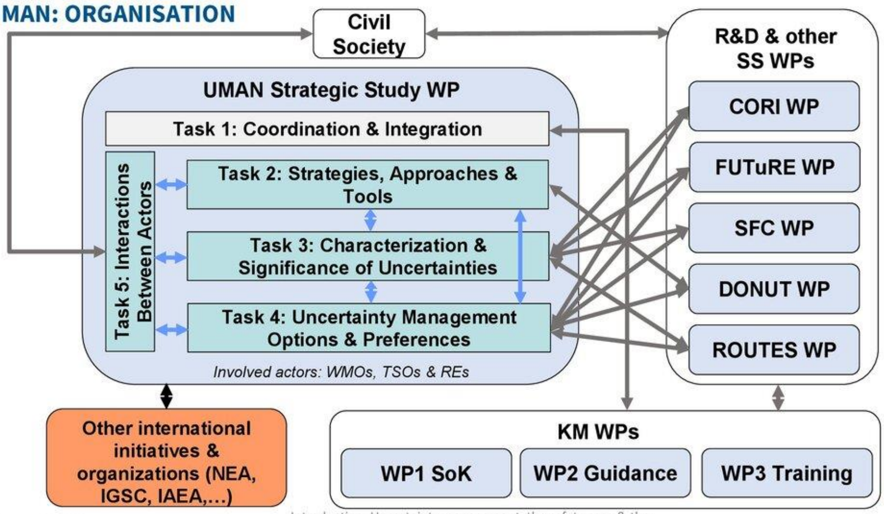
February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 8

UMAN: PARTICIPANTS

Belgium	ONDRAF, BEL V, SCK•CEN	Netherlands	COVRA, NRG
Bulgaria	Technical University Sofia	Romania	RATEN ICN PITEȘTI
Czech Republic	SÚRAO, SÚRO	Slovakia	STU
Finland	VTT, EnviroCase	Slovenia	Jožef Stefan Institute Ljubljana, Slovenia; EIMV
France	ANDRA, IRSN, cnrs, MUTADIS, NTW	Spain	enresa, Ciemat
Germany	BGE, GRS, KIT, HZDR, TU Clausthal	Switzerland	nagra, PAUL SCHERRER INSTITUT PSI
Hungary	TS ENERCON Engineering and Consulting	UK	Radioactive Waste Management, Galson Sciences Ltd
Lithuania	Center for Physical Sciences and Technology, LEI	Ukraina	SSTC NRS

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 9

UMAN: ORGANISATION



February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 10

UMAN SUBTASK 1.2: TRAINING

- **The main aim of the training is to address the training need "7.3.1 Treatment of uncertainty" identified in EURAD deliverable D13.1 as one the five most urgent and highest priority topics.**
- **The training will also address other urgent and high priority topics such as:**
  - "7.1 Safety strategy",
  - "3.1 Confirm wasteform compositions, properties and behaviour under storage and disposal conditions, including impact on the disposal environment (wasteform)" or
  - "'3.1.1 Spent Nuclear Fuel".

February 14, 2023 | Introduction: Uncertainty management, the safety case & the decision-making process | eurad 11

PROGRAMME OF THE COURSE

A journey into the world of uncertainties

	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
A Tuesday 14/02/23	**Day 1: Uncertainty management strategies, methods & tools**								
	A.1 Introduction: Uncertainty management, the safety case & the decision-making process **A.2 Types of uncertainties** *Valéry Detilleux, Bel V*		**A.3 Uncertainty management strategy and approaches** *Tim Hicks, GSL*	**Lunch**	**A.4 Uncertainty identification and quantification** *Vincenz Brendler, HZDR*		**A.5 Approaches to uncertainty and sensitivity analysis – Overview** *Klaus Röhlig, TUC*		**A6. Approaches to uncertainty and sensitivity analysis – Practical examples from the DONUT project** Dirk Alexander Becker, GRS
B Wednesday 15/02/23	**Day 2: Management of uncertainties related to the waste inventory**								
	B.1 Characterization and significance of uncertainties related to the waste inventory *Attila Baksay, TSENERCON*		**B.2 Uncertainties in the radiological characterization of spent fuel** *Peter Schillebeeckx, JRC*	**Lunch**	**B.3. Uncertainties associated with waste management routes** *Chris de Bock, ONDRAF/NIRAS*		**B.5. Options for the management of uncertainties related to the waste inventory** *Jeroen Mertens, Bel V*		
C Thursday 16/02/23	**Day 3: Views of Civil Society & management of uncertainties related to human aspects**								
	C.1 Views of Civil Society on Uncertainty Management *Julien Dewoghélaëre, NTW*		**C.2 Characterization and significance of uncertainties related to human aspects** *Jeroen Bartol, COVRA*		**C.3 Options for the management of uncertainties related to human aspects (Part 1)** *Jitka Miksova, SURO*	**Lunch**	**C.3 Options for the management of uncertainties related to human aspects (Part 2)** *Jitka Miksova, SURO*	**Test**	**Feedback**

February 14, 2023 | Introduction: Uncertainty management, the safety case & the decision-making process | eurad 12

LEARNING OUTCOMES (FULL COURSE)

Upon successful completion of this training course, participants should be able to:

- Understand and classify the different types of uncertainties that may need to be managed in a RW disposal programme
- Explain the links between uncertainty management, the safety case and the decision-making process
- Use the global UMAN scheme of uncertainty management strategies
- Explain the main strategies and approaches available to manage uncertainties
- List the approaches available to perform uncertainty and sensitivity analyses and discuss their pros and cons
- Grasp the views of Civil Society representatives involved in EURAD on uncertainty management
- Understand potentially significant uncertainties related to the waste inventory (with a special focus on problematic wastes, organic-bearing wastes and the radiological characteristics of spent nuclear fuel) and discuss their significance
- Understand potentially significant uncertainties related to human aspects and discuss their significance
- Describe and discuss the options available to manage specific examples of uncertainties related to the waste inventory and human-related aspects

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process eurad 13

LEARNING OUTCOMES (LESSONS A1, A2)

Upon successful completion of this training course, participants should be able to:

- Understand and classify the different types of uncertainties that may need to be managed in a RW disposal programme
- Explain the links between uncertainty management, the safety case and the decision-making process
- Use the global UMAN scheme of uncertainty management strategies
- Explain the main strategies and approaches available to manage uncertainties
- List the approaches available to perform uncertainty and sensitivity analyses and discuss their pros and cons
- Grasp the views of Civil Society representatives involved in EURAD on uncertainty management
- Understand potentially significant uncertainties related to the waste inventory (with a special focus on problematic wastes, organic-bearing wastes and the radiological characteristics of spent nuclear fuel) and discuss their significance
- Understand potentially significant uncertainties related to human aspects and discuss their significance
- Describe and discuss the options available to manage specific examples of uncertainties related to the waste inventory and human-related aspects

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process eurad 14

LET'S QUICKLY PRESENT OURSELVES

UNCERTAINTY MANAGEMENT, THE SAFETY CASE & THE DECISION-MAKING PROCESS

- Definitions (uncertainty, risk)
- Uncertainty and the decision making process
- Uncertainty and the safety case
- Types and classification of uncertainties
- Elements of an uncertainty management strategy

WHAT DOES « UNCERTAINTY » MEAN ?

"A situation in which something is not known, or something that is not known or certain"

Source: https://dictionary.cambridge.org

February 14, 2023 | Introduction: Uncertainty management, the safety case & the decision-making process | eurad 17

« UNCERTAINTY » VS. « RISK »

- **Uncertainty ≠ Risk !**
- **Risk**
  - related to a scenario or sequence of events
  - = Probability x Consequences
  - can be interpreted as the measure of significance of an uncertainty
- **The significance of uncertainties needs to be assessed**

February 14, 2023 | Introduction: Uncertainty management, the safety case & the decision-making process | eurad 18

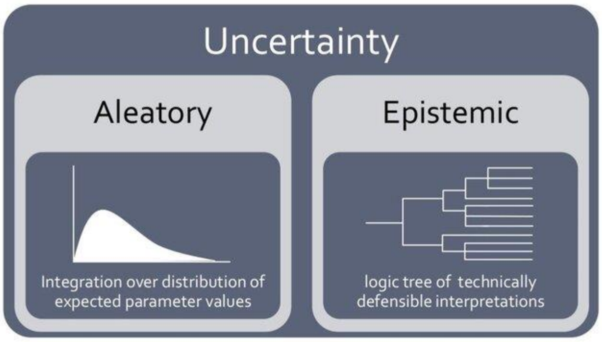
TYPES OF UNCERTAINTIES: « EPISTEMIC » VS. « ALEATORY »

An uncertainty can be:

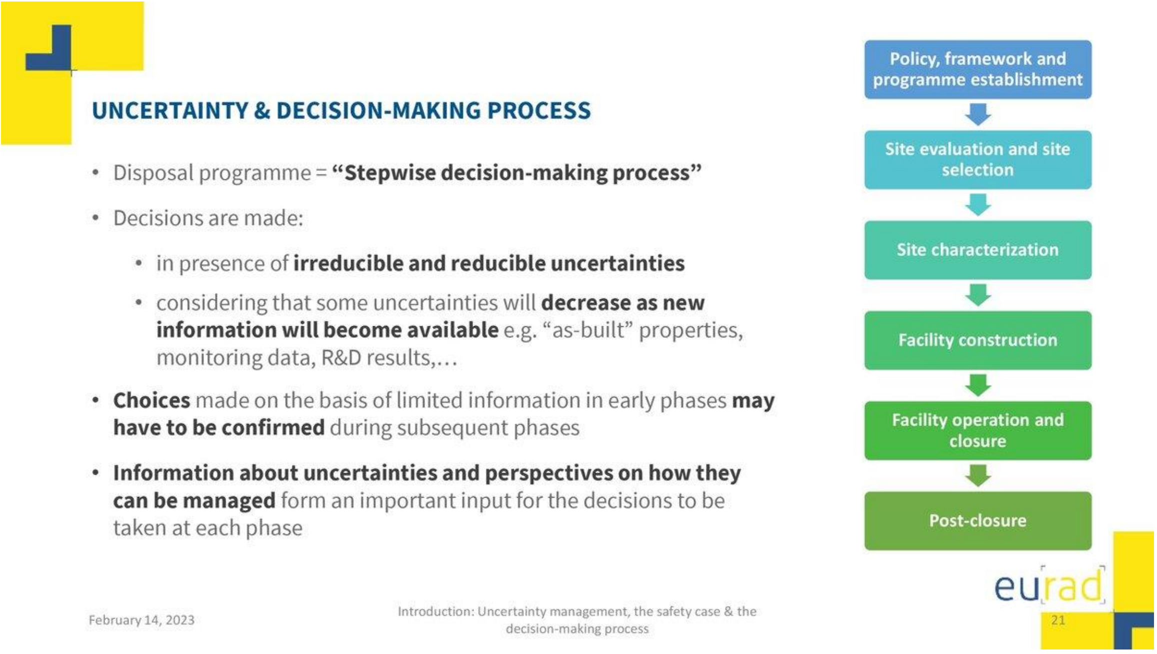
- « **epistemic** »
  - i.e. relating to knowledge or to the degree of its validation
  - e.g. lack of knowledge about site characteristics
  - *can be reduced*
- « **aleatory** »
  - i.e. related to random variability
  - e.g. uncertainty over the time of occurrence or magnitude of rare events
  - *cannot be reduced*

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process eurad 19

TYPES OF UNCERTAINTIES: « EPISTEMIC » VS. « ALEATORY »



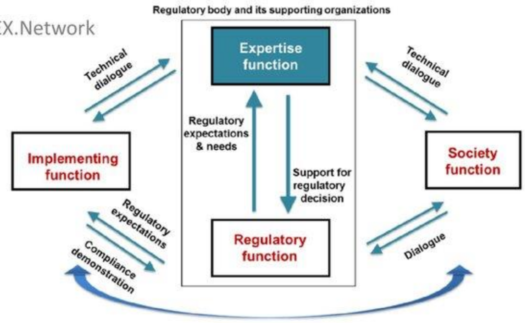
February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process eurad 20


UNCERTAINTY & DECISION-MAKING PROCESS
Disposal programme = "Stepwise decision-making process"
Decisions are made:
in presence of irreducible and reducible uncertainties
considering that some uncertainties will decrease as new information will become available e.g. "as-built" properties, monitoring data, R&D results,…
Choices made on the basis of limited information in early phases may have to be confirmed during subsequent phases
Information about uncertainties and perspectives on how they can be managed form an important input for the decisions to be taken at each phase
Policy, framework and programme establishment
Site evaluation and site selection
Site characterization
Facility construction
Facility operation and closure
Post-closure
February 14, 2023
Introduction: Uncertainty management, the safety case & the decision-making process
eurad
21


ROLES OF THE SAFETY CASE
The safety case provides the basis for demonstration of safety and for licensing
They assist and guide decisions made at each programme phase
The safety case will also be the main basis on which:
dialogue with interested parties will be conducted
confidence in the safety of the disposal facility will be developed
February 14, 2023
Introduction: Uncertainty management, the safety case & the decision-making process
eurad
22

SAFETY CASE INTERESTED PARTIES

Source: SITEX.Network



EURAD key actors
WMO: Implementing function
TSO: Expertise function
RE: Could intervene in implementing, society and expertise functions
CS: Society function

February 14, 2023 | Introduction: Uncertainty management, the safety case & the decision-making process | eurad 23

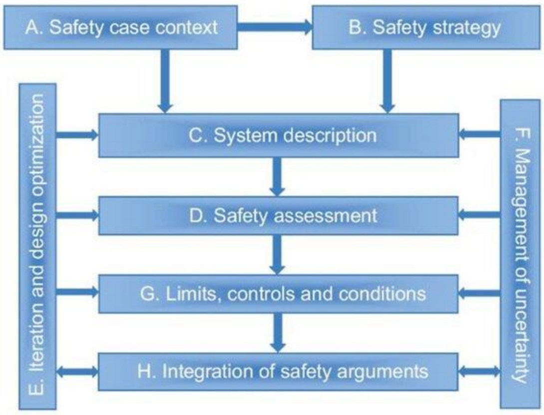
UNCERTAINTY & THE SAFETY CASE

=> The safety case needs to:

- describe the **approach to managing uncertainties**
- acknowledge and **identify significant uncertainties**
- **assess the impact** of uncertainties
- show that **existing levels of uncertainty are acceptable** given the decision(s) to be taken
- show **how significant uncertainties will be managed** in subsequent phases
- be **regularly updated** so that it remains an adequate basis for making decisions

February 14, 2023 | Introduction: Uncertainty management, the safety case & the decision-making process | eurad 24

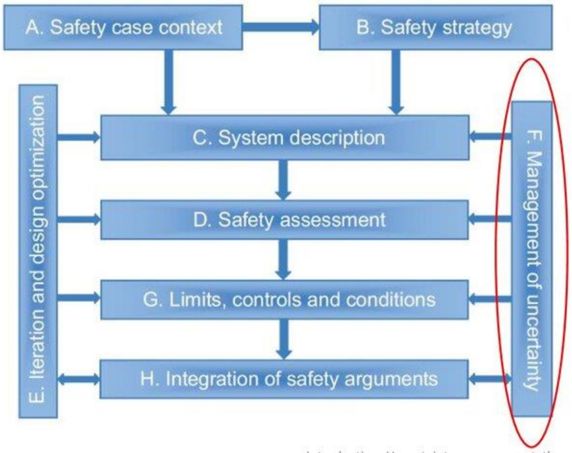
COMPONENTS OF THE SAFETY CASE



Source:
IAEA Safety Guide SSG-23

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 25

MANAGEMENT OF UNCERTAINTY



- Uncertainty management is a **cross-cutting element of the safety case**

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 26

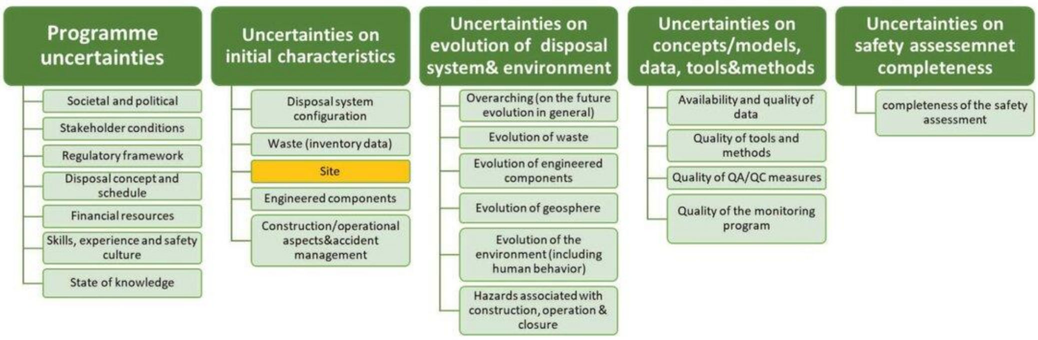
TYPES OF UNCERTAINTIES: UMAN CLASSIFICATION (LEVEL 1)

- Views of a large number of actors representing WMOs, TSOs and REs on the uncertainties associated with radioactive waste disposal safety where collected via UMAN.
- This led to a three-level classification scheme of uncertainties, integrating all points of views and covering all stages of a RWM programme.
- This scheme distinguishes 5 main types of uncertainties:
  1. Programme uncertainties, associated with the RWM programme and other prevailing circumstances (societal, resources, etc.);
  2. Uncertainties associated with the initial characteristics of the disposal system and its environment;
  3. Uncertainties associated with the evolution of the disposal system and its environment, which include effects of events and processes that may affect the initial characteristics (e.g. uncertainties associated with the radiotoxic and chemotoxic elements) as well as human influence or intrusion;
  4. Uncertainties related to concepts (models) and parameters (data) used in the safety assessment;
  5. Uncertainties associated with the completeness of the safety assessment (uncertainty in overlooking certain aspects relevant to safety).

February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 27

TYPES OF UNCERTAINTIES: UMAN CLASSIFICATION (LEVEL 2)

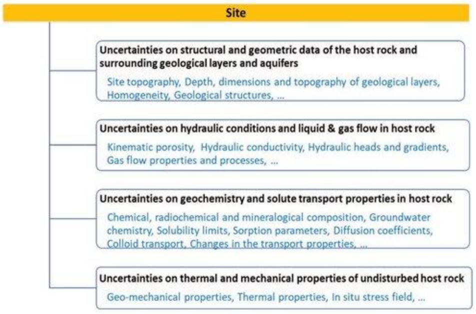
- Each type of uncertainty is grouped in topical groups of uncertainties, which represent the second level of the UMAN classification.



February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 28

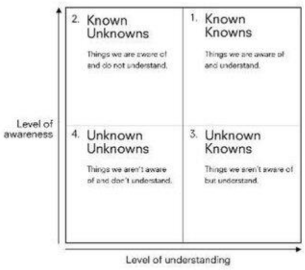
TYPES OF UNCERTAINTIES: UMAN CLASSIFICATION (LEVEL 3)

- The third level of the classication scheme includes the uncertainties potentially signicant for the disposal safety of each level 2 topical group.
- Below an illustration of the third level for the uncertainties associated with the site and geosphere, as identied in UMAN.



February 14, 2023 | Introduction: Uncertainty management, the safety case & the decision-making process | eurad 29

UNCERTAINTIES & AVAILABILITY OF KNOWLEDGE

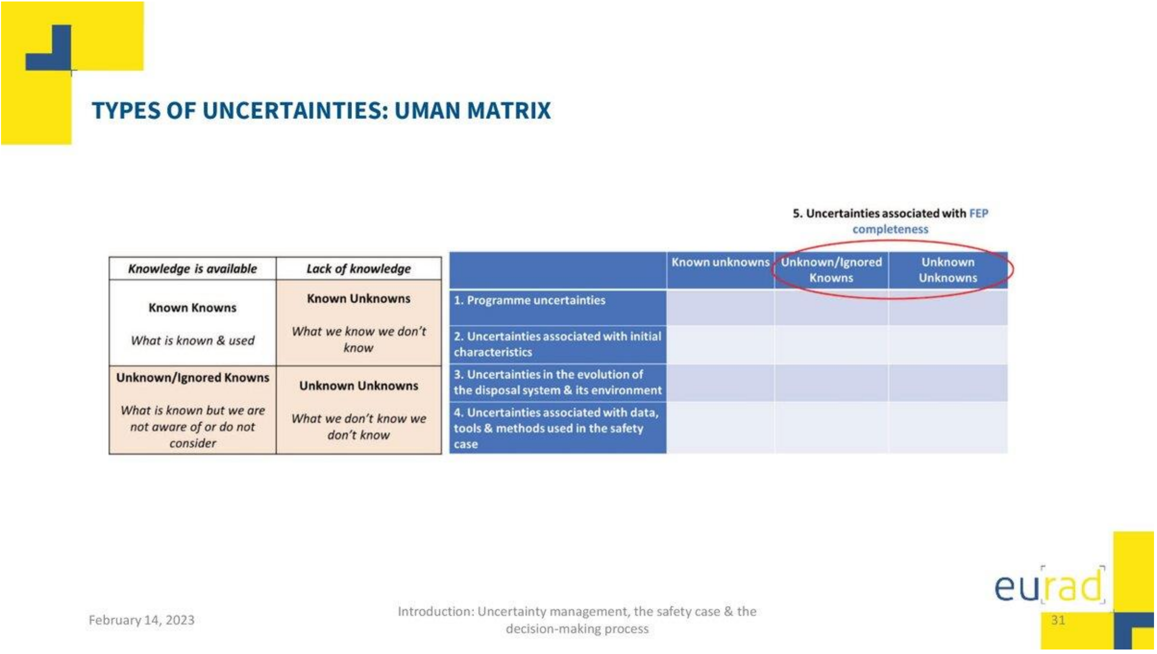


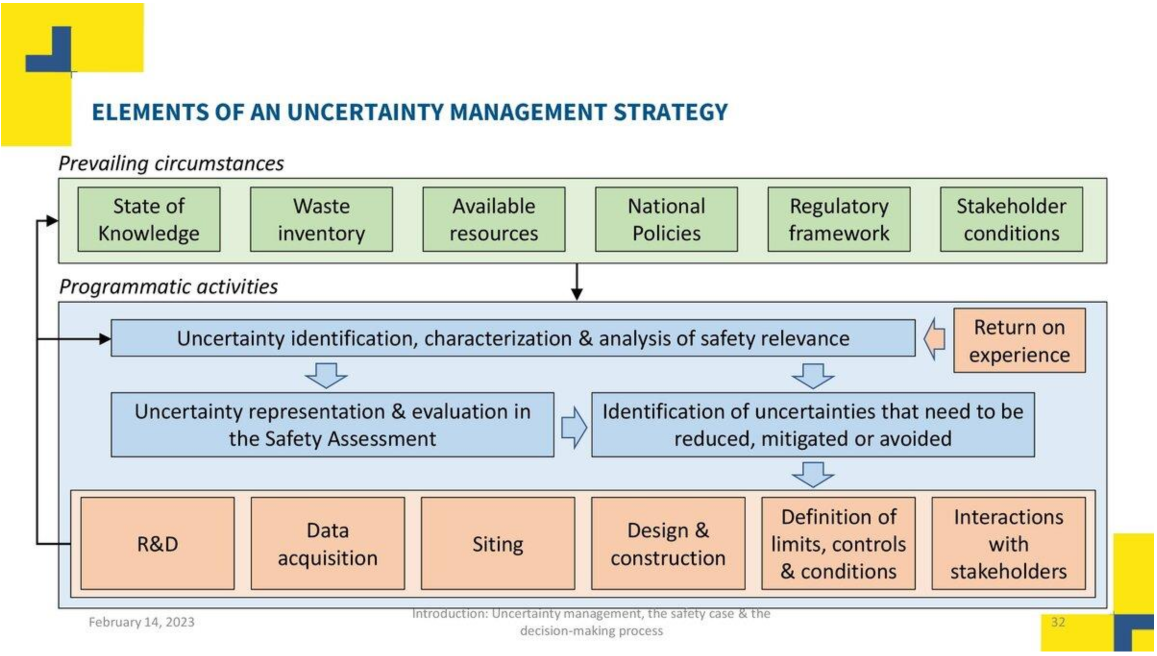
From the point of view of the availability of knowledge, uncertainties can belong to one of the three following categories:

- 2: we know what we don't know (known unknowns)
- 3: we don't know that knowledge exists or we ignore existing knowledge (unknown/ignored knowns)
- 4: we don't know we don't know (unknown unknowns).

The last two circumstances represent the uncertainties associated with the completeness of the safety assessment.

February 14, 2023 | Introduction: Uncertainty management, the safety case & the decision-making process | eurad 30


TYPES OF UNCERTAINTIES: UMAN MATRIX
Knowledge is available
Lack of knowledge
Known Knowns
What is known & used
Known Unknowns
What we know we don't know
Unknown/Ignored Knowns
What is known but we are not aware of or do not consider
Unknown Unknowns
What we don't know we don't know
5. Uncertainties associated with FEP completeness
Known unknowns
Unknown/Ignored Knowns
Unknown Unknowns
1. Programme uncertainties
2. Uncertainties associated with initial characteristics
3. Uncertainties in the evolution of the disposal system & its environment
4. Uncertainties associated with data, tools & methods used in the safety case
February 14, 2023
Introduction: Uncertainty management, the safety case & the decision-making process
eurad
31


ELEMENTS OF AN UNCERTAINTY MANAGEMENT STRATEGY
Prevailing circumstances
State of Knowledge
Waste inventory
Available resources
National Policies
Regulatory framework
Stakeholder conditions
Programmatic activities
Uncertainty identification, characterization & analysis of safety relevance
Return on experience
Uncertainty representation & evaluation in the Safety Assessment
Identification of uncertainties that need to be reduced, mitigated or avoided
R&D
Data acquisition
Siting
Design & construction
Definition of limits, controls & conditions
Interactions with stakeholders
February 14, 2023
Introduction: Uncertainty management, the safety case & the decision-making process
32

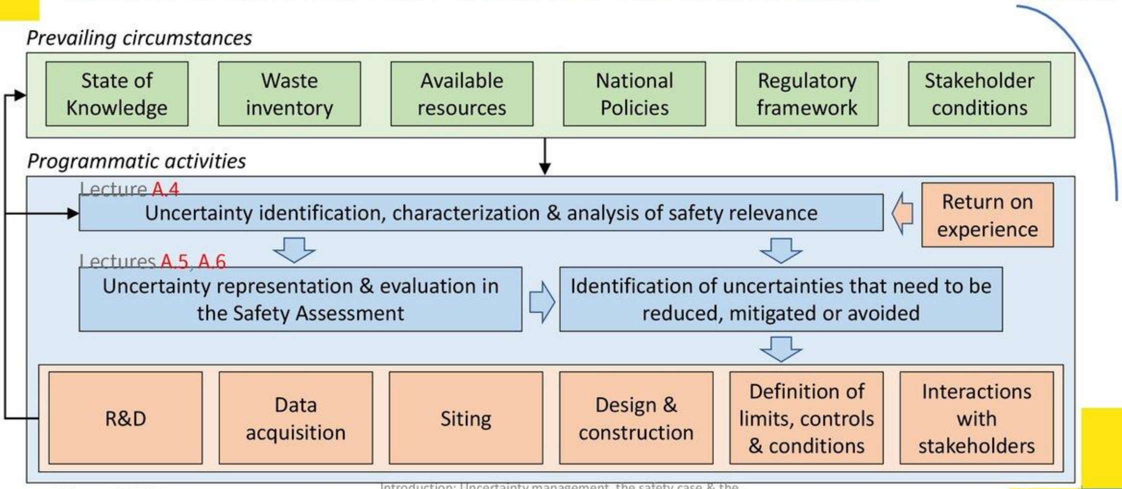
SUMMARY AND CONCLUSIONS

- *"Uncertainty is the only certainty there is, and knowing how to live with insecurity is the only security"* (John Allen Paulos)
- Uncertainty ≠ Risk
- Managing uncertainties is key when developing a disposal system and assessing its safety
- Various types of uncertainties need to be managed in a disposal programme
- Several options might be available to reduce, avoid or mitigate these uncertainties
- Uncertainty management is an iterative process associated with the stepwise implementation of the disposal programme

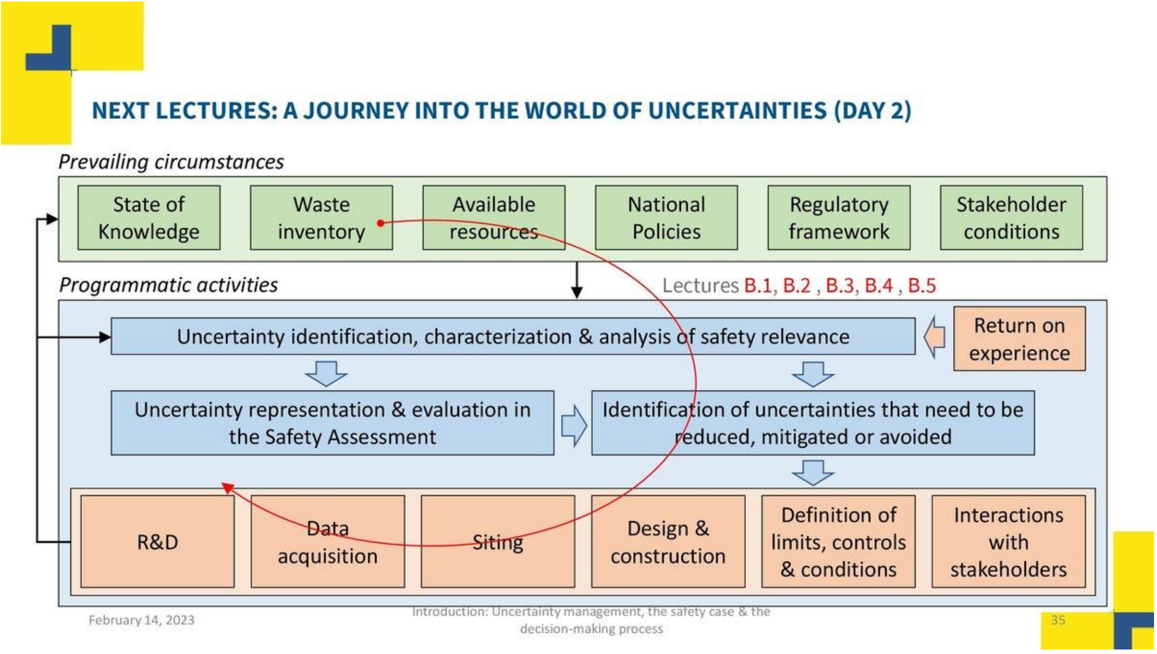
February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 33

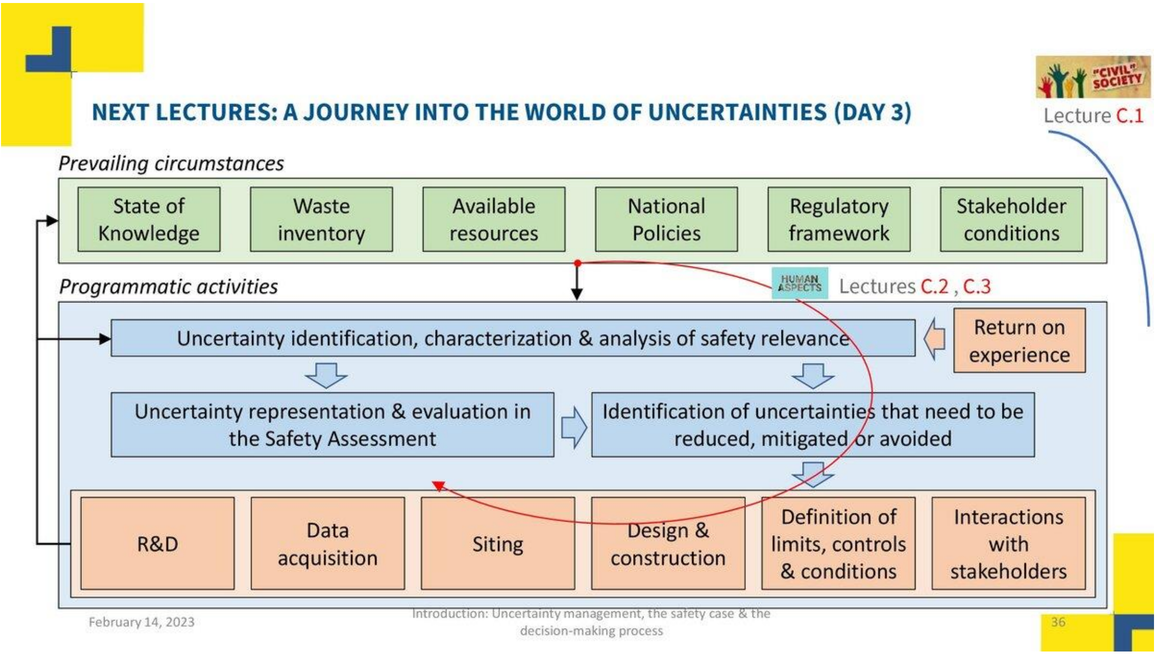
NEXT LECTURES: A JOURNEY INTO THE WORLD OF UNCERTAINTIES (DAY 1)

Lecture A.3



February 14, 2023 Introduction: Uncertainty management, the safety case & the decision-making process 34


NEXT LECTURES: A JOURNEY INTO THE WORLD OF UNCERTAINTIES (DAY 2)
Prevailing circumstances
State of Knowledge
Waste inventory
Available resources
National Policies
Regulatory framework
Stakeholder conditions
Programmatic activities
Lectures B.1, B.2 , B.3, B.4 , B.5
Uncertainty identification, characterization & analysis of safety relevance
Return on experience
Uncertainty representation & evaluation in the Safety Assessment
Identification of uncertainties that need to be reduced, mitigated or avoided
R&D
Data acquisition
Siting
Design & construction
Definition of limits, controls & conditions
Interactions with stakeholders
February 14, 2023
Introduction: Uncertainty management, the safety case & the decision-making process
35


NEXT LECTURES: A JOURNEY INTO THE WORLD OF UNCERTAINTIES (DAY 3)
"CIVIL" SOCIETY
Lecture C.1
Prevailing circumstances
State of Knowledge
Waste inventory
Available resources
National Policies
Regulatory framework
Stakeholder conditions
Programmatic activities
HUMAN ASPECTS
Lectures C.2 , C.3
Uncertainty identification, characterization & analysis of safety relevance
Return on experience
Uncertainty representation & evaluation in the Safety Assessment
Identification of uncertainties that need to be reduced, mitigated or avoided
R&D
Data acquisition
Siting
Design & construction
Definition of limits, controls & conditions
Interactions with stakeholders
February 14, 2023
Introduction: Uncertainty management, the safety case & the decision-making process
36

BIBLIOGRAPHY AND/OR REFERENCES.

- UMAN - a pluralistic view of uncertainty management, Daniela Diaconu, Valéry Detilleux, Agnieszka Strusinska-Correia and Astrid Göbel, Julien Dewoghelaere, and Dirk-Alexander Becker, EPJ Nuclear Sci. Technol. 9, 2 (2023) https://doi.org/10.1051/epjn/2022049

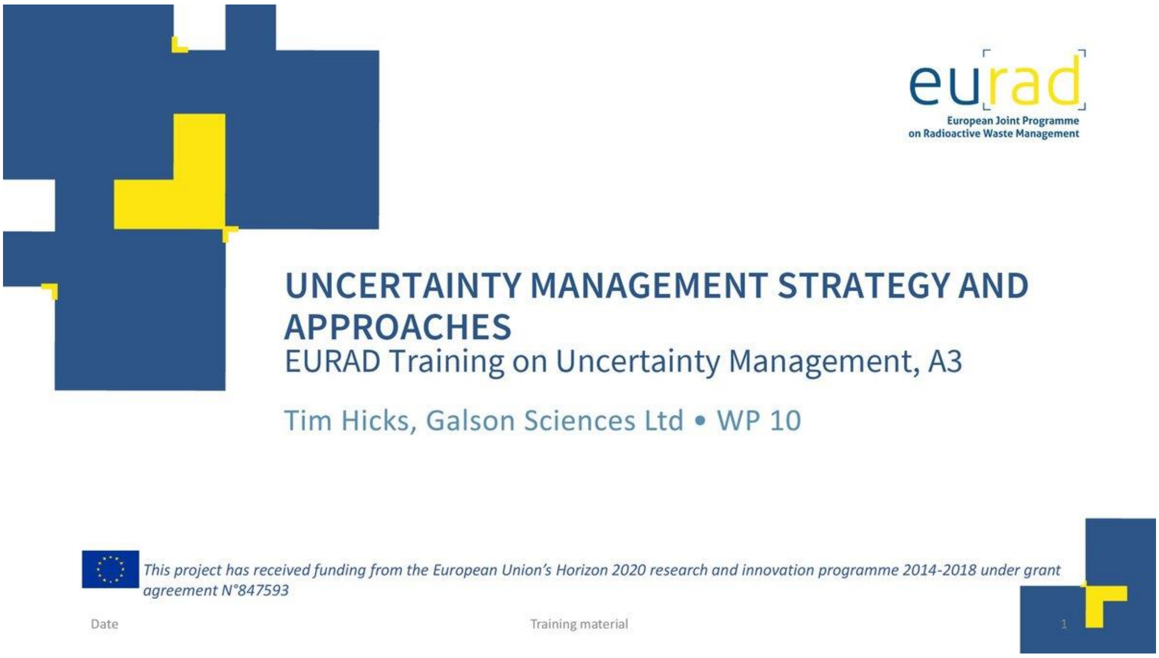
+ References therein.

February 14, 2023 — Introduction: Uncertainty management, the safety case & the decision-making process — eurad 37

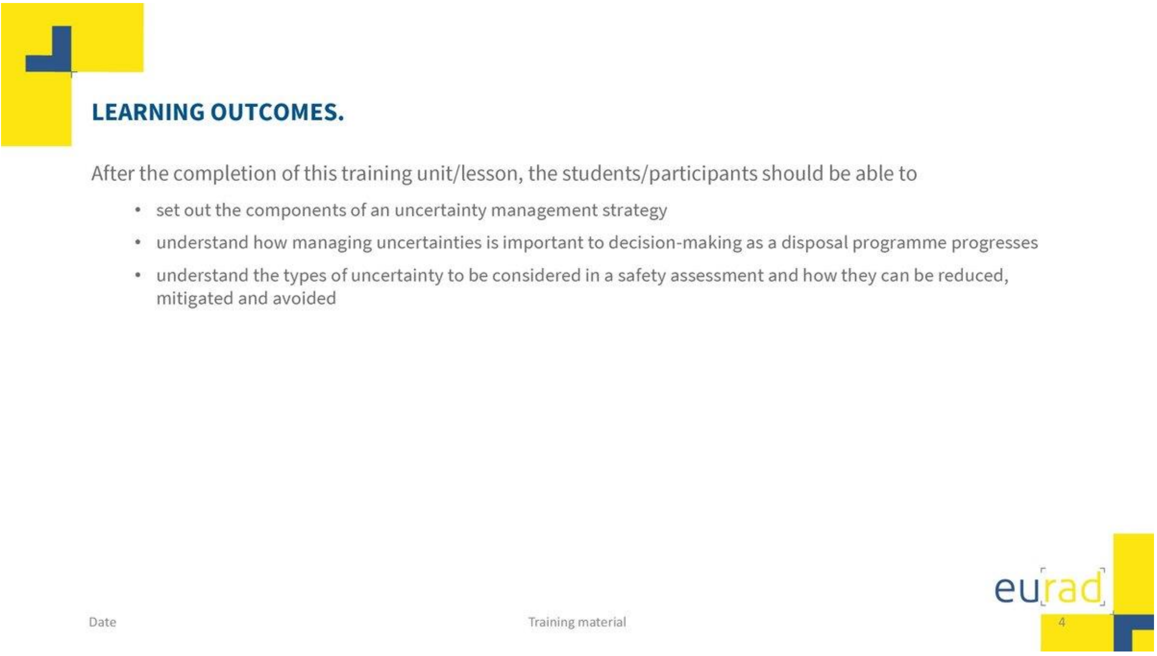
Appendix B. Slides of lecture A.3

A.3 Uncertainty management strategy and approaches

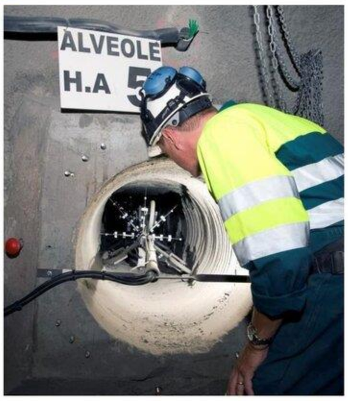
Prepared by Tim Hicks, GSL




CONTENTS
• Learning outcomes.
• Introduction.
• Safety case for disposal.
• Elements of an uncertainty management strategy.
• Managing uncertainty throughout a disposal programme.
• Regulatory framework.
• Types of uncertainty.
• Avoidance, mitigation and reduction of uncertainty
• disposal programme.
• inventory.
• disposal concept.
• as-built conditions.
• disposal system evolution.
• data and models.
• FEPs and scenarios.
• Summary and conclusions.
• Bibliography and/or References.
Date
Training material
eurad
3


LEARNING OUTCOMES.
After the completion of this training unit/lesson, the students/participants should be able to
• set out the components of an uncertainty management strategy
• understand how managing uncertainties is important to decision-making as a disposal programme progresses
• understand the types of uncertainty to be considered in a safety assessment and how they can be reduced, mitigated and avoided
Date
Training material
eurad
4

INTRODUCTION



- We need to make choices and decisions through all phases of radioactive waste disposal facility development.
- There are many uncertainties that we need to be aware of when we make these decisions so that our judgments are as well informed as they can be and we can achieve our desired outcomes.
- Uncertainties range from those associated with the overall disposal programme and inventory to those associated with the data and models that underpin our safety assessments.
- By implementing a strategy for managing these uncertainties throughout the lifetime of a disposal facility, we have the best chance of arriving at the optimum solution for the long-term safety of disposal.
- This lecture discusses the components of an **uncertainty management strategy.**

eurad

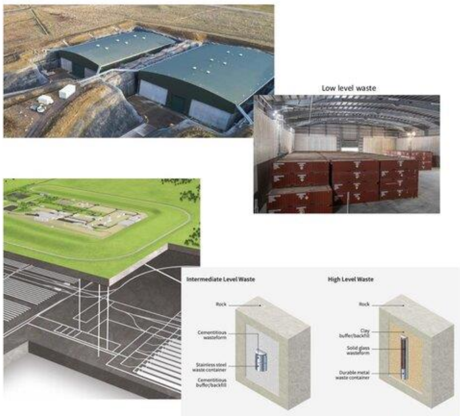
Date Training material 5

BACKGROUND

- The IAEA established the fundamental safety objective for all circumstances that give rise to radiation risks:

  'The fundamental safety objective to protect people and the environment from harmful effects of ionising radiation'

- We need to dispose of radioactive waste in a way that ensures that this objective is met
- We do this by designing, operating and closing disposal facilities in a way that **isolates and contains** the waste sufficiently to ensure safety
  - operational safety is achieved through engineering features and operational controls
  - post-closure safety is achieved through engineered and natural barriers (safety concept) that contribute to **passive safety** after facility closure
- The safety of disposal is demonstrated in a safety case

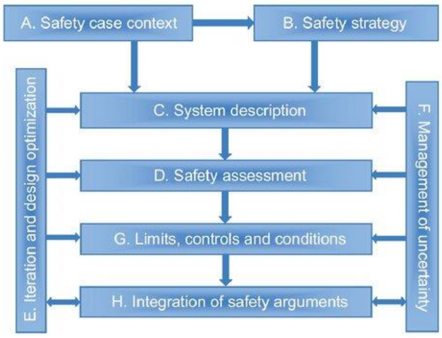


"The safety case is the collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility" IAEA SSG-23

eurad

Date Training material 6

COMPONENTS OF A SAFETY CASE



IAEA SSG-23

A. A **safety case** is developed and refined as a disposal programme progresses; its context needs to be set out as a basis for decision-making

B. Is part of an **integrated safety strategy**

C. **Documents knowledge** of the disposal system, which will evolve and mature as the disposal programme progresses and assessment are carried out

D. Includes **safety assessments** to quantify dose, risks etc. that may arise from the disposal facility, potentially over long timescales, for comparison with safety standards

G. Helps to **establish requirements** on processes, operations, methods, and materials relevant to the safety demonstration (WAC, construction processes, emplacement operations, EBS materials, monitoring etc.)

H. Provides a synthesis of **safety arguments** against safety claims, with reference to underpinning evidence,

E. Supports an iterative decision-making process that will lead to **optimisation** of facility design

F. **Identifies uncertainties**, shows how they have been addressed, and sets out the approach by which any open questions and uncertainties with the potential to undermine safety will be addressed and managed; this is a cross-cutting element of the safety case

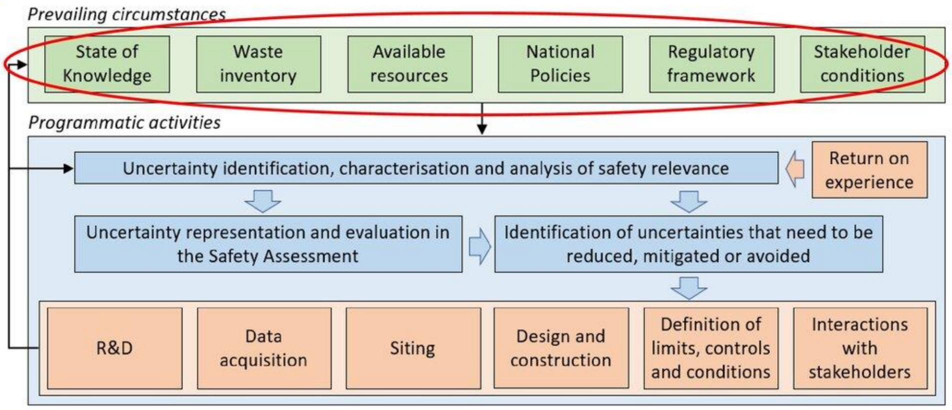
Date Training material eurad 7

ELEMENTS OF AN UNCERTAINTY MANAGEMENT STRATEGY

- An uncertainty management strategy generally involves the following steps
  - identification and characterisation of uncertainties to be managed
  - analysis of the safety relevance of uncertainties
  - representation of safety-relevant uncertainties in the safety assessment
  - identification of uncertainties that need to be reduced, mitigated or avoided based on assessment results
  - actions to avoid, mitigate or reduce uncertainties
- **Views developed as part of UMAN Subtask 2.1, including questionnaire on uncertainty management sent to UMAN participants and literature review**

Date Training material eurad 8

ELEMENTS OF AN UNCERTAINTY MANAGEMENT STRATEGY



eurad

Date | Training material | 9

UNCERTAINTY MANAGEMENT AS THE DISPOSAL PROGRAMME PROGRESSES

- Safety cases are produced to support decisions in different programme phases
  - An **initial safety case** is typically produced in the framework of a pre-licensing process in support of:
    - disposal concept development
    - site selection
    - dialogue with stakeholders
  - A **complete safety case** is submitted in the framework of a licence application for the construction and operation of a disposal facility
  - **Safety case updates** are likely to be needed during operation of the facility (e.g. to account for as-built properties, waste characteristics, RD&D, monitoring, design changes) and prior to facility closure
- How uncertainties are accepted and managed evolves throughout these programme phases, with various methods used to **avoid, mitigate or reduce uncertainties**
- The safety case should include a description of the programme for **uncertainty management** consistent with the prevailing circumstances in the disposal programme

eurad

Date | Training material | 10

UNCERTAINTY MANAGEMENT AS THE DISPOSAL PROGRAMME PROGRESSES

- An uncertainty management strategy is thus an important component of a radioactive waste disposal programme
  - information about uncertainties and how they can be managed informs decisions to be taken at any programme step
  - how much uncertainty can be accepted at a given step depends on the decisions to be taken
- Each step in the identification, characterisation, assessment and treatment of uncertainties is updated progressively and iteratively as the disposal programme progresses
  - iterative safety assessments to understand parameters to which performance measures are most sensitive, which **can guide uncertainty reduction** through data acquisition activities
  - iterative approach to research and data acquisition activities aimed at **reducing or mitigating uncertainties**

Date Training material eurad 11

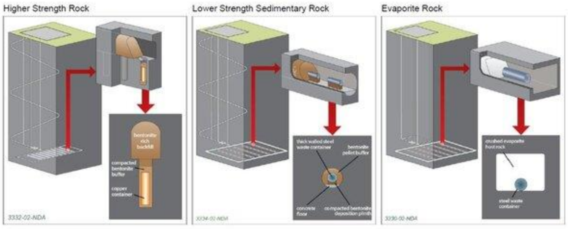
UNCERTAINTY MANAGEMENT AS THE DISPOSAL PROGRAMME PROGRESSES

- At each major step of a disposal programme, the safety case will need to explain
  - whether any remaining uncertainties are significant for safety; residual uncertainties will remain at any licensing stage, but it is important to show that they will not undermine the goals of the present stage and can be dealt with as necessary in future stages
  - why it is appropriate to move to the next stage of facility development despite these uncertainties
  - the strategies to be employed to address remaining uncertainties
- Each revision of the safety case should therefore include a plan for further work to address significant unresolved issues, in particular to reduce significant remaining uncertainties or to reduce their relevance or avoid them entirely
  - **reducible uncertainties** that have a **substantial influence** on the results of a safety assessment would need to be addressed through, for example, further research, improved modelling, or design modifications
  - **irreducible uncertainties** that have a **substantial influence** on the results of a safety assessment would need to be addressed through, for example, further analysis of specific scenarios, conservative assumptions, or probabilistic assessments
  - **uncertainties that have a minor influence** on the results of a safety assessment may not need further consideration

Date Training material eurad 12

UNCERTAINTY MANAGEMENT AS THE DISPOSAL PROGRAMME PROGRESSES

- Examples of safety assessment approaches in early programme phases
  - Safety assessments may be undertaken in the context of a range of different disposal concept options where, for example, decisions are yet to be made on waste packaging options or the type and location of host rock for the facility (e.g., Netherlands, UK)
    - enables key parameters associated with disposal system performance (and uncertainties in those parameters) to be identified, albeit in the context of credible generic assumptions about natural and engineered barrier system characteristics



NDA 2016

Date Training material 13

UNCERTAINTY MANAGEMENT AS THE DISPOSAL PROGRAMME PROGRESSES

- Examples of safety assessment approaches in early programme phases
  - safety assessments may be undertaken in support of site evaluations as part of a site selection process
    - supports decisions about the feasibility of disposal and identifies key uncertainties to be investigated in the next phase of site characterisation (e.g. through intrusive investigations) and RD&D (UK)
  - preparatory safety assessments may done in parallel with system development (Belgium)
    - used repeatedly to determine the relevance of uncertainties to safety and provide guidance on RD&D activities

Date Training material 14

MANAGING EMERGING UNCERTAINTIES

- Some uncertainties will decrease as new information becomes available (e.g., 'as-built' properties, monitoring data, and RD&D results), but activities associated with the programme (process modelling, safety assessment, siting, and construction) can lead to new viewpoints and sometimes new uncertainties (i.e. **emerging uncertainties**)
- Issues associated with emerging uncertainties can be dealt with, mitigated or guarded against by for example
  - verification of assumptions during each programme phase through RD&D, characterisation, monitoring and inspection activities, and feedback from construction and operational phase observations
  - learning from international experience
  - use of proven methods and materials
  - implementation of quality management system principles (QA/QC) in the various activities carried out in the programme (modelling, design, construction)
  - the mitigation of programme uncertainties and associated risks (e.g., financial resources, stakeholder conditions, available knowledge and skill)
  - implementation of the defence in depth principle

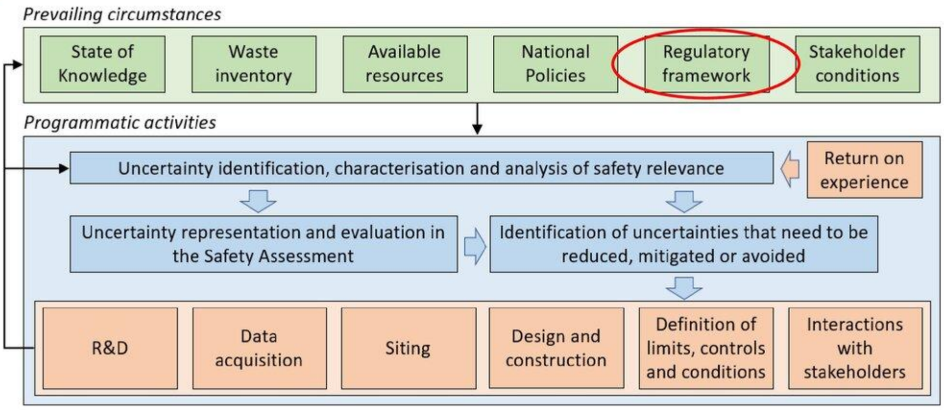
Date Training material eurad 15

MANAGING EMERGING UNCERTAINTIES

- Implementation of the **defence in depth principle** may include
  - implementation of a **multi-barrier disposal system** that provides independent and complementary safety functions and components, ensuring sufficient safety is maintained following occurrence of an uncertain disruptive event or process
  - measures to **prevent deviations** from normal operation and the failure of items important to safety (such as when subjected to disturbances)
    - use of safety margins and reduction or avoidance of sources of uncertainty having the potential to jeopardise safety (e.g., by modifying the location or design of the repository)
    - preservation of knowledge about the repository
    - quality control measures and procedures to prevent defects and damage to disposal system components
  - implement measures to **detect deviations** from normal operation, defects or damage to the disposal system so that corrective measures can be taken where needed (e.g., waste retrieval where allowed for)
  - measures to **prevent or mitigate the consequences** of accidents that would result from failure of other measures

Date Training material eurad 16

ELEMENTS OF AN UNCERTAINTY MANAGEMENT STRATEGY



Date Training material 17

REGULATORY FRAMEWORK

- Regulatory requirements cover a range of safety standards that need to be addressed in the safety case
  - radiological dose and/or radiological risk constraints
  - protection of non-human organisms and the accessible environment
  - protection against non-radiological hazards
  - groundwater protection
- Assessments against these requirements will influence
  - the safety functions to be provided by different components of the barrier system
  - disposal system optimisation
- Regulatory guidance on how to address these requirements influences how uncertainty is addressed in the safety demonstration

Date Training material 18

REGULATORY FRAMEWORK

- Examples of how radiological dose or risk constraints may vary to reflect uncertainties associated with long disposal system evolution **timescales** and **unlikely scenarios**
- Such requirements ensure that assessments of unlikely scenarios or scenarios over very long timescales do not unduly influence design optimisation

	Constraint	Conditions
General	Dose: 0.1 to 0.5 mSv/year	Typical post-closure dose constraint for members of the public
	Risk: 10^{-6} per year	Typical annual risk constraint for an individual member of a potentially exposed group
France	Dose: 0.25 mSv/year	Reference conditions (normal evolution) on a timescale of at least 10,000 years
	Calculated dose levels should not be unacceptable (0.25 mSv/year is used as a reference level)	Reference conditions on timescales greater than 10,000 years
	Calculated dose should be low compared to levels that could lead to deterministic effects	Altered evolution scenarios
Belgium	Dose: 0.1 mSv/year	Expected evolution scenario
	Dose: 0.3 mSv/year	Reference scenarios (conservative assumptions)
	Dose: 3 mSv/year	'Penalising' scenarios (stylised worst-case illustrations)
	Risk: 10^{-6} per year	Expected evolution scenario
	Risk: 10^{-5} per year	Altered evolution scenarios
Slovenia	0.3 mSv/year	normal evolution scenario
	Calculated dose: < 10 mSv/year	Altered evolution scenarios for which no optimisation is required
	Calculated dose: 10 - 100 mSv/year	Altered evolution scenarios for which measures to minimise scenario probability are required
	Calculated dose: > 100 mSv/year	Altered evolution scenarios for which measures to minimise scenario consequences are required
UK	Dose calculation supports design optimisation	Human intrusion scenarios

Date Training material 19

REGULATORY FRAMEWORK

- Example of requirements on post-closure criticality scenario assessment, where regulations generally require a demonstration that criticality is not possible during transport and disposal of fissile wastes, which is achieved in part through packaging constraints, but requirements relating to post-closure criticality differ
  - it may be necessary to show that post-closure criticality is not a significant concern (UK)
    - a post-closure scenario assessment would aim to show that criticality is unlikely and, if it did occur, it would be of low consequence to repository performance
    - the unlikely post-closure criticality scenario has limited influence on design optimisation
  - alternatively, it may be necessary to show that appropriate measure have been taken to ensure criticality could not occur after repository closure (Switzerland)
    - a post-closure scenario assessment would need to show that criticality would not occur, with uncertainties in waste package evolution over long timescales taken into account
    - uncertainty about waste package evolution over long timescales may greatly influence waste package design, with defence in depth in design being important to eliminate the possibility of criticality occurring

Date Training material 20

REGULATORY FRAMEWORK

- Other types of regulatory requirements or guidance relating to uncertainty treatment
  - decisions about implementing uncertainty avoidance, reduction or mitigation options should be made in the context of the overall objective of ensuring that the detrimental impacts of disposal are as low as is reasonably achievable (ALARA) (i.e. with reference to the principle of **optimisation** and the use of Best Available Techniques (BAT))
  - there is adequate **defence in depth** (which may be part of an uncertainty management strategy), so that there is a combination of several layers of protection (e.g., safety functions provided by physical barriers, systems to protect the barriers, and administrative procedures) that would have to fail or be bypassed before there could be any consequences for people or the environment
  - it may be required that wastes remain **retrievable** after disposal, at least for a certain period of time, which may mitigate concerns that, ultimately, it may not be possible to reduce uncertainties sufficiently to satisfy all safety requirements
    - uncertainty may increase if the disposal system design becomes more complicated
    - long-term safety should not be impacted by measures that allow for retrievability

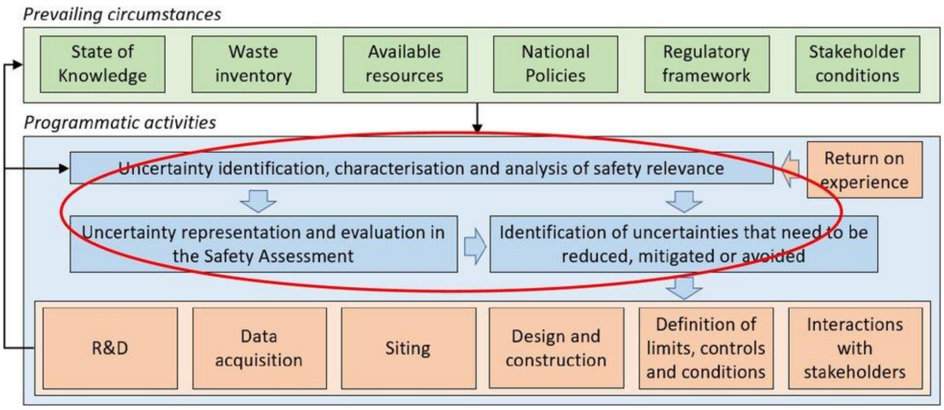
Date Training material eurad 21

REGULATORY FRAMEWORK

- Other types of regulatory requirements or guidance relating to uncertainty treatment (cont.)
  - **all uncertainties significant to safety** should be identified and adequately taken into account in the safety case
  - a scenario analysis should be included that considers all **features, events and processes** (FEPs) that might affect the performance of the disposal system
  - a programme of **uncertainty management** should be presented in the safety case
  - a **register of significant uncertainties** should be maintained, informed by safety assessment calculations, which will inform future phases of disposal system development (e.g., site characterisation activities and design modifications) and future research needs, with the aim of focusing on reduction or mitigation of the key uncertainties

Date Training material eurad 22

ELEMENTS OF AN UNCERTAINTY MANAGEMENT STRATEGY



Date Training material 23

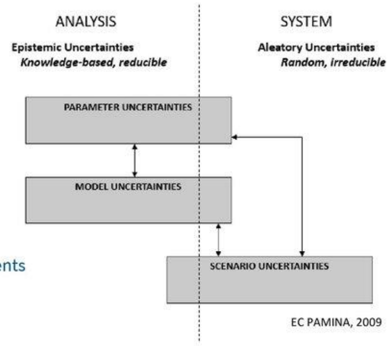
TYPES OF UNCERTAINTY

- Uncertainties relevant to the safety assessment have to be identified and characterised with respect to their source, nature and degree, using quantitative methods, professional judgment or both
  - analysis of FEPs that could affect disposal system behaviour commonly forms part of the uncertainty identification process
- In general, the following types of uncertainty need to be managed in a disposal programme and their relevance to safety assessed
  - programme uncertainties
  - uncertainties associated with the initial characteristics of the waste, site and engineered components
  - uncertainties in the evolution of the disposal system and its environment, including the effects of events and processes that may affect the initial characteristics of the disposal facility (e.g., hazards that may occur during construction and operation)
  - uncertainties associated with the data/parameters, models and methods used in the safety case
  - uncertainties associated with the completeness of the FEPs considered in the safety case

Date Training material 24

TYPES OF UNCERTAINTY

- These uncertainties can be classed as
  - epistemic uncertainties
    - relate to knowledge or the degree of its validation
    - e.g. uncertainty about site characteristics
    - can be reduced
  - aleatory uncertainties
    - relate to random events
    - e.g. uncertainty over the time of occurrence or magnitude of rare events
    - cannot be reduced



EC PAMINA, 2009

Date Training material eurad 25

TREATMENT OF UNCERTAINTY IN SAFETY ASSESSMENTS

- Uncertainties over future states of the disposal system are typically addressed in a safety assessment by considering different scenarios of disposal system evolution (**scenario uncertainties**)
- **Data/parameter and model uncertainties** associated with each scenario can be addressed by
  - demonstrating that the uncertainty is irrelevant or of low consequence to safety
  - representing the uncertainty explicitly using, for example, probabilistic techniques
  - bounding the uncertainty and showing that the bounding case gives acceptable safety
  - taking a stylised approach to handling uncertainty where few relevant data are available or can be gathered, which involves making plausible assumptions that tend to err on the side of conservatism
  - testing sensitivity to alternative credible models of uncertain processes
  - ruling out an uncertain but potentially significant FEP on the grounds of very low probability of occurrence, or because other consequences, were the FEP to occur, would far outweigh concerns over disposal facility performance
- **Vinzenz will discuss different methods for identifying, categorising and characterising these types of uncertainty, and ranking their importance to safety assessments**

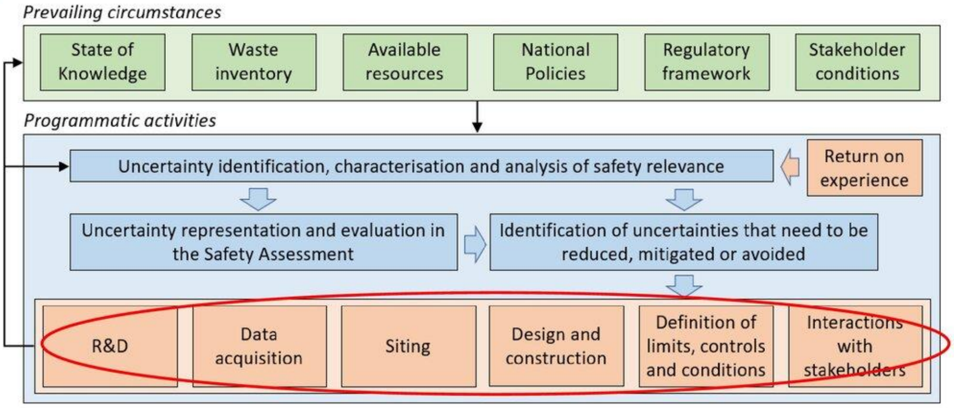
Date Training material eurad 26

TREATMENT OF UNCERTAINTY IN SAFETY ASSESSMENTS

- Assessing the impact of uncertainties is done through
  - **sensitivity analysis**, which looks at how calculated indicators of safety are influenced by uncertainty in input parameters
  - **uncertainty analysis**, which looks at uncertainty in calculated indicators of safety
- **Klaus will discuss approaches to sensitivity and uncertainty analysis**

Date Training material 27

ELEMENTS OF AN UNCERTAINTY MANAGEMENT STRATEGY



Date Training material 28

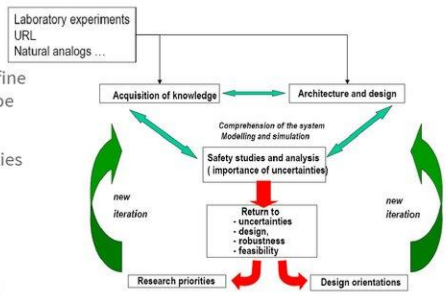
AVOIDANCE, MITIGATION AND REDUCTION OF UNCERTAINTIES

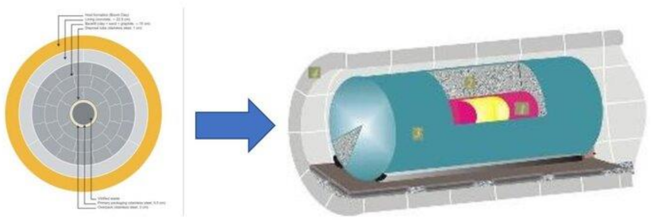
- Strategies for addressing uncertainties will involve a mixture of reduction, avoidance and mitigation that will adapt as programmes progress
  - further data acquisition
  - RD&D, although this is not likely to reduce unquantifiable uncertainties, particularly those relating to the very long timescales considered by assessments
  - constraining the inventory
  - characterisation or processing of waste
  - site selection and site characterisation
  - adapting the disposal concept
  - adopting particular construction, operation and closure methods (use of BAT)
  - maintaining/updating the management system (e.g., reduction of uncertainties on as-built properties through QA/QC measures)
  - allowing for retrieval in the event that it is not possible to reduce uncertainties sufficiently to satisfy all safety requirements

Date Training material eurad 29

AVOIDANCE, MITIGATION AND REDUCTION OF UNCERTAINTIES

- Examples of approaches to uncertainty reduction and avoidance
  - successive safety assessments in the French programme were used to refine site investigations and focus on those features of the host rock found to be most significant to its performance as a barrier
  - the Belgian 'supercontainer' concept was introduced to avoid uncertainties concerning near-field corrosion processes (amongst other things)





Date Training material eurad 30

MANAGING DISPOSAL DIFFERENT TYPES OF UNCERTAINTY

- Next will discuss options for managing
  - programme uncertainties
  - inventory uncertainties
  - disposal concept uncertainties
  - uncertainties in as-built conditions
  - uncertainties in disposal system evolution
  - uncertainties in data and models
  - uncertainties in the completeness of FEP and scenario analysis

Date Training material eurad 31

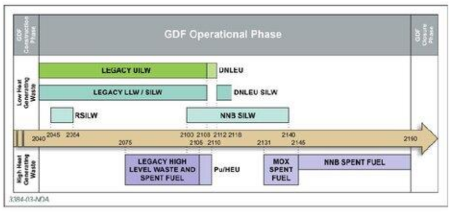
MANAGING DISPOSAL PROGRAMME UNCERTAINTIES

- Programme uncertainties include those related to
  - decisions on future energy policy (i.e., nuclear versus other technologies)
  - decisions on waste management practice (e.g., storage versus disposal, disposal of spent nuclear fuel versus reprocessing).
  - timing of repository programme decisions and their implementation (siting, construction, operation, and closure of facilities)
    - the regulatory framework
    - schedule of waste arisings
    - available financial resources, skills and experience

Date Training material eurad 32

MANAGING DISPOSAL PROGRAMME UNCERTAINTIES

- Addressing programme uncertainties
  - mitigation measures to address uncertainties in timing of programme decisions include stakeholder communication and involvement, review of strategy, monitoring of costs and allocation of resources, knowledge management, maintenance of technical skills, and ensuring political awareness of the long-term necessity of sufficient resources and maintenance of competences
  - in the early stages of a disposal programme, uncertainties may be managed through 'planning' assumptions about when facilities will become available, where facilities might be located, and what wastes will arise



NDA 2016

  - in later stages, uncertainties are related to facility closure and the possible need for remedial action in light of developing waste management practices

Date Training material 33

MANAGING DISPOSAL PROGRAMME UNCERTAINTIES

- Programme uncertainties may be addressed in cost estimations, which consider
  - uncertainties related to the maturity of the technologies used (e.g. innovative technologies) (e.g. technology contingencies in Slovenia programme).
  - uncertainties related to the maturity of the project, which include omissions and unforeseen costs caused by an incomplete definition of the project and its engineering (e.g. project contingencies in the Slovenian programme).
- Programme uncertainties may be managed by basing techniques for repository construction, operation and closure (and their costs) on available and proven technologies (BAT), and only adopting new technologies when they become sufficiently mature (e.g., Belgium, Netherlands)
- Socio-economic costs may be managed by acquiring finances for the facility upfront and the facility developer becoming the owner of the waste, which mitigates uncertainties relating to financial resources and the long-term existence of organisations that have generated the waste (Netherlands)

Date Training material 34

MANAGING INVENTORY UNCERTAINTIES

- Programme uncertainties can lead to uncertainties in the waste inventory, wasteforms for disposal and waste packaging options
  - address by considering alternative inventories in the safety assessment or cost estimate
  - adopt disposal concept that can be readily extended to accommodate additional waste volumes using (Netherlands)
- Uncertainties in estimates of waste arisings occur because of uncertainties in waste characterisation, waste conditioning, waste packaging, and the disposal programme schedule
  - regular inventory tracking and reporting - inventory uncertainties reduce as programmes evolve and the wastes are actually packaged and emplaced
  - use statistical analysis of historical data collected from nuclear power plants or other relevant facilities in operation
  - use upper bounding values or conservative scaling factors for inventory parameters
  - develop waste acceptance criteria (WAC) derived from the safety assessment to ensure waste packages conform to a standard
  - impose controls during waste acceptance to minimise possibility of emplacing waste packages that would not meet the WAC

Date Training material eurad 35

MANAGING DISPOSAL CONCEPT UNCERTAINTIES

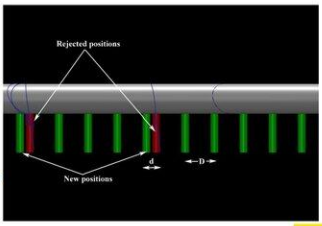
- Disposal concept uncertainty is greatest in the early programme phase and reflects decisions to be made about the wastes for disposal and the type of disposal facility
  - illustrative designs for the disposal of different categories of waste in different types of host rock may be assessed to provide demonstrations of how safety cases could be made (e.g. UK)
  - design variants (e.g. drift vs. shaft) may be assessed (e.g. Switzerland)
  - robustness of disposal concepts may be assessed through sensitivity analyses, which may account for human factors such as defects in design or manufacture, human error, etc. (France, Switzerland)
- Once the type of facility and the host rock have been decided, disposal concept uncertainties will reduce

TRU waste package disposal in vaults and test emplacement of borehole disposal in evaporite at WIPP, USA

Date Training material eurad 36

MANAGING UNCERTAINTIES IN AS-BUILT CONDITIONS

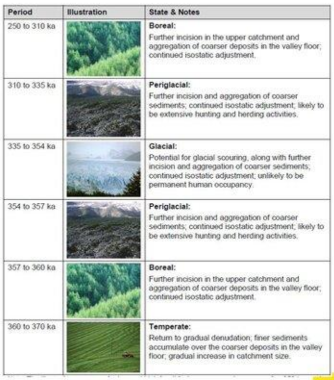
- A safety assessment must address the feasibility and reliability of proposed construction methods and the technical feasibility of the proposed design options
  - where there are large uncertainties, such as in the use of novel techniques, design alternatives may need to be considered based on technical options that have been demonstrated to be feasible
  - analysis of potential material QC or barrier emplacement errors, or undetected accidents, may be used to define conservative assumptions or alternative disposal system evolution scenarios based on different assumptions about conditions at the time of facility closure (Belgium, Sweden, UK)
  - feedback from experience during construction, and the results of maintenance, periodic testing, and inspection, will support uncertainty reduction
  - QA/QC activities during repository construction, operation and closure will help to reduce uncertainties in the as-built state



Date Training material 37

MANAGING UNCERTAINTIES IN DISPOSAL SYSTEM EVOLUTION

- Safety assessments generally address uncertainties in long-term evolution as follows
  - uncertainties in parameter values may be captured in parameter value distributions for use in probabilistic assessments, or upper and lower values of a range for use in deterministic assessments
  - uncertainties in barrier performance may be captured by defining different scenarios of disposal system evolution based on different assumptions about how the barriers provide safety functions when subject to the effects of uncertain events or processes
  - uncertainties in conditions in the very long-term may be treated by defining different scenarios of disposal system evolution (such as associated with different assumptions about climate change and its impacts or seismic events) and assessing those scenarios deterministically



Period	Illustration	State & Notes
250 to 310 ka		**Boreal:** Further incision in the upper catchment and aggregation of coarser deposits in the valley floor; continued isostatic adjustment.
310 to 335 ka		**Periglacial:** Further incision and aggregation of coarser sediments; continued isostatic adjustment; likely to be extensive hunting and herding activities.
335 to 354 ka		**Glacial:** Potential for glacial scouring, along with further incision and aggregation of coarser sediments; continued isostatic adjustment; unlikely to be permanent human occupancy.
354 to 357 ka		**Periglacial:** Further incision and aggregation of coarser sediments; continued isostatic adjustment; likely to be extensive hunting and herding activities.
357 to 360 ka		**Boreal:** Further incision in the upper catchment and aggregation of coarser deposits in the valley floor; continued isostatic adjustment.
360 to 370 ka		**Temperate:** Return to gradual denudation; finer sediments accumulate over the coarser deposits in the valley floor; gradual increase in catchment size.

Date Training material 38

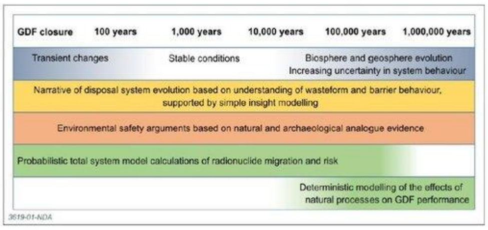
MANAGING UNCERTAINTIES IN DISPOSAL SYSTEM EVOLUTION

- Scenarios of disposal system evolution
  - typically a base or reference scenario is assessed which describes the features of the disposal system at closure and the way in which that system is expected to evolve, taking account of significant quantifiable uncertainties
  - deviations from the base scenario caused by FEPs that may or may not occur are considered as variant scenarios
  - human activities relevant to long-term safety assessments are always likely to be highly uncertain and are treated as variant or 'what-if' scenarios
- Site characterisation and material research will reduce quantifiable uncertainty in the long-term performance of natural and engineered barrier systems

Date Training material eurad 39

MANAGING UNCERTAINTIES IN DISPOSAL SYSTEM EVOLUTION

- An analysis of system uncertainties can be used to define a timescale for probabilistic calculations; that is a timescale during which all significant uncertainties can reasonably be represented explicitly
- For uncertainties that cannot readily be quantified, consider the timescale on which these become more significant than those that can be quantified
  - when cycles of major climate change (including glaciations) become possible, significant unquantifiable uncertainties relating to the evolution of a disposal system exist
  - beyond this timescale, deterministic 'what-if' calculations and reasoned qualitative arguments might be preferred over probabilistic analysis to illustrate possible system performance

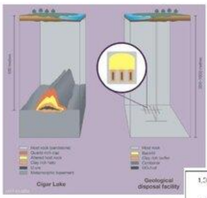


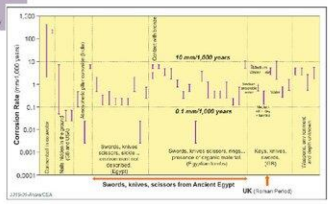
NDA 2016

Date Training material eurad 40

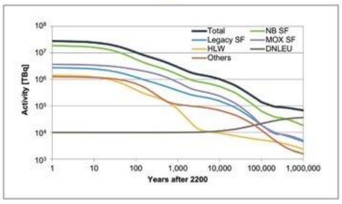
MANAGING UNCERTAINTIES IN DISPOSAL SYSTEM EVOLUTION

- Qualitative arguments regarding uncertainties in long-term evolution might involve
  - consideration of natural analogues and anthropogenic evidence
  - balancing increasing uncertainty with time against a decrease in radiotoxicity





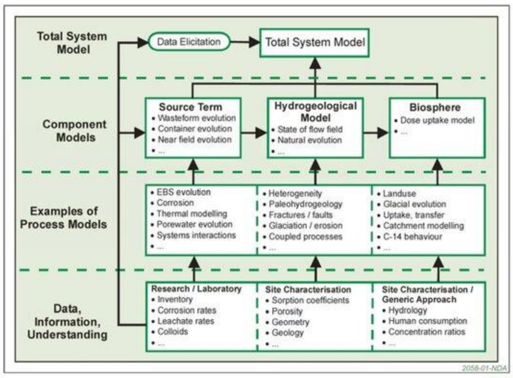
NDA 2016



Date Training material 41

MANAGING UNCERTAINTIES IN DATA AND MODELS

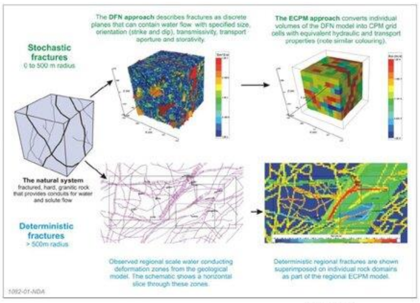
- How data are stored and recorded is relevant to the management of uncertainties
  - a data management system is important to ensuring the quality of data at all levels in safety assessment models
    - will need to store metadata, including provenance and sources of uncertainty
    - there are likely to be hierarchies of models through which data and information about uncertainties need to be propagated



Date Training material 42

MANAGING UNCERTAINTIES IN DATA AND MODELS

- Model uncertainty is the uncertainty in the calculation models used in the safety assessment
  - where there is model uncertainty, assumptions can be made that overestimate the consequences of unfavourable processes and conversely that underestimate or neglect the potentially positive consequences of favourable processes
  - alternative models or alternative approaches to simplification may be used to illustrate uncertainties caused by model simplifications
- Verification and, as far as possible, validation of models and computer codes used in safety assessments supports avoidance or minimisation of model uncertainties
  - validation usually involves comparing the results of specific process simulations with experimental data, field observations, and/or natural analogues

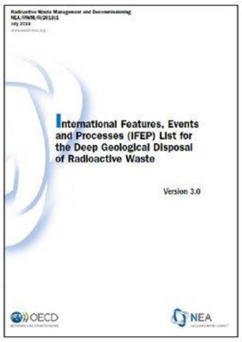


NDA 2016

Date Training material 43

MANAGING UNCERTAINTIES IN COMPLETENESS OF FEP AND SCENARIO ANALYSIS

- The scope of FEP identification and analysis needs to be sufficient to meet the needs of the safety assessment; uncertainty in the completeness of FEP analysis can be reduced through
  - the use of well-understood and compatible materials for the engineered barriers and the selection of a host rock that is unlikely to be affected in the future by any unrecognised natural phenomenon or future human action
  - the application of a FEP management process throughout the disposal programme
  - the use of safety margins in the design of engineered repository components (e.g., cautious waste container thickness)
  - participation in or reference to international projects and FEP analysis done by other organisations



Date Training material 44

MANAGING UNCERTAINTIES IN COMPLETENESS OF FEP AND SCENARIO ANALYSIS

- A safety case is likely to include a FEP analysis with a justification of why FEPs are discarded from scenario development or how they have been treated
  - the scenario development methodology should provide sufficient confidence in the completeness of the scenarios identified and, hence, minimise uncertainties associated with the completeness of the FEPs considered
  - altered evolution scenarios and what-if scenarios assuming the loss of a barrier or a safety function can be used to assess the robustness and defence-in-depth provided by the disposal system; such an approach substantiates that some degree of uncertainty in the completeness of FEPs would not jeopardise safety

Date Training material 45

SUMMARY AND CONCLUSIONS.

- This lecture has explained the importance of implementing an uncertainty management strategy in the early stages of a disposal programme
  - information about uncertainties informs decisions to be taken at any programme step
  - how uncertainties are accepted and managed evolves throughout programme phases, and is influenced by factors such as
    - the state of knowledge
    - the regulatory framework
  - various methods may be used to avoid, mitigate or reduce uncertainties and a description of the programme for uncertainty management needs to be included in a safety case
- The various types of uncertainty to be addressed in a safety case have been described and options for managing them have been summarised (detailed approaches to the treatment of different types of uncertainty in safety assessments are discussed in later lectures)
- A well managed uncertainty management strategy is an essential part of a programme that will lead to implementation of an optimum solution for the long-term safety of radioactive waste disposal

Date Training material 46

BIBLIOGRAPHY AND/OR REFERENCES.

- International Atomic Energy Agency, Fundamental Safety Principles, IAEA Safety Fundamentals Report No. SF-1, 2006.
- Nuclear Energy Agency, The Safety Case for Deep Geological Disposal of Radioactive Waste: 2013 State of the Art, Symposium Proceedings, 7-9 October 2013, Paris, France. NEA Radioactive Waste Management Committee Report NEA/RWM/R(2013)9, 2013.
- International Atomic Energy Agency, The Safety Case and Safety Assessment for the Disposal of Radioactive Waste, IAEA Specific Safety Guide No. SSG-23, 2012.
- J. Vigfusson, J. Maudoux, P. Raimbault, K-J. Röhlig and R.E. Smith, European Pilot Study on the Regulatory Review of the Safety Case for Geological Disposal of Radioactive Waste - Case Study: Uncertainties and their Management, 2007.
- European Commission, PAMINA - Performance Assessment Methodologies in Application to Guide the Development of the safety Case: The Treatment of Uncertainty in Performance Assessment and Safety Case Development: Synthesis of PAMINA RTDC-2, Deliverable D2.3.1, 2009.
- Nuclear Energy Agency, Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste: Outcomes of the NEA MeSA Initiative, NEA No. 6923, Organisation for Economic Co-operation and Development, Paris, France, 2012.
- P. Lebon, Lessons learnt from Dossier 2005. Overview of the Disposal Feasibility Assessment in Meuse/Haute-Marne: From the Preliminary Geoscientific Survey to the Safety Case, 3rd OECD/NEA AMIGO Workshop, Nancy, April 2008.
- Western European Nuclear Regulators' Association, Radioactive Waste Disposal Facilities Safety Reference Levels, 22 December 2014.
- International Atomic Energy Agency, Safety Assessment for Facilities and Activities, IAEA Safety Standards Series No. GSR Part 4, 2009.

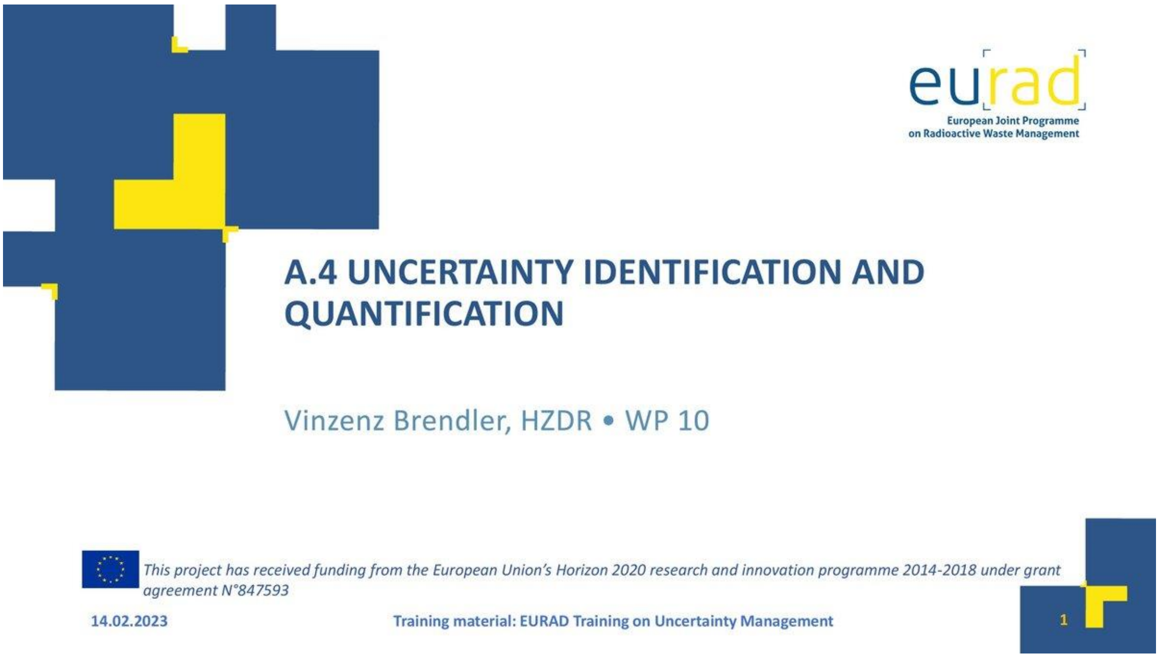
BIBLIOGRAPHY AND/OR REFERENCES.

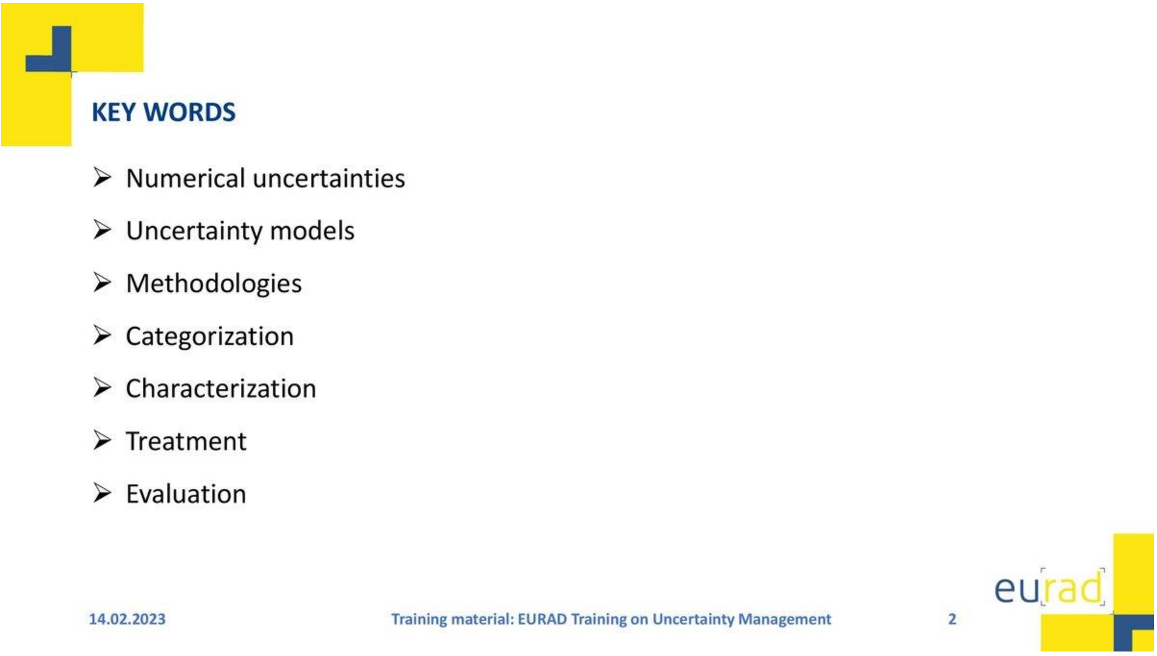
- International Atomic Energy Agency, Disposal of Radioactive Waste, IAEA Safety Standards Specific Safety Requirements No. SSR-5, 2011.
- NDA, Geological Disposal: Technical Background to the generic Disposal System Safety Case, DSSC/421/01, December 2016.
- NDA, Geological Disposal: Geosphere Status Report, DSSC/453/01, December 2016.
- Environment Agency and Northern Ireland Environment Agency, Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation, February 2009.
- NDA, Geological Disposal: Generic Environmental Safety Case – Main Report, DSSC/203/01, December 2016.
- NDA, Geological Disposal: Engineered Barrier System Status Report, DSSC/452/01, December 2016.
- NDA, Geological Disposal: Waste Package Evolution Status Report, DSSC/451/01, December 2016.

Appendix C. Slides of lecture A.4

A.4 Uncertainty identification and quantification

Prepared by Vincenz Brendler, HZDR





CONTENTS

- **Learning outcomes**
- **Introduction:**
  - Why are uncertainties that important & how you can benefit from the lecture
  - UMAN – a little bit of history
  - Selected Glossary terms
  - Major Goal →Draft a Methodology
- **Identification:**
  - Relevance criteria
  - Bottom-Up *vs.* Top-Down
  - Survey methods for established approaches
  - Questionnaire – How to include a variety of opinions & approaches
- **Uncertainty characterization:**
  - Examples from geochemistry, geology and long-term stability
- **Uncertainty categorization:**
  - Alternative categorization Types
  - Uncertainty categorization specific to EURAD
- **Uncertainty quantification & Numerical evaluation**
- **Summary & Conclusions**
- **Bibliography**

14.02.2023 Training material: EURAD Training on Uncertainty Management 3

eurad

LEARNING OUTCOMES

After the completion of this training unit/lesson:

1. Students/participants should be able to understand the major elements and internal logics of uncertainty identification focussed on numerical parameters
2. Participants can apply important definitions linked to uncertainty treatments
3. Different ways of uncertainty categorization and presentation are known

14.02.2023 Training material: EURAD Training on Uncertainty Management 4

eurad

INTRODUCTION – WHY ARE UNCERTAINTIES THAT IMPORTANT?

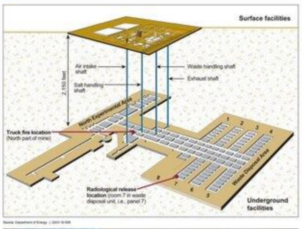
Rui Zink – Die Installation der Angst | lustauflesen.de

- Decisions associated with Radioactive Waste Management (RWM) programs are made in the presence of irreducible and reducible uncertainties.
  => Uncertainty creates an uncomfortable position for a large part of the public (anxiety).
- Uncertainties are a **big challenge** (known unknowns, unknown unknowns etc.; difficulties to express them numerically, multi-dimensional problem, variety of mathematical approaches, scenario-dependent, …)

Identification \ Certainty		Certain (Known)	Uncertain (Unknown)	
			Impact	Occurrence
Identified (Known)		Known known (identified knowledge)	Known unknown (identified risk)	
Unidentified (Unknown)	Consequence	Unknown known (untapped knowledge)	Unknown unknown (unidentified risk)	
	Event			

14.02.2023 Training material: EURAD Training on Uncertainty Management 5

INTRODUCTION – HOW YOU CAN BENEFIT FROM THE LECTURE



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

14.02.2023 Training material: EURAD Training on Uncertainty Management 6

UMAN – A LITTLE BIT OF HISTORY …

- Subtask 2.2 (ST 2.2) "Uncertainty identification, classification and quantification" started work in June 2019.
- Team of ST 2.2 is composed of partners from:
  CIEMAT, EIMV, GRS, HZDR, Nagra, NDA, SCK-CEN, STUBA, SURAO, TU Sofia
- A questionnaire was developed together with ST 2.3 "Methodological approaches to uncertainty and sensitivity analysis" to ask for established knowledge on:
  - how to identify numerical uncertainties (i.e. uncertainties concerning quantities, sometimes also called parameter uncertainties) that might be of relevance
  - which possible schemes of classification of uncertainties are utilized so far
- Together with my colleague *Solveig Pospiech* and substantial help from various ST 2.2 members (plus Andra, IRSN, TUL, UDC & UJV) a report was drafted, with its final version under external review since December 2022.

14.02.2023 Training material: EURAD Training on Uncertainty Management 7

eurad

SELECTED GLOSSARY TERMS *(MAY ALSO BE HELPFUL FOR FOLLOWING LECTURES)*

- **Aleatory Uncertainty:** The stochastic part of the uncertainty of an input parameter that forms an intrinsic property of the parameter and that cannot be reduced. An aleatory random variable represents the possible outcome of an observation of the quantity.
- **Epistemic Uncertainty:** The part of the uncertainty of an input parameter resulting from limited knowledge of the natural conditions and processes that can in principle be reduced by obtaining more information. An epistemic random variable represents the state of knowledge about the quantity.
- **Features, Events, and Processes (FEP):** These are terms used in the fields of radioactive waste management, carbon capture and storage, and hydraulic fracturing to define relevant scenarios for safety assessment studies.
- **Geological Domain:** A spatial distinct region or subregion in the geological formation with similar modal mineral composition, structural properties, spatial orientation and anisotropy, rock density, porosity and rock mechanic properties.

14.02.2023 Training material: EURAD Training on Uncertainty Management 8

eurad

SELECTED GLOSSARY TERMS (CONTD.)

- **Goal Breakdown Structure (GBS):** The EURAD goals breakdown structure is a thematic breakdown of knowledge and generic activities essential for radioactive waste management.
  It comprises Themes (Level 1), Subthemes (Level 2) and Domains (Level 3), each formulated as goals.
  Although hierarchical and numbered, the knowledge and activities presented across the GBS should be considered collectively with no weighting to order of importance. Rather it is emphasised that there are many inter-dependencies and linked data across the GBS, where knowledge and activities can be centred in different ways, depending on the end user role and precise boundary conditions of a specific RWM programme.
- **Sensitivity Analysis (SA):** The process of appreciating the dependency of the model output from model input. It also investigates how important each model input is in determining the output.
- **Uncertainty:** Lack of objective information (evidence) or subjective information (knowledge).
- **Uncertainty Analysis (UA):** The process of exploring the uncertainty in the model output.

14.02.2023 Training material: EURAD Training on Uncertainty Management 9

MAJOR GOAL: DRAFT FIRST STEPS FOR A METHODOLOGY FOR UNCERTAINTY TREATMENT

Strategy
- Compare Bottom-up and Top-down strategies to identify processes with high relevance for RWM (including a description of the methodology and criteria utilized to identify them).

Survey
- Survey methods for the assessment of uncertainties with respect to their potential treatment in numerical models. This includes (but is not limited to) their "degree of quantification" and ways to transform them (if necessary and feasible) into pdfs.

Structure
- Characterize uncertainties and their underlying structure / relationships and interdependencies.

14.02.2023 Training material: EURAD Training on Uncertainty Management 10

MAJOR GOAL:
DRAFT FIRST STEPS FOR A METHODOLOGY FOR UNCERTAINTY TREATMENT

- **Category**
  - Select an appropriate categorization scheme for uncertainties to support further processing, supported by respective characterization types. This may depend on a variety of common properties / features.
- **Values**
  - Assign uncertainties and refine the relevance ranking if appropriate.
- **Outlook**
  - Recommend future activities / research direction to promote the points described above.
- **Papers**
  - Provide a bibliographic basis for further reviews and surveys, ideally also assisting the development of "State-of-knowledge" contributions aimed at in WP 11 of EURAD.

14.02.2023 Training material: EURAD Training on Uncertainty Management 11

IDENTIFICATION OF RELEVANCE CRITERIA

Checks for relevance are essential as the sheer number of uncertainties is overwhelming …

Relevance can be derived from:

- Level of impact on safety
- Level of impact on decision-making process
- Priority for further investigation
- Cost-benefit-ratio

		Uncertainty		
		Large Amount of Knowledge	Medium Amount of Knowledge	Low Amount of Knowledge
Severity	Catastrophic Impact	Critical	Critical	Critical
	Medium Impact	Potential	Potential	Potential
	Low Impact	Non-Critical	Non-Critical	Potential

Problem: such criteria are obviously regularly used but seldom specified !?

14.02.2023 Training material: EURAD Training on Uncertainty Management 12

IDENTIFICATION: BOTTOM-UP *VS.* TOP-DOWN

Bottom-up (BU) and **top-down (TD)** modelling strategies are utilized for many complex application cases in science and society beyond RWM. It is advised to have understanding of both philosophies, their strengths and weaknesses.

BU: builds on detailed knowledge and process understanding on a mechanistic level, which fosters public acceptance of specific safety cases. But typically it has an enormous amount of details (200+ parameters collected by the OECD/NEA Crystalline Club alone for assessing host rock properties in the safety case) => hard to parameterize, requires huge amount of computing time. On the other side, it allows many parameters to be declared insensitive already at an early stage of model development.

TD: focuses on integration of system components & can handle large numbers of uncertain parameters often easier, but may overlook higher-order effects and not cover all regions of interest.

- **Combine them**: BU approaches can provide generic parameters requested by TD models that usually start on a rather coarse level and will then be iteratively refined.

A hierarchy of models (often to be refined iteratively) can be required for complex systems. Depending on the specific application field within RWM, the mutual relationships between BU and TD and their respective weight may vary. BU models clearly scale with the dimensionality.

14.02.2023 Training material: EURAD Training on Uncertainty Management 13

SURVEY METHODS UTILIZING ESTABLISHED APPROACHES

Description of sources used for to identify and rank uncertainties:

- Compilation from expert elicitation,
  here primarily based on a respective **questionnaire** send out in 2021
  to UMAN ST 2.2 & ST2.3 participants
- Interactions with UMAN Task 3 teams, utilizing their reports
- Evaluation of a literature survey
  (with feedback from 14 UMAN partners)

14.02.2023 Training material: EURAD Training on Uncertainty Management 14

QUESTIONNAIRE – INCLUDE A BROAD VARIETY OF OPINIONS & APPROACHES

1) Which category of numerical uncertainties do you typically encounter in your work? Please label your answers whether they are aleatory or epistemic.
2) Which rules / handbooks / best practices / … are used in your work group to treat uncertainties?
3) How do you identify the relevance of uncertainties?
4) Which numerical parameters are in the focus of your experimental or modelling work, to which processes / phenomena are they related?
5) Describe the types of uncertainties relevant for the example.
6) By which means did you quantify these uncertainties?
7) How do you parameterize the uncertainties?
8) Which methods are used to verify *post mortem* a correct assignment of approach and parameterization?

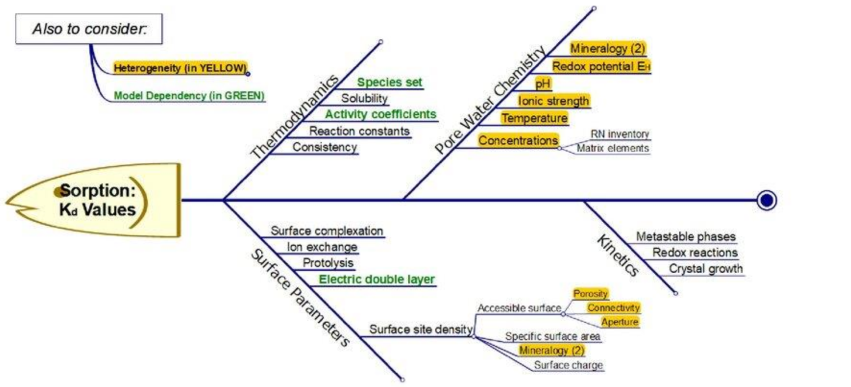
14.02.2023 Training material: EURAD Training on Uncertainty Management 15

UNCERTAINTY CHARACTERIZATION

- Advices on how uncertainties can be **characterized, illustrated and structured** to pave the way to a comprehensive assessment of numerical uncertainties:
  - Fishbone (Ishikawa) diagrams
  - Uncertainty table
  - Verbal description (see Tim Hicks about Managing Disposal Programme Uncertainties slides #11-14 - and others)
  - ➢ Representative examples will follow for uncertainty hierarchies & interdependencies (already grouped according to the EURAD GBS)
- **Specifics** for the **Bottom-up** approach**:**
  - Basic uncertainties will effect "very different processes very differently"
  - Uncertainties may be different for alternative models (for the same process)
  - There is a hierarchy of models, up-scaling is a serious challenge calling for model reduction (+ ML applications)

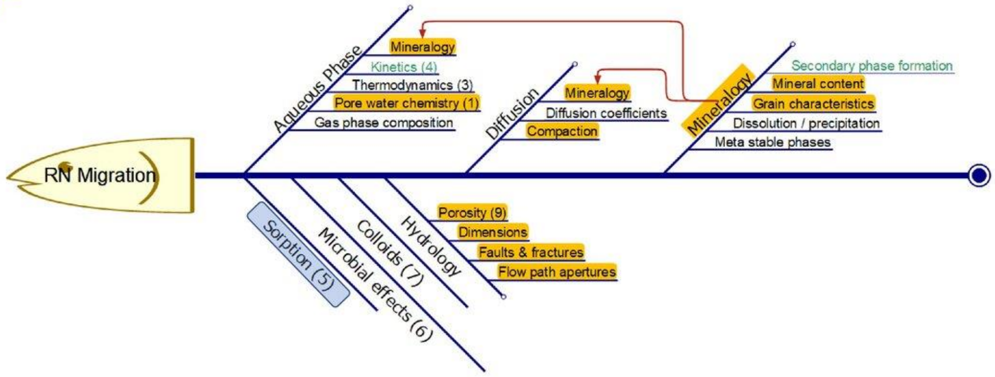
14.02.2023 Training material: EURAD Training on Uncertainty Management 16

UNCERTAINTY CHARACTERIZATION: GEOCHEMISTRY EXAMPLE #1



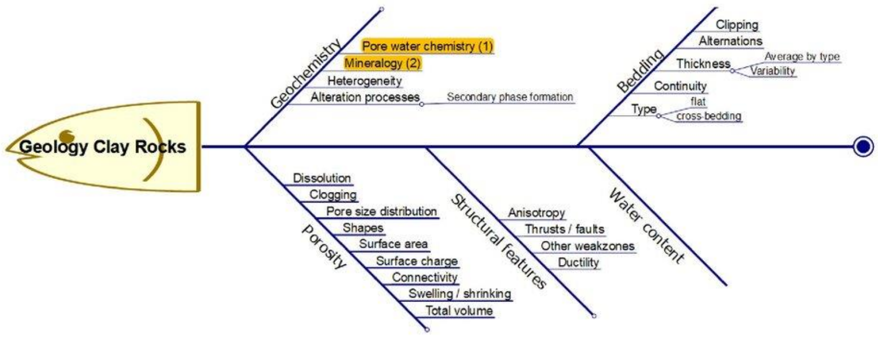
Fishbone (Ishikawa) diagram, highlighting the mutual relationship between uncertainties contributing to the overall uncertainty of distribution coefficients describing sorption.

UNCERTAINTY CHARACTERIZATION: GEOCHEMISTRY EXAMPLE #2



Fishbone (Ishikawa) diagram analyzing radionuclide migration (with sorption being one [important] submodel.

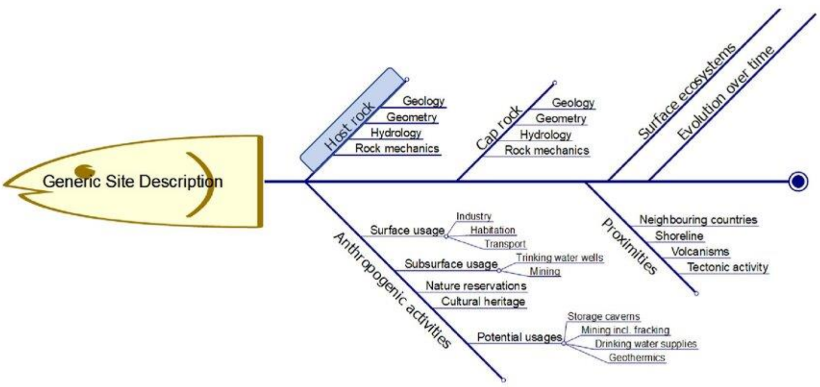
UNCERTAINTY CHARACTERIZATION: GEOLOGY EXAMPLE #1



Fishbone (Ishikawa) diagram illustrating the uncertainties related to argillaceous host rocks.

14.02.2023 Training material: EURAD Training on Uncertainty Management 19

UNCERTAINTY CHARACTERIZATION: GEOLOGY EXAMPLE #2



Fishbone (Ishikawa) diagram describing uncertainties for a generic DGR site.

14.02.2023 Training material: EURAD Training on Uncertainty Management 20

UNCERTAINTY CHARACTERIZATION: LONG-TERM STABILITY EXAMPLE #1

- Uncertainty table describing the hierarchy of contributions to the overall uncertainty associated with the geological and tectonic evolution of a DGR.

EURAD Subtheme	EURAD Domain	Induced effects	Associated uncertainties	Epistemic / Aleatoric
Long-term stability	Geological and tectonic evolution (Seismicity & Faulting)	changes in hydrogeology (seismic pumping)	frequency; amplitude; time of occurrence	A
		faults growth	fault size	A
		new faults creation --> changes in the water field and transport	fault size and permeability, geometry of aquifers (thickness, depth and extent)	A
		new fractures	hydraulic properties	E

14.02.2023 Training material: EURAD Training on Uncertainty Management 21

UNCERTAINTY CHARACTERIZATION: LONG-TERM STABILITY EXAMPLE #2

- Climate uncertainty table.

EURAD Subtheme	EURAD Domain	Induced effects	Associated uncertainties
Long-term stability	Climate (general and extreme conditions)	Cooling (up to permafrost) or warm-up: porosity changes	Temperature shift, water table level; time interval of wet periods, permafrost depth
		wet periods: changing infiltration and recharge rates; water table level; groundwater chemistry	Infiltration / evapo-transpiration rate; time interval of wet periods
		desertification: increased soil erosion	erosion rate
		shoreline displacement	time of occurrence, extent of displacement

14.02.2023 Training material: EURAD Training on Uncertainty Management 22

UNCERTAINTY CHARACTERIZATION: LONG-TERM STABILITY EXAMPLE #3

- Glaciation uncertainty table.

EURAD Subtheme	EURAD Domain	Induced effects	Associated uncertainties
Long-term stability	Climate (Glaciation)	interglacials: large volumes of surface water (ice melts) affects topology, ground water fluxes, flow directions	interglacial cycle & their numbers; stress fields; flow parameters; water chemistry; temperature
		glacial periods: effects on the surface environment and groundwater	glacial cycle/amplitude; permafrost depth; ice thickness; stress fields; flow parameters; temperature
		repeated glaciations: may exhume the repository	erosion rate
		blockage of pathway due to precipitation and filtration of colloids and particles	flow field

14.02.2023 Training material: EURAD Training on Uncertainty Management 23

UNCERTAINTY CATEGORIZATION

- Categorization supports the identification of uncertainties with high relevance for RWM:
  - Provides a systematic and uniform approach to describe uncertainties
  - Gives hints on how to manage them
  - Provides hierarchical structures and mutual dependencies
- The internet is full of respective taxonomies – but they are either too specific or too general
- Nine suitable categories are identified (next slide).

14.02.2023 Training material: EURAD Training on Uncertainty Management 24

CATEGORIZATION TYPES PREVIOUSLY USED IN RWM

Often used categorizations:

- Parameter, model or scenario uncertainties
- Order of relative magnitude
- Epistemic or aleatory
- Parameter applicability in models (globally to specific)
- Relevance for RWM
- Temporal order of occurrence
- Assignment to system (component or process)
- Type of heterogeneity

Categorization specific to EURAD:

- **EURAD Roadmap / Goal Breakdown Structure = Themes, Subthemes & Domains**

14.02.2023 Training material: EURAD Training on Uncertainty Management 25

UNCERTAINTY CATEGORIZATION - SPECIFIC TO EURAD …

- EURAD Roadmap / Goal Breakdown Structure (GBS) = Themes, Subthemes & Domains
- In UMAN it was advised already at an early stage to categorize uncertainties according to the occurrence by system phenomena, following the themes and subthemes of the EURAD GBS.
- All EURAD documents follow that approach, i.e. respective information is already pre-categorized (see task 3 subdivisions of UMAN and also the KMS Domain insight documents)

14.02.2023 Training material: EURAD Training on Uncertainty Management 26

UNCERTAINTY QUANTIFICATION

Here: Focus on numerical uncertainties => reference to other types (from slide #24 by Tim Hicks):

- programme uncertainties
- uncertainties associated with the initial characteristics of the waste, site and engineered components
- uncertainties in the evolution of the disposal system and its environment including the effects of events and processes that may affect the initial characteristics of the disposal facility (e.g., hazards that may occur during construction and operation)
- uncertainties associated with the data, tools and methods used in the safety case
- uncertainties associated with the completeness of the FEPs considered in the safety case

The last part of this lecture briefly points to the evaluation as well as quantification of uncertainties:

- Incomplete information (missing data due to too large efforts or lacking access in principle)
- Imprecise data (non-ideal experiments: method, device, boundary conditions etc.)
- Inherent heterogeneities (in space and/or time), i.e. variability

The following lectures by Klaus-Jürgen Röhlig and Dirk-Alexander Becker will provide more details.

14.02.2023 Training material: EURAD Training on Uncertainty Management 27

NUMERICAL EVALUATION

- Three levels of uncertainty evaluation:
  - Experimental stage: Specific designed experiments allow to determine and quantify uncertainties of single uncertainty components.
  - Uncertainty model: Conceptual models are transformed into mathematical models.
  - Mathematical theory: Deterministic/probability statistics, worst case analysis and fuzzy set theory.
- Most reports and experts use **probability statistics**.
  Two main branches are frequency statistics and Bayesian statistics
- A frequently used mathematical tool to characterize the value range and the likelihood are probability density functions (pdf).
- **Worst-case analysis**
- **Fuzzy set theory**
- ***Challenge:*** transfer verbal descriptions into numerical approaches.

14.02.2023 Training material: EURAD Training on Uncertainty Management 28

SUMMARY: PROPOSED WORKFLOW FOR NUMERICAL UNCERTAINTY TREATMENT

- Identify all FEPs (features/events/processes)
- Assign importance to the FEPs (related to the safety case) following the GBS
- Assign numerical models to all processes (Top-Down or Bottom-Up)
- Check available parameterization
- Categorize uncertainties to ease further processing
- Assign numerical uncertainties to model parameters, convert information into numerics if necessary and possible, e.g. by applying fuzzy theory
- Derive pdfs
- Define appropriate target function(s) based, e.g., on the regulatory framework
- Apply uncertainty and sensitivity analysis
- Re-iterate on importance and identify uncertainties that need treatment
- Start management of uncertainties, e.g. by model reduction or fixation (see previous talk by Tim Hicks)
  - Reduce
  - Mitigate
  - Avoid

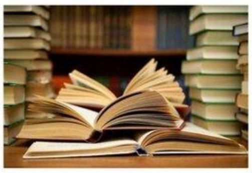
14.02.2023 Training material: EURAD Training on Uncertainty Management 29

CONCLUSIONS

- "Relevance/Importance" and associated criteria for them with respect to the various topics require a more intensive discussion
- Have a more detailed look on the temporal order of occurrences of uncertainties
- Reduce uncertainties due to poor communication between "applied" persons (field expert, lab expert, etc.) and "geeks" (safety assessor, modeller, etc.).
- Better connect transition from geosphere models to biosphere models
- Investigate the issue of uncertainty correlation
- Extend codes to make directly use of uncertainties and combine uncertainty components in a model other than additive

14.02.2023 Training material: EURAD Training on Uncertainty Management 30

BIBLIOGRAPHY



- Aaltonen, J. Engström, K. Front, S. Gehör, P. Kosunen, A. Kärki, M. Paananen, Mattila, J. A., S. Paulamäki (2016). Geology of Olkiluoto. Report 2016-16, Posiva, Eurojoki.
- Bailey, L. E. (2005). Performance Assessment in Context. Report N/117, Nirex.
- Bandemer, H., Gottwald, S. (1995). Fuzzy sets, fuzzy logic, fuzzy methods: With applications. Chichester, Wiley.
- Bárdossy, G., Fodor, J. (2004). Evaluation of uncertainties and risks in geology: new mathematical approaches for their handling (1st ed.), Springer.
- Brendler, V.; Pospiech, S. (2022): Uncertainty identification, classification and quantification. Final version as of 05.08.2022 of deliverable D10.3 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.
- **EURAD Roadmap - A generic framework to organise typical scientific and technical domains/ sub-domains in a logical manner against different phases of a RWM programme. https://www.ejp-eurad.eu/roadmap.**
- Galson, D. A., Khursheed, A. (2007). The Treatment of Uncertainty of Performance Assessment and Safety Case Development: State-of-the-Art Overview Milestone (No.:M1.2. Tech. rep., PAMINA. Retrieved from http://www.ip-pamina.eu/downloads/pamina.m1.2.1.pdf.
- Galson, D. A., Richardson, P. J. (2009). Performance assessment methodologies in application to guide the development of the safety case (PAMINA). Report, Galson Sciences Limited. Retrieved from http://www.ip-pamina.eu/downloads/pamina.summaryweb.pdf.
- International Organization for Standardization. (2008). Uncertainty of Measurement–Part 3: Guide to the expression of Uncertainty in Measurement (GUM: 1995). ISO. Retrieved from https://www.iso.org/standard/50461.html.
- Marivoet, J., Beuth, T., Alonso, J., Becker, D.-A. (2008). Uncertainty Management and Uncertainty Analysis, Task reports for the first group of topics: Part3, Deliverabe (D-N:1.1.1). Report PAMINA. Retrieved from http://www.ip-pamina.eu/downloads/pamina1.1.1.pdf.
- McManus, H & Hasting, D.E. (2004) A Framework for Understanding Uncertainty and Its Mitigation and Exploitation in Complex Systems, IEEE Engineering Management Review 34, 1-19, DOI: 10.1109/EMR.2006.261384.

eurad

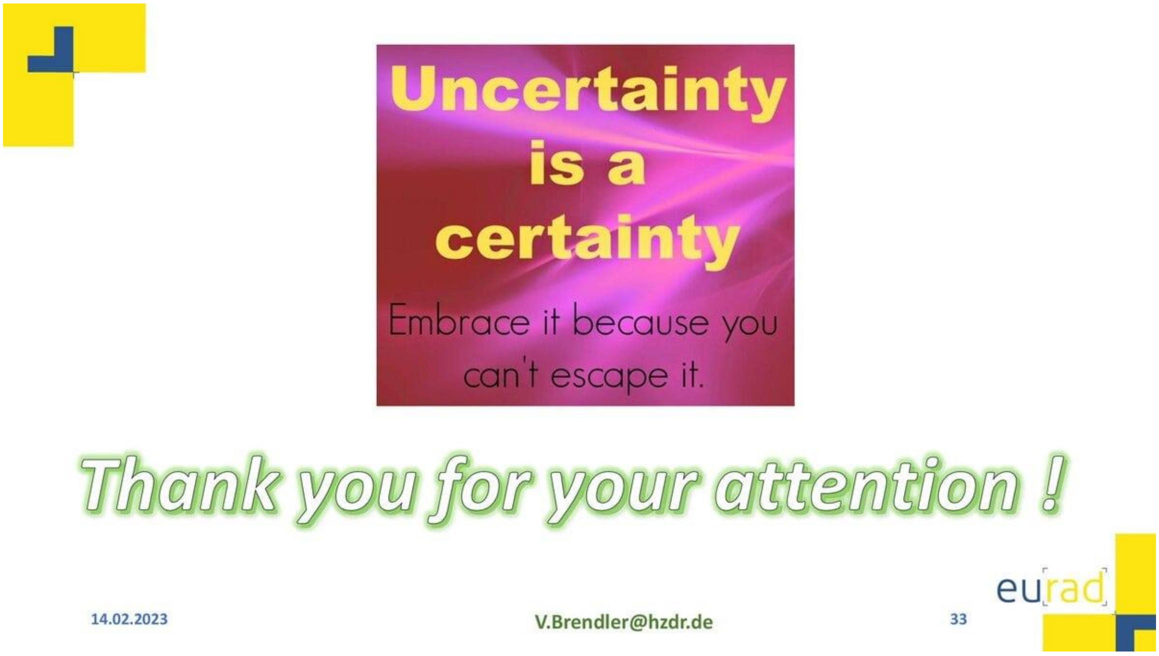
14.02.2023 Training material: EURAD Training on Uncertainty Management 31

BIBLIOGRAPHY (II)

- Mönig, J., Bailey, L., Capouet, M., van Luik, A., Sevougian, S. D., Gierszewski, P. (2012). Treatment of uncertainties. In Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste. OECD Publishing. DOI: 10.1787/9789264991903-en.
- Morgan, M. G., Henrion, M. (1990). Uncertainty. Cambridge University Press. ISBN: 978-0521365420. DOI: 10.1017/CBO9780511840609
- Nagra. (2019). Management of Uncertainty in the Assessment of Post-Closure Safety of Deep Geological Repositories (NAB 18-043), available upon request at Nagra.
- Nuclear Decommissioning Authority (2013) Geological Disposal: Framework for Application of Modelling in the Radioactive Waste Management Directorate, NDA Report NDA/RWMD/101.
- Nuclear Decommissioning Authority (2017), Geological Disposal: Methods for Management and Quantification of Uncertainty, NDA Report NDA/RWM/153.
- Nuclear Energy Agency. (2012). Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste. Report of the NEA MeSA Initiative. DOI: 10.1787/9789264991903-en.
- Nuclear Energy Agency. (2019). International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste. Report of the Radioactive Waste Management Committee.
- Spiessl, S., Becker, D.-A. (2017). Investigation of modern methods of probabilistic sensitivity analysis of final repository performance assessment models (MOSEL). Report GRS–412. Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) gGmbH, Braunschweig.
- Swiler, L. P., Becker, D.-A., Brooks, D., Govaerts, J., Koskinen, L., Plischke, E., Röhlig, K.-J., Saveleva, E., Spiessl, S. M., Stein, E., Svitelman, V. (2021). Sensitivity Analysis Comparisons on Geologic Case Studies: An International Collaboration. Report SAND2021-11053, Sandia National Lab., Albuquerque. DOI: 10.2172/1822591.
- Wanner, H., Östhols, E. (1999). TDB-3 Guidelines for the Assignment of Uncertainties. Issy-les-Moulineaux: OECD-NEA.

eurad

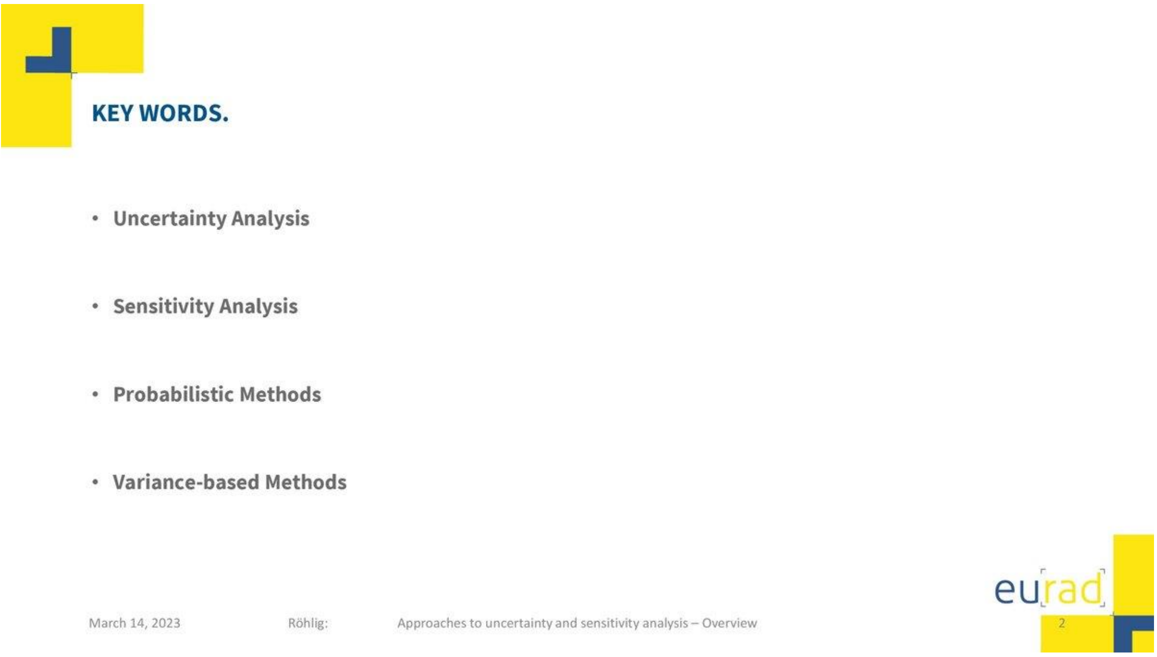
14.02.2023 Training material: EURAD Training on Uncertainty Management 32


Uncertainty
is a
certainty
Embrace it because you
can't escape it.
Thank you for your attention !
14.02.2023
V.Brendler@hzdr.de
33
eurad

Appendix D. Slides of lecture A.5

A.5 Approaches to uncertainty and sensitivity analysis – Overview

Prepared by Klaus Röhlig, TUC



CONTENTS.

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview

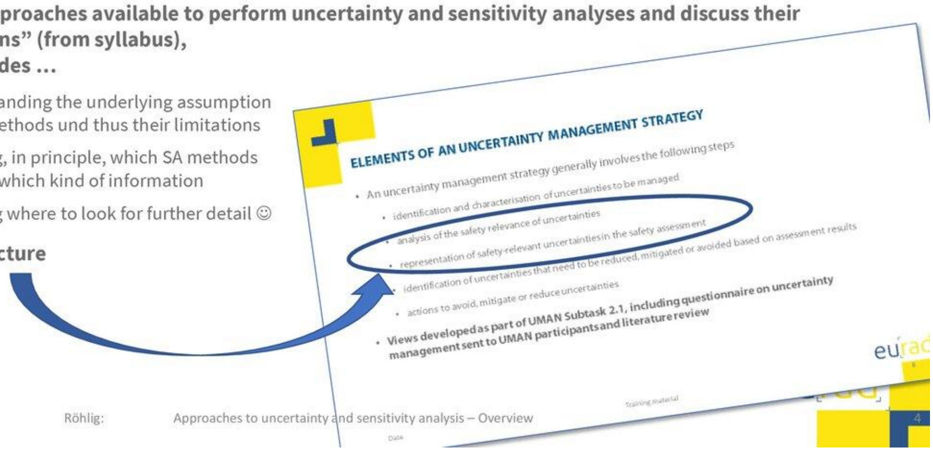
eurad 3

LEARNING OUTCOMES.

After the completion of this training unit/lesson, the students/participants should be able to….

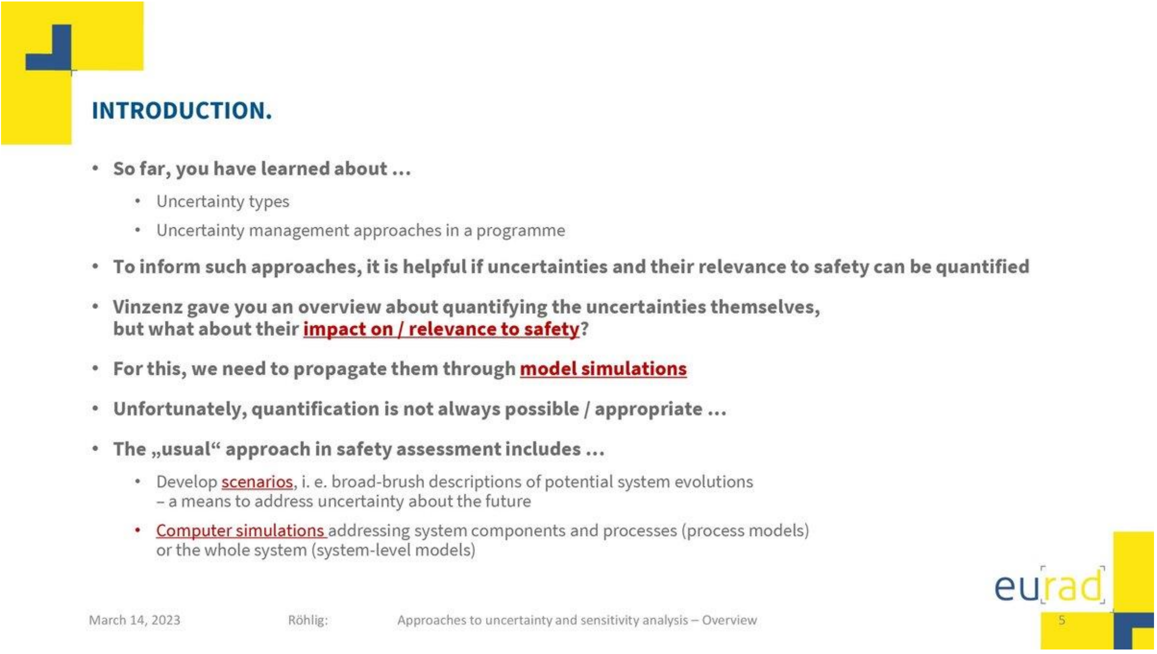
- **"List the approaches available to perform uncertainty and sensitivity analyses and discuss their pros and cons" (from syllabus), which includes …**
  - Understanding the underlying assumption of the methods und thus their limitations
  - Knowing, in principle, which SA methods provide which kind of information
  - Knowing where to look for further detail ☺

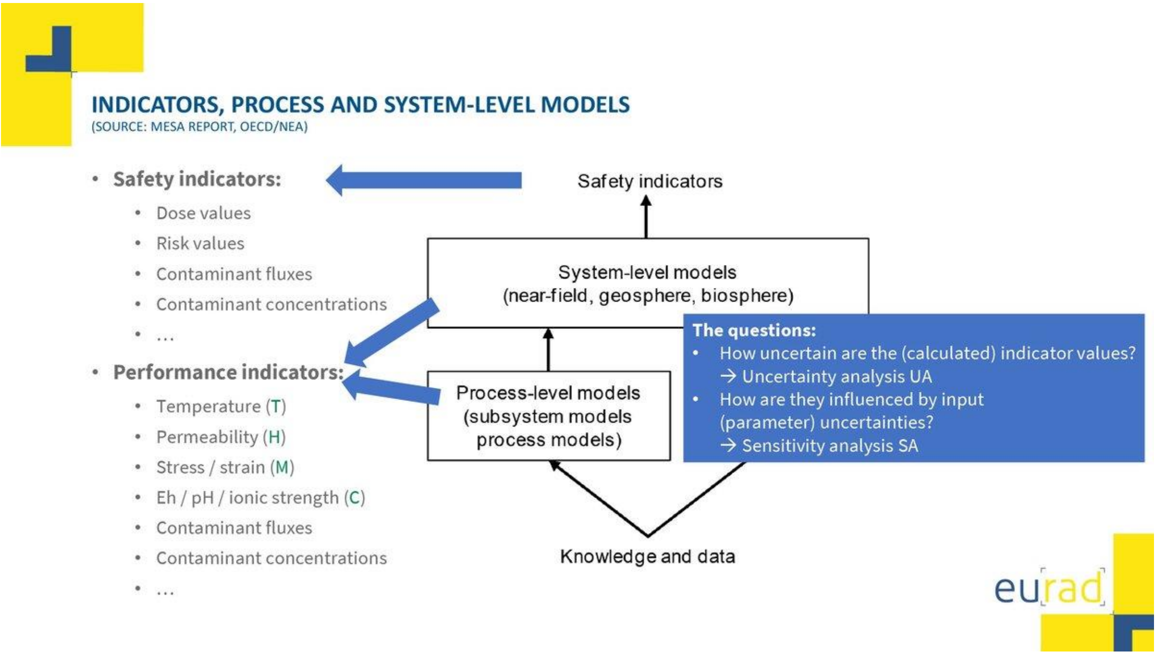
➢ **cf. Tim's lecture**



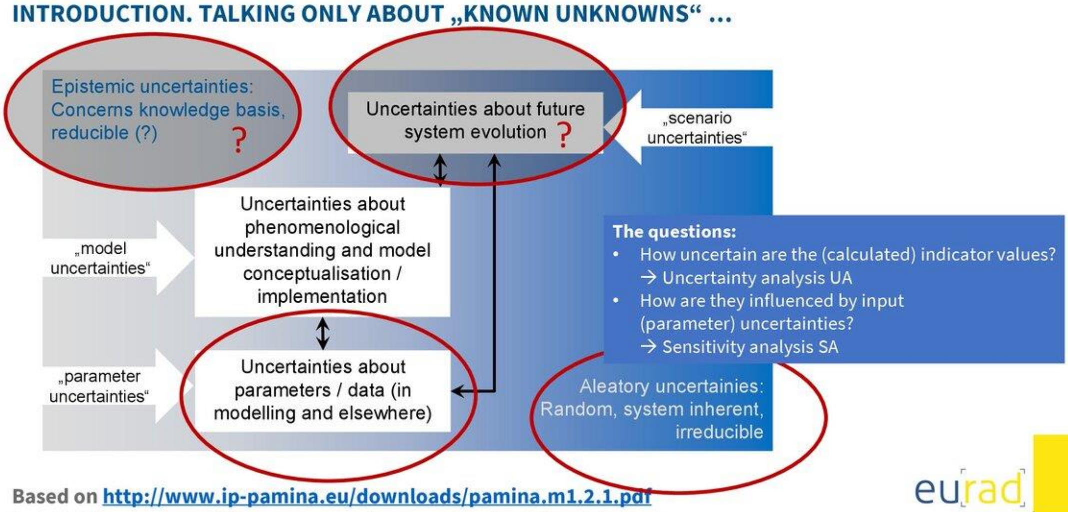
March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview

eurad 4


INTRODUCTION.
So far, you have learned about …
Uncertainty types
Uncertainty management approaches in a programme
To inform such approaches, it is helpful if uncertainties and their relevance to safety can be quantified
Vinzenz gave you an overview about quantifying the uncertainties themselves, but what about their impact on / relevance to safety?
For this, we need to propagate them through model simulations
Unfortunately, quantification is not always possible / appropriate …
The „usual“ approach in safety assessment includes …
Develop scenarios, i. e. broad-brush descriptions of potential system evolutions – a means to address uncertainty about the future
Computer simulations addressing system components and processes (process models) or the whole system (system-level models)
March 14, 2023
Röhlig:
Approaches to uncertainty and sensitivity analysis – Overview
eurad
5


INDICATORS, PROCESS AND SYSTEM-LEVEL MODELS
(SOURCE: MESA REPORT, OECD/NEA)
Safety indicators:
Dose values
Risk values
Contaminant fluxes
Contaminant concentrations
…
Performance indicators:
Temperature (T)
Permeability (H)
Stress / strain (M)
Eh / pH / ionic strength (C)
Contaminant fluxes
Contaminant concentrations
…
Safety indicators
System-level models
(near-field, geosphere, biosphere)
Process-level models
(subsystem models
process models)
Knowledge and data
The questions:
How uncertain are the (calculated) indicator values?
→ Uncertainty analysis UA
How are they influenced by input (parameter) uncertainties?
→ Sensitivity analysis SA
eurad

INTRODUCTION. TALKING ONLY ABOUT „KNOWN UNKNOWNS“ …



Based on http://www.ip-pamina.eu/downloads/pamina.m1.2.1.pdf

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 7

ADDRESSING UNCERTAINTY QUANTITATIVELY: METHODS.

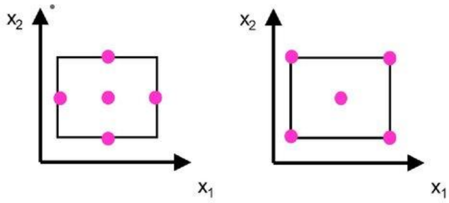
- **Let's assume we did everything reasonably conceivable to qualify the scenarios and models we are working with (good science, structured scenario approaches, model qualification, …) and are now aiming just at these two statements:**
  - How uncertain are the (calculated) indicator values? → Uncertainty analysis UA
  - How are they influenced by input (parameter) uncertainties? → Sensitivity analysis SA
- **What can we do?**
  - Testing the model using various input parameter sets ("realisations").
  - But this can be done in various ways, we need to be clever!
    - We might have limitations concerning the number of realizations / model runs.
    - Given such boundary conditions, we want to "squeeze out" as much information as possible.
    - By doing so, our aims might be:
      - Quantification of uncertainty
      - Traceabilty, reproduceability
      - Transparency, good communication

    → Need for clever design of computer experiments

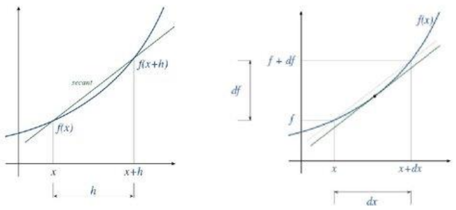
March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 8

ADDRESSING UNCERTAINTY QUANTITATIVELY: METHODS.

- **Deterministic methods: Testing one-by-one according to a plan, e.g. screening by using …**
  - Minimum – best estimate (guess) – maximum
  - [favorable] – best estimate (guess) – unfavorable (“conservative”) (conservatism needs to be demonstrated!)
  - phenomenological – conservative – penalizing / alternative (from Andra Dossier 2005)
- **Local methods – gradient-based information …**



Plans for two input parameters



Estimating sensitivities using numerical derivatives (difference quotients) (picture source: Wikipedia)

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 9

ADDRESSING UNCERTAINTY QUANTITATIVELY: METHODS.

- **Deterministic methods: Testing one-by-one according to a plan, e.g.**
  - Minimum – best estimate (guess) – maximum
  - [favorable] – best estimate (guess) – unfavorable (“conservative”) (conservatism needs to be demonstrated!)
  - phenomenological – conservative – penalizing / alternative (from Andra Dossier 2005)
- **Probabilistic methods,**
  i. e. methods utilizing the theory and toolboxes of probability theory and statistics
  - Require two types of models:
    One describing physico-chemical (THMC) phenomena, the other one describing input uncertainty
  - The latter one: Need to derive a joint pdf for the input parameter set (cf. Vinzenz’ lecture)

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 10

ADDRESSING UNCERTAINTY QUANTITATIVELY: METHODS.

- **Deterministic methods: Testing one-by-one according to a plan, e.g.**
  - Minimum – best estimate (guess) – maximum
  - [favorable] – best estimate (guess) – unfavorable ("concervative") (conservativity needs to be demonstrated!)
  - phenomenological – conservative – penalizing / alternative (from Andra Dossier 2005)
- **Probabilistic methods,**
  i. e. methods utilizing the theory and toolboxes of probability theory and statistics
  - Sometimes questioned as being inappropriate for epistemic uncertainties, this is often linked to other proposals such as …
    - Interval math
    - Fuzzy methods (Zadeh, can work with non-additive measures)
    - Possibility theory (Zadeh, working with "possibility" & "necessity")
    - Dempster-Shafer theory of belief (or evidence theory, "belief" & "plausibility")
    - "upper" & "lower" probabilities (Dempster)
    - Other hybrid methods

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview eurad 11

ADDRESSING UNCERTAINTY QUANTITATIVELY: METHODS.

- **Deterministic methods: Testing one-by-one according to a plan, e.g.**
  - Minimum – best estimate (guess) – maximum
  - [favorable] – best estimate (guess) – unfavorable ("concervative") (conservatism needs to be demonstrated!)
  - phenomenological – conservative – penalizing / alternative (from Andra Dossier 2005)
- **Probabilistic methods,**
  i. e. methods utilizing the theory and toolboxes of probability theory and statistics
  - Sometimes questioned in literature as being inappropriate for epistemic uncertainties …
- **… but nevertheless widely used**
  - based on the arguments that Kolmogorov's axioms do not require a frequentistic interpretation of probability,
  - the applicability of Bayesian information updating and
  - "justified" by the power of the toolboxes,

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview eurad 12

PROBABILISTIC METHODS: UNDERLYING ASSUMPTIONS, STRATEGY AND WORKFLOW.

The steps.	The underlying assumptions.
• Quantifying uncertainties via pdfs. Watch out for dependencies!!!	• The „true" parameter set $(x_1, x_2, \dots, x_n)$ is a realisation of an n-dimensional random variable $(X_1, X_2, \dots, X_n)$ with a joint pdf P
• Sampling	• The sampled parameter sets (realisations) $\{({}^ix_1, {}^ix_2, \dots, {}^ix_n), i=1, \dots, m\}$ are a good approximation of the „true" pdf P
• Model runs for each realization	• For each realisation No. i, the (deterministic!) THMC model produces the „correct" result ${}^if = f({}^ix_1, {}^ix_2, \dots, {}^ix_n)$
• UA, possibly for "quantities of interest"	• The $\{{}^if, i=1, \dots, m\}$ are a good approximation of the output distribution
• SA	• The joint set of inputs and outputs $\{({}^ix_1, {}^ix_2, \dots, {}^ix_n, {}^if), i=1, \dots, m\}$ is a good approximation of the „true" relationships

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview

eurad 13

SAMPLING METHODS: A WISH LIST.

We would like to get a series of parameter sets which …

- … approximates the given joint pdf P
- … the realisations of which are independent
- … which leaves no „gaps" in the parameter space
- … the sample size of which is not greater than ???

As we will see …

➢ Some of the wishes compete with each other.

➢ Different sampling schemes satisfy different wishes differently well.

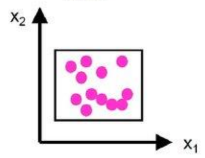
March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview

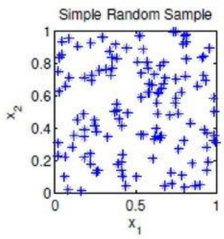
eurad 14

SAMPLING METHODS: A WISH LIST.

We would like to get a series of parameter sets which …

- \+ … approximates the given joint pdf P
- \+ … the realisations of which are independent
- − … which leaves no „gaps" in the parameter space
- \+ … the sample size of which is not greater than ???



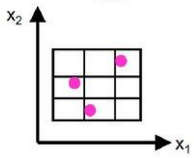


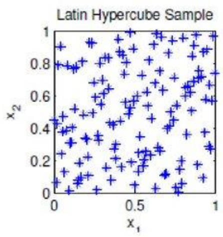
March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 15

SAMPLING METHODS: A WISH LIST.

We would like to get a series of parameter sets which …

- \+ … approximates the given joint pdf P (choose intervals of equal probability!)
- − … the realisations of which are independent
- ± … which leaves no „gaps" in the parameter space
- ± … the sample size of which is not greater than ???



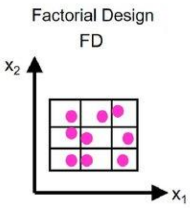


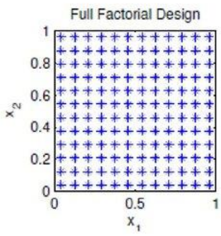
March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 16

SAMPLING METHODS: A WISH LIST.

We would like to get a series of parameter sets which …

- \+ … approximates the given joint pdf P (choose intervals of equal probability!)
- – … the realisations of which are independent
- \+ … which leaves no „gaps“ in the parameter space
- – … the sample size of which is not greater than ???
  (way out: Fractional FD)





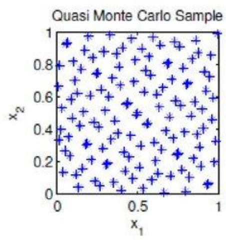
March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview

eurad 17

SAMPLING METHODS: A WISH LIST.

We would like to get a series of parameter sets which …

- \+ … approximates the given joint pdf P
- – … the realisations of which are independent
- ± … which leaves no „gaps“ in the parameter space
- – … the sample size of which is not greater than ???

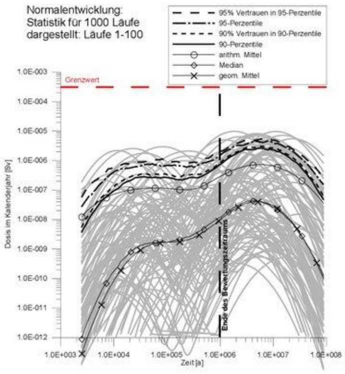


March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview

eurad 18

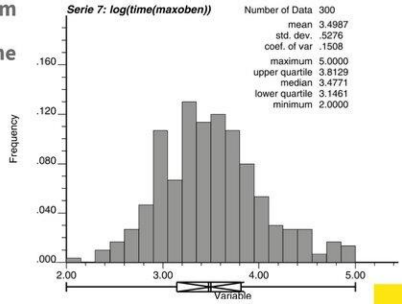
UNCERTAINTY ANALYSIS (UA): STATISTICS FOR CALCULATED INDICATORS AND QUANTITIES OF INTEREST.

Statistics for time series …



… or for „quanities of interest“ such as:

- **Maximum**
- **Time of maximum**
- **Integral over time**



eurad

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 19

UNCERTAINTY ANALYSIS (UA): STATISTICS FOR CALCULATED INDICATORS AND QUANTITIES OF INTEREST.

Note:

- **In principle, all „classic“ statistical estimates (for moments, quantiles) could be applied.**
- **The statistical confidence in the estimate depends on the sample size, though.**
- **Many confidence statements presuppose a certain probability type (e.g. a normal distribution). There are, however, also possibilities of avoiding such presumptions.**
- **If the quantity of interest is an indicator addressed in regulations (e. g. by setting a limit for individual effective annual dose), you need to make up your mind about what to do if single (perhaps very few, perhaps just one) realization(s) exceed the limit!**
- **In the case of risk-based regulations, one might use probabilistics to estimate it (since risk in the conventional sense „consequence times probability“ is an expectation of the consequence)**
  – but there are other ways as well!

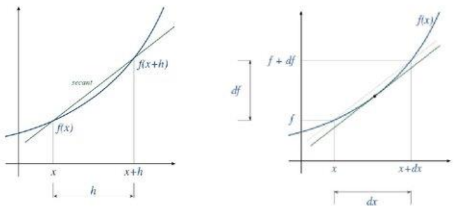
eurad

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 20

SENSITIVITY ANALYSIS (SA): LOCAL METHODS.

- Study model (deterministically) around a default or reference value / base case / working point
- Partial derivatives or difference quotients varying one input parameter at a time (OAT)
- However: Comparability of parameters? (different units)
- Suggestion: Importance measure

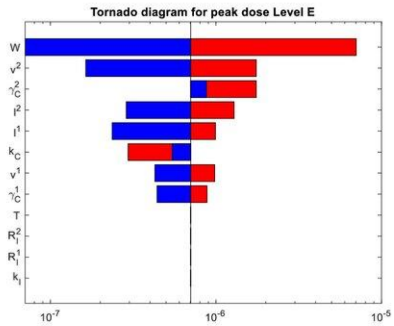
$$DIM_i = \frac{\partial f(x^0)}{\partial x_i} dx_i \left(\sum_{i=1}^{d} \frac{\partial f(x^0)}{\partial x_j} dx_j \right)^{-1}$$



March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview eurad 21

SENSITIVITY ANALYSIS (SA): SCREENING

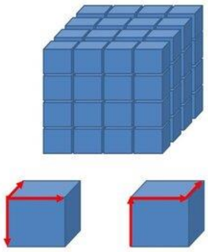
- Purpose: Identify uninfluential input parameters with relative few model evaluations
- Tornado diagrams: OAT variations from base case (“worst” and “best” cases) → calculate output deviations

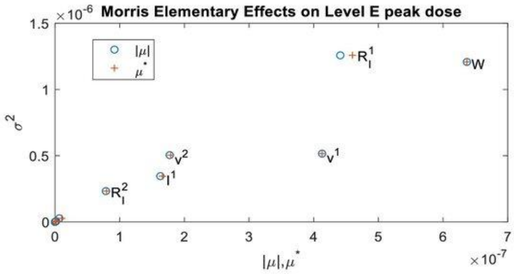


March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview eurad 22

SENSITIVITY ANALYSIS (SA): SCREENING

- **Purpose: Identify uninfluential input parameters with relative few model evaluations**
- **Tornado diagrams: OAT variations from base case**
  → calculate output deviations
- **Morris methods: Randomized choice of hypercube, OAT designs, take e.g. mean and variance of the (absolute) difference quotients as sensitivity measures**

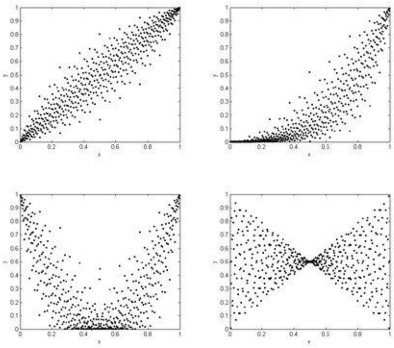




March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview

eurad 23

GLOBAL SA: WHICH EFFECTS CAN BE DETECTED?



March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview

eurad 24

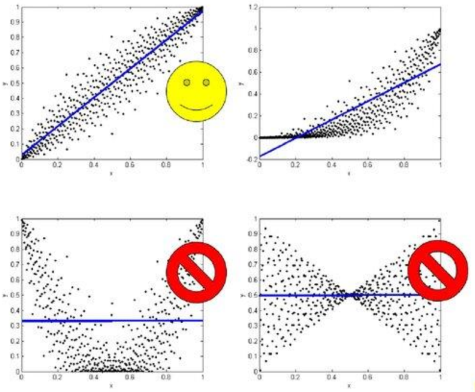
GLOBAL SA: CORRELATION ANALYSIS / PEARSON COEFFICIENTS / LINEAR REGRESSION

- **Estimate e.g. correlation coefficient**

$$\varrho(X_j, Y) = \frac{\text{cov}\,(x_{j}, Y)}{\sqrt{V(x_j)V(Y)}}$$

by

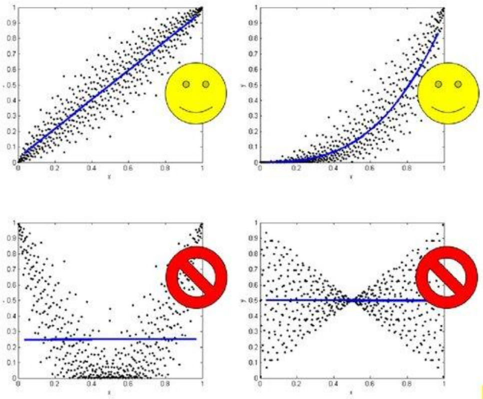
$$CC = \frac{\sum_{i=1}^{n}(x_{ij}-\bar{x}_j)(y_i-\bar{y})}{\left[\sum_{i=1}^{n}(x_{ij}-\bar{x}_j)^2\right]^{1/2}\left[\sum_{i=1}^{n}(y_i-\bar{y})^2\right]^{1/2}}$$



March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 25

GLOBAL SA: RANK CORRELATION ANALYSIS / SPEARMAN COEFFICIENTS

- **Replace parameters and outputs by their ranks, i.e. order them according to value and assign numbers in that order („ranks“)**
- **Then calculate correlation coefficients of these ranks**



March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 26

GLOBAL SA: VARIANCE-BASED METHODS

- **Idea: Decomposition**

$$Y = f(X_1,\ldots,X_k) = f_0 + \sum_i f_i(X_i) + \sum_{i<j} f_{ij}(X_i,X_j) + \ldots + f_{1\ldots k}(X_1,\ldots,X_k)$$

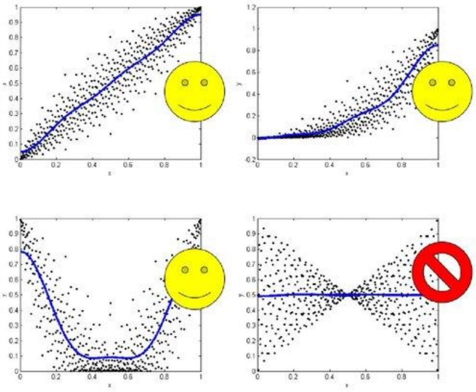
- **For independent inputs:**

$$V = Var(Y) = \sum_i V_i + \sum_{i<j} V_{ij} + \ldots + V_{1\ldots k}$$

with

$$V_i = Var(E[Y \mid X_i])$$
$$V_{ij} = Var(E[Y \mid X_i, X_j]) - V_i - V_j$$
$$V_{ijk} = Var(E[Y \mid X_i, X_j, X_k]) - V_{ij} - V_{jk} - V_{ki} - V_i - V_j - V_k$$
$$\ldots$$

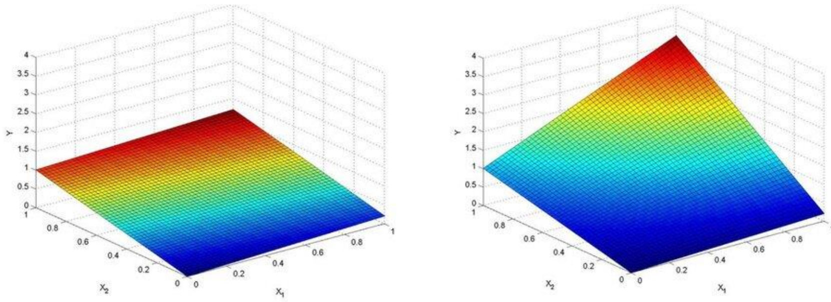
→ **Sobol's indices** $S_i = \frac{V_i}{V}$, $S_{ij} = \frac{V_{ij}}{V}$ **etc.**



March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 27

GLOBAL SA: VARIANCE-BASED METHODS ...

- **... are able to detect non-linear and even non-monotonic effects**
- **... and interactions**



March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 28

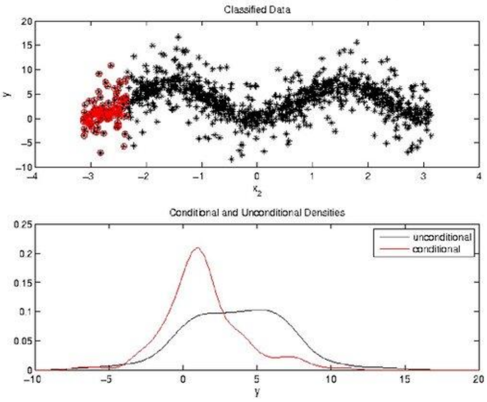
GLOBAL SA: VARIANCE-BASED METHODS …

- … are able to detect non-linear and even non-monotonic effects
- … and interactions
- … but indices, especially higher ones, are not easy to estimate,
- … methods often require specific space-filling sampling schemes and high sample sizes

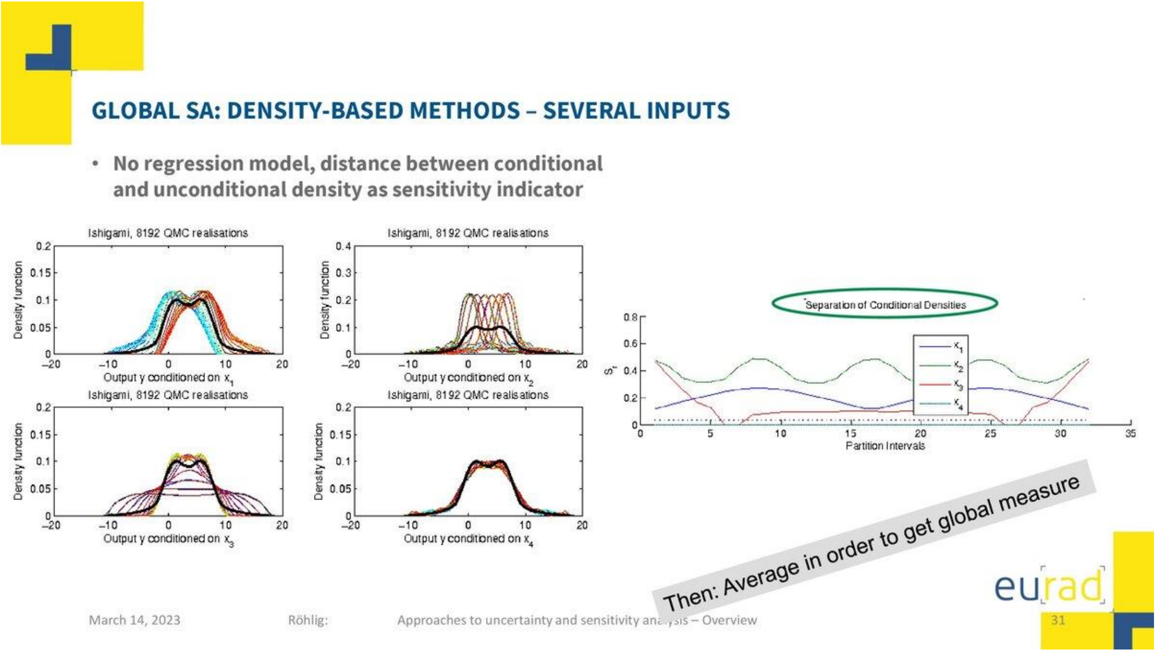
March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 29

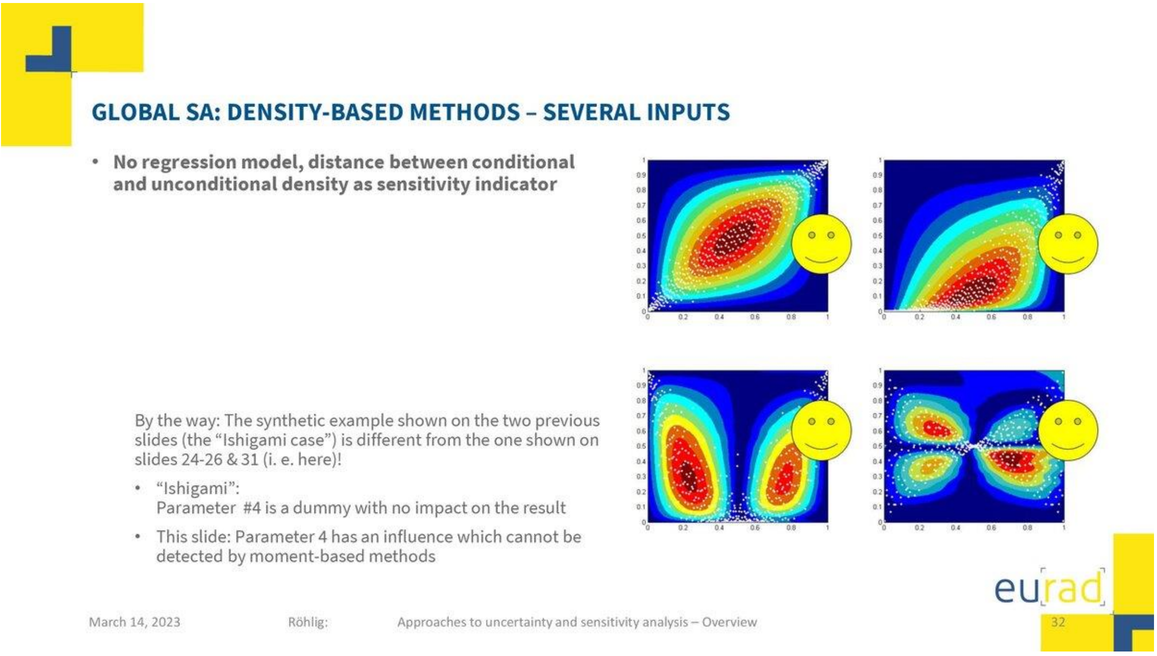
GLOBAL SA: DENSITY-BASED METHODS

- No regression model, distance between conditional and unconditional density as sensitivity indicator



March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 30


GLOBAL SA: DENSITY-BASED METHODS – SEVERAL INPUTS
• No regression model, distance between conditional and unconditional density as sensitivity indicator
Ishigami, 8192 QMC realisations
Density function
Output y conditioned on x1
Output y conditioned on x2
Output y conditioned on x3
Output y conditioned on x4
Separation of Conditional Densities
Partition Intervals
Then: Average in order to get global measure
March 14, 2023
Röhlig:
Approaches to uncertainty and sensitivity analysis – Overview
31


GLOBAL SA: DENSITY-BASED METHODS – SEVERAL INPUTS
• No regression model, distance between conditional and unconditional density as sensitivity indicator
By the way: The synthetic example shown on the two previous slides (the "Ishigami case") is different from the one shown on slides 24-26 & 31 (i. e. here)!
• "Ishigami":
Parameter #4 is a dummy with no impact on the result
• This slide: Parameter 4 has an influence which cannot be detected by moment-based methods
March 14, 2023
Röhlig:
Approaches to uncertainty and sensitivity analysis – Overview
32

SA: VARIOUS METHODS WITH PROS AND CONS, OFTEN COMPLICATED AND EXPENSIVE

Advice

- **Start with graphics (not addressed in this lecture, sorry ☹)**
- **Then step by step from simple to complicated**
- **For each step: check to which degree your results explain the behavior (goodness of fit, sum of indices)**
- **Stop if explanation is „satisfactory“**

→ Feedback to decision makers!

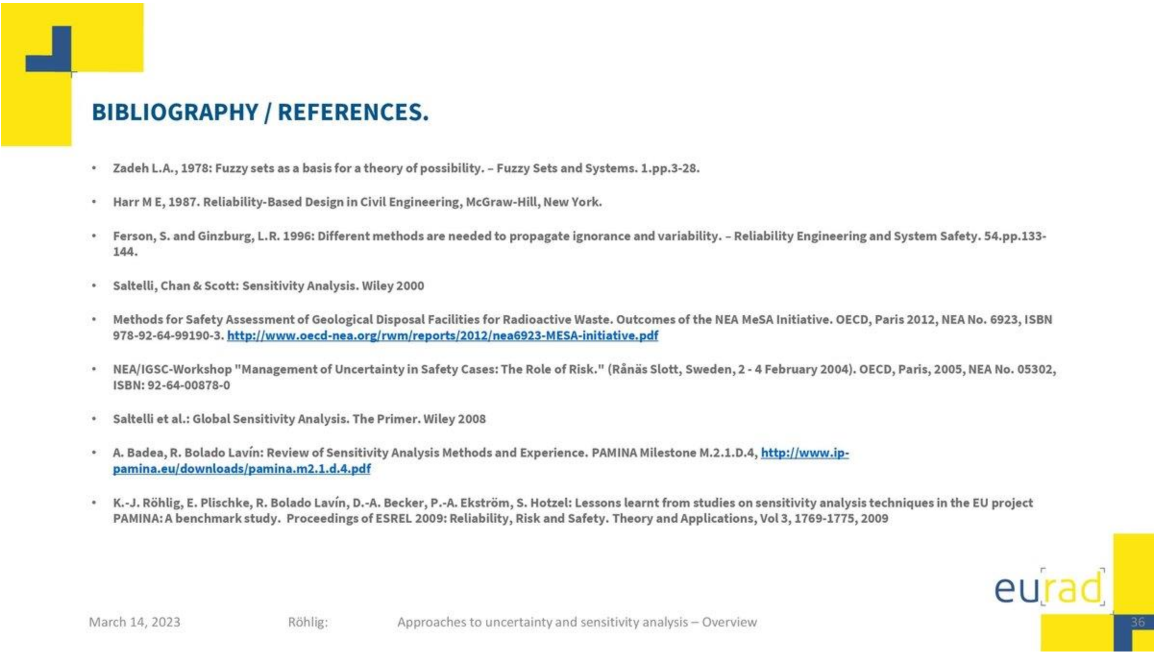
March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview eurad 33

SUMMARY AND CONCLUSIONS.

- **This lecture was about quantifying model output uncertainties (UA) and their relationship to input uncertainties (SA)**
- **A combination of deterministic and probabilistic methods is the established (and powerful) way of doing this**
- **Especially SA is tricky:**
  - Methods often expensive, sometimes hard to understand
  - Ongoing research about advanced methods
  - Gap between practitioners on one hand and SA researchers on the other
  - Note graphical methods (not addressed in this lecture)!
    - Graphics are often instructive
    - However, rationale behind is not always easy to understand

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview eurad 34


BIBLIOGRAPHY / REFERENCES.
SANDIA REPORT
SAND2021-11053
Printed September 2021
Sandia National Laboratories
Sensitivity Analysis Comparisons on Geologic Case Studies: An International Collaboration
Laura P. Swiler, Dirk-Alexander Becker, Dusty Brooks, Joan Govaerts, Lasse Koskinen, Pekka Kupiainen, Elmar Plischke, Klaus-Jürgen Röhlig, Elena Saveleva, Sabine M. Spiessl, Emily Stein, Valentina Svitelman
eurad
European Joint Programme on Radioactive Waste Management
Deliverable 10.4: Methodological Approaches to Uncertainty and Sensitivity Analysis
Work Package 10: Strategic Study WP – Uncertainty Management Multi-Actor Network (UMAN)
DRAFT
https://doi.org/10.2172/1822591
… in preparation
eurad
March 14, 2023
Röhlig:
Approaches to uncertainty and sensitivity analysis – Overview
35


BIBLIOGRAPHY / REFERENCES.
• Zadeh L.A., 1978: Fuzzy sets as a basis for a theory of possibility. – Fuzzy Sets and Systems. 1.pp.3-28.
• Harr M E, 1987. Reliability-Based Design in Civil Engineering, McGraw-Hill, New York.
• Ferson, S. and Ginzburg, L.R. 1996: Different methods are needed to propagate ignorance and variability. – Reliability Engineering and System Safety. 54.pp.133-144.
• Saltelli, Chan & Scott: Sensitivity Analysis. Wiley 2000
• Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste. Outcomes of the NEA MeSA Initiative. OECD, Paris 2012, NEA No. 6923, ISBN 978-92-64-99190-3. http://www.oecd-nea.org/rwm/reports/2012/nea6923-MESA-initiative.pdf
• NEA/IGSC-Workshop "Management of Uncertainty in Safety Cases: The Role of Risk." (Rånäs Slott, Sweden, 2 - 4 February 2004). OECD, Paris, 2005, NEA No. 05302, ISBN: 92-64-00878-0
• Saltelli et al.: Global Sensitivity Analysis. The Primer. Wiley 2008
• A. Badea, R. Bolado Lavín: Review of Sensitivity Analysis Methods and Experience. PAMINA Milestone M.2.1.D.4, http://www.ip-pamina.eu/downloads/pamina.m2.1.d.4.pdf
• K.-J. Röhlig, E. Plischke, R. Bolado Lavín, D.-A. Becker, P.-A. Ekström, S. Hotzel: Lessons learnt from studies on sensitivity analysis techniques in the EU project PAMINA: A benchmark study. Proceedings of ESREL 2009: Reliability, Risk and Safety. Theory and Applications, Vol 3, 1769-1775, 2009
eurad
March 14, 2023
Röhlig:
Approaches to uncertainty and sensitivity analysis – Overview
36

BIBLIOGRAPHY / REFERENCES.

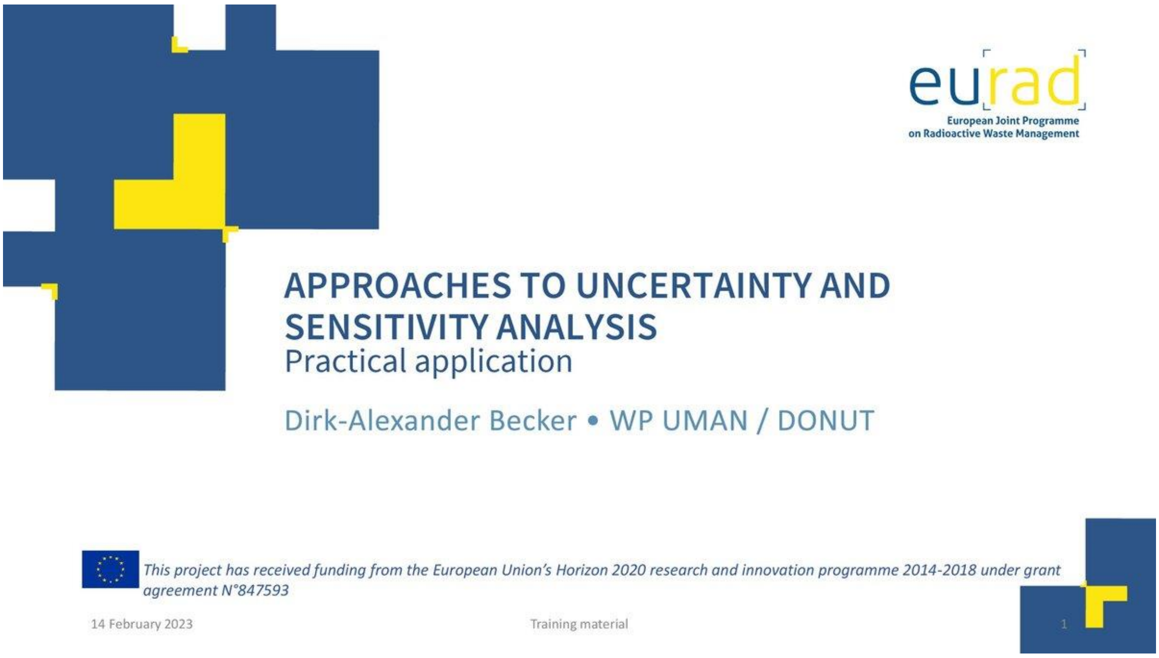
- R. Bolado-Lavín, K.-J. Röhlig, D.-A. Becker: Sensitivity analysis techniques for the performance assessment of a radioactive waste repository. Euradwaste '08, Seventh European Commission Conference on the Management and Disposal of Radioactive Waste, 20-22 October 2008, Luxembourg.
- D.-A. Becker, S. Spießl, K.-J. Röhlig, E. Plischke, R. Bolado-Lavín, A. Badea, J. L. Cormenzana, T. J. Schröder, J. Hart, R. Ávila, P.-A. Ekström, R. Broed: Evaluation of Approaches to Sensitivity Analysis. PAMINA Deliverable 2.1.D.1, November 2009, www.ip-pamina.eu/downloads/pamina2.1.d.1.pdf
- E. Plischke, An effective algorithm for computing global sensitivity indices (EASI). Reliability Engineering & System Safety 95, 354-360 (2010)
- A. Saltelli, P. Annoni: How to avoid a perfunctory sensitivity analysis. EnvModSoft 25, 1508—1517 (2010)
- E. Plischke, How to compute variance-based sensitivity indicators with your spreadsheet software. Environmental Modelling & Software 35, 188-191 (2012).
- Elmar Plischke, Emanuele Borgonovo, Curtis L. Smith, Global Sensitivity Measures from Given Data. European Journal of Operations Research 226, No. 3, 536-550 (2013).
- S. Kuhlmann, E. Plischke, K.-J. Röhlig, D-A. Becker: Sensitivity analysis: Theory and practical application in safety cases. The Safety Case for Deep Geological Disposal of Radioactive Waste: 2013 State of the Art. Symposium Proceedings. 7-9 October 2013, Paris, France. NEA/RWM/R(2013)9, March 2014, http://www.oecd-nea.org/rwm/docs/2013/rwm-r2013-9.pdf
- Emanuele Borgonovo, Elmar Plischke, Sensitivity analysis: A review of recent advances. European Journal of Operational Research 248(3): 869-887 (2016).
- Emanuele Borgonovo, Gordon B. Hazen, Elmar Plischke, A Common Rationale for Global Sensitivity Measures and Their Estimation. Risk Analysis 36(10), 1871-1895 (2016)
- L. P. Swiler, D.-A. Becker, D. Brooks, J. Govaerts, L. Koskinen, P. Kupiainen, E. Plischke, K.-J. Röhlig, E. Saveleva, S. M. Spiessl, E. Stein, V. Svitelman: Sensitivity Analysis Comparisons on Geologic Case Studies: An International Collaboration. Sandia National Laboratories Technical Report SAND2021-11053. Albuquerque, NM. Sept. 2021. https://doi.org/10.2172/1822591
- Sébastien Da Veiga, Fabrice Gamboa, Bertrand Iooss, and Clémentine Prieur: Basics and Trends in Sensitivity Analysis. SIAM, https://doi.org/10.1137/1.9781611976694

March 14, 2023 Röhlig: Approaches to uncertainty and sensitivity analysis – Overview 37

Appendix E. Slides of lecture A.6

A.6 Approaches to uncertainty and sensitivity analysis – Practical examples from the DONUT project

Prepared by Dirk Alexander Becker, GRS



CONTENTS

- **Learning outcomes**
- **Introduction**
- **Methods of global sensitivity analysis:**
  - Overview, methods and problems
- **Practical examples**
  - GRS LILW model
  - SNL crystalline reference case
  - UDC Reactive transport model
  - Overview of DONUT investigations
- **Summary and conclusions**
- **Bibliography and/or References**

14 February 2023 Training material eurad 3

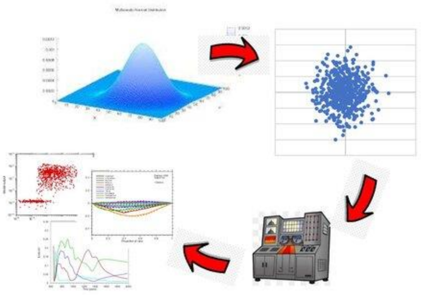
LEARNING OUTCOMES

After the completion of this training unit/lesson, the students/participants should be able to

- understand why and how probabilistic uncertainty and sensitivity analysis is applied
- understand the outcome of probabilistic uncertainty and sensitivity analysis
- distinguish different types of sensitivity analysis methods and understand their particularities in practice

14 February 2023 Training material eurad 4

INTRODUCTION



- **Why do we perform uncertainty and sensitivity analysis?**
  - Assess the overall uncertainty of a model calculation,
  - Identify influential parameters,
  - Improve model understanding.
- **You have learned in the previous talk ...**
  ... what the general idea of probabilistic UA/SA is,
  ... which types of mathematical method exist,
  ... how one can interpret the results.
- **In this talk you will ...**
  ... get acquainted with some UA/SA methods,
  ... see a few actual UA/SA studies,
  ... learn which practical problems might occur,
  ... learn what one can conclude from the results.

14 February 2023 Training material eurad 5

METHODS OF GLOBAL SENSITIVITY ANALYSIS – OVERVIEW (NOT COMPLETE!)

Uncertainty
- Scatterplots
- Horsetail plots
- Histograms
- Output distribution characteristics

Screening
- Morris
- Tornado diagram

Graphical
- Scatterplots
- CSM
- CSV
- CUSUNORO

Linearisation

	Direct	Rank-based
Regression	SRC	SRRC
Correlation	Pearson	Spearman
Partial correlation	PCC	PRCC

Variance-based

	Tailored sampling	Free sampling
1st order	SOBOL FAST EFAST RBD	EASI COSI
Higher order	SOBOL	Metamodeling
Total order	SOBOL EFAST	PCE RS-HDMR

Moment-independent / Nonparametrical / density-based
- Two-sample tests
  - Kolmogorov-Smirnov
  - Cramer-von-Mises
- CDF distance
  - Gini
  - Borgonovo
  - Pianosi-Wagener (PAWN)

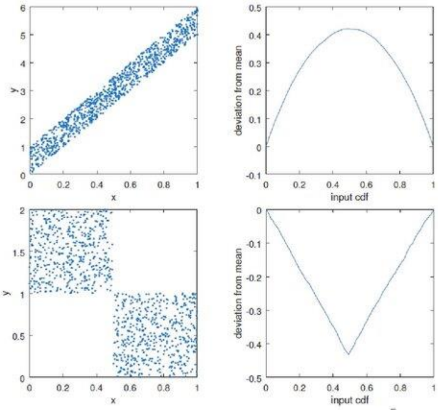
Other
- Shapely
- VARS

14 February 2023 Training material eurad 6

IN SHORT: CUSUNORO

Cumulative Sum of Normalised Reordered Output (Plischke 2012)

- **Analysis of a set of model runs**
  - Reorder the model runs
    - increasing value of the parameter of interest.
  - For each value y_i calculate its difference to the mean and normalise by the standard deviation
    - $c_i = \frac{y_i - \bar{y}}{\sigma_y}$.
  - Calculate the cumulative sum
    - $s_i = \sum_{l \leq i} c_i$.
  - Plot s_i/n over i/n (sometimes: $-s_i/n$)
- **Deviation of the curve from the horizontal line indicates parameter sensitivity**
  - the more curved, the more sensitive!



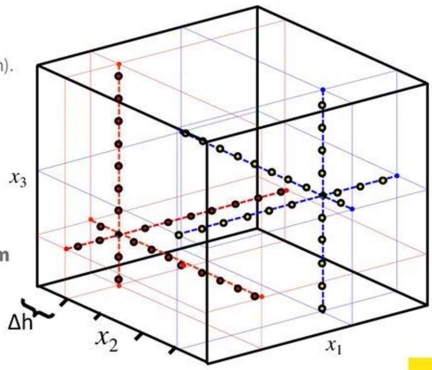
14 February 2023 Training material

eurad 7

IN SHORT: VARS

Variogram analysis of response surfaces (Razavi and Gupta, 2016)

- **Parameters x_i are normalized into [0, 1] intervals**
  - Each axis is discretized with constant parameter increments Δh (resolution).
- **Perform quasi Monte-Carlo sampling defining first the so-called "star centers"**
  - Latin hypercube sampling (LHS), Halton, …
- **Draw lines parallel to the axes & evaluate the function Z at all the discretized points.**
- **Estimate the experimental variogram of Z along each direction from the values of (Z_i, x_i).**
- **VARS includes Sobol and Morris analysis as specific cases.**
- (see **https://www.youtube.com/watch?v=YxeMdA8QIfU**)

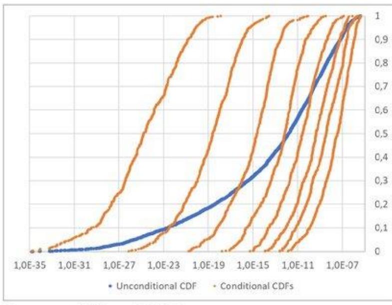


14 February 2023 Training material

eurad 8

IN SHORT: PAWN

Pianosi and Wagener (2015, 2018)

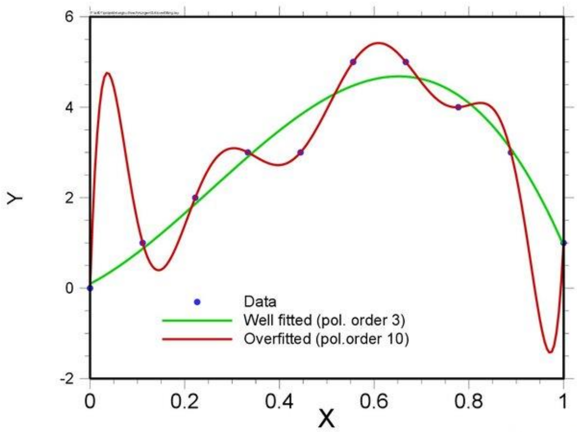


- **Calculate the unconditional cumulated density function (CDF).**
- **Divide the model runs into a number of groups**
  - according to values of the parameter of interest,
  - equal group population highly recommended (though not originally proposed by the authors).
- **Calculate the conditional CDF for each group.**
- **Calculate the maximum absolute difference between conditional and unconditional CDF.**
- **Calculate the mean of all these differences over the groups:**
  - this is a measure for the sensitivity of the parameter,
  - always between 0 and 1.
- **PAWN is subject to random noise:**
  - does not reach 0.

14 February 2023 Training material eurad 9

METAMODELING: THE PROBLEM OF OVERFITTING

- **Polynomial metamodel:**
  - to be fitted to the given data,
  - polynomial order has to be defined,
  - a higher order hits data points more exactly but
  - can lead to fitting artifacts.
- **Chose the polynomial order with care!**
  - Higher is not necessarily better,
  - too high orders can completely corrupt the metamodel.



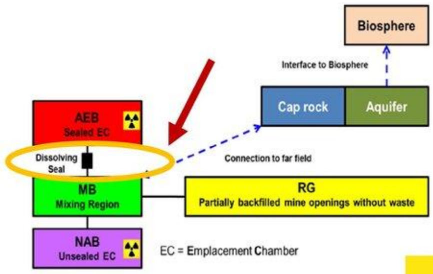
14 February 2023 Training material eurad 10

PRACTICAL EXAMPLE 1: SALT LILW MODEL (GRS)

14 February 2023 Training material 11

SALT LILW MODEL: DESCRIPTION

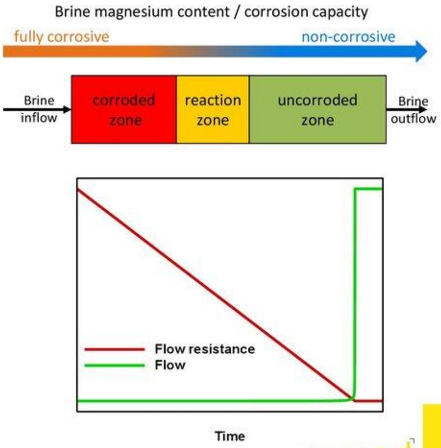
- **Repository for Low- and Intermediate-Level Waste (LILW) in rock salt**
- **Simplified model for radionuclide transport**
  - Near field
    - one sealed emplacement chamber with longer-lived waste
    - one unsealed emplacement chamber with short-lived waste
    - one compartment for all mine openings without waste
    - one mixing compartment
  - Far field
    - 1D-transport through cap rock and aquifer
  - Biosphere
    - annual dose to a human individual



14 February 2023 Training material 12

SALT LILW MODEL: SEAL CORROSION

- The seal of the sealed emplacement chamber is made of salt concrete, which is chemically instable against magnesium-containing brine.
- The corrosion process disintegrates the salt concrete while consuming magnesium, so that the brine loses its corrosion capacity.
- This leads to a narrow reaction zone slowly propagating through the seal, which can be idealised as a sharp front.
- The permeability is assumed to increase by four orders of magnitude at the front.
- Since the flow resistance is dominated by the non-corroded part of the seal, it decreases by several orders of magnitude nearly suddenly when the front reaches the end of the salt concrete body.



14 February 2023 Training material eurad 13

SALT LILW MODEL: PLANNING OF PROBABILISTIC ANALYSIS

- **Large number of model parameters**
  - Which of them are most interesting?
  - 20 parameters were selected for probabilistic variation
  - "Plausible" probabilistic distributions were assigned to all of them
    - Caution: For real cases, this should be done with care. The pdfs should reflect the "real" uncertainty as well as possible to produce reliable UA/SA results. This is an extra task and requires a lot of effort!
- **A rough sensitivity analysis lead to some findings:**
  - Six parameters seem to be most influential.
  - Five parameters are less sensitive but seem to play a certain role.
  - Nine parameters show negligible sensitivity.
- **Further analysis with different sets of parameters**
- **Different sampling strategies**
  - random sampling
  - quasirandom sampling (LpTau)
  - sample sizes from 512 to 16384

14 February 2023 Training material eurad 14

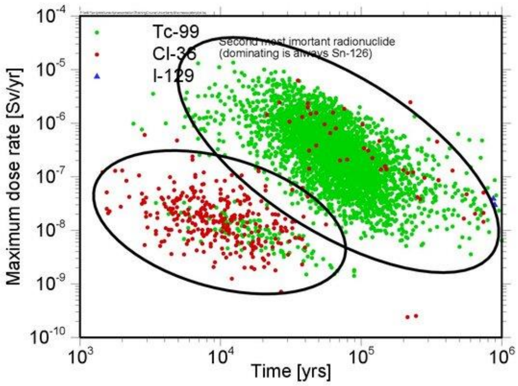
SALT LILW MODEL: PARAMETERS

Parameter	Type of pdf	Range or pdf parameters	Standard value
GasEntryP: Gas entry pressure	Uniform	0 - 2.5	2.0
IniPermSeal: Initial permeability of dissolving seal	Log-normal	μ=41.0605 σ=1.9809	1.0E-18
RefConv: Reference convergence rate	Log-uniform	1.0E-5 - 1.0E-4	4.0E-5
AEBConv: Factor of local convergence variation in AEB	Log-uniform	0.05 - 5.0	1.0
GasCorrPE: Organics corrosion rate	Log-normal	μ=12.6642 σ=1.1177	1.0E-5
TBrine: Time of brine intrusion	Log-normal	μ=8.8857 σ=0.6933	7500
BrineMgSat: Relative magnesium saturation of brine	Triangular	0 - 0.1 - 1.0	0.1
RGConv: *Factor of local convergence variation in RG*	Log-uniform	0.25 - 2.5	1.0
GasCorrFe: Metal corrosion rate	Log-normal	μ=-6.6728 σ=1.1177	4.0E-3
AEBGasProd: *Proportion of the material involved in gas production in AEB*	Triangular	0.1 - 0.8 - 1.0	0.8
NABGasProd: Proportion of the material involved in gas production in NAB	Triangular	0.1 - 0.8 - 1.0	0.8

Parameter	Type of pdf	Range or pdf parameters	Standard value
RGGasProd: Proportion of the material involved in gas production in RG	Triangular	0.1 - 0.8 - 1.0	0.8
NABConv: Factor of local convergence variation in NAB	Log-uniform	0.05 - 5.0	0.2
MBConv: Factor of local convergence variation in MB	Log-uniform	0.075 - 0.75	0.2
DiffCoeff: Diffusion coefficient	Log-uniform	1.0E-10 - 1.0E-8	1.0E-9
RefPor: Reference porosity	Triangular	0.15 - 0.3 - 0.4	0.3
FacDisp: Longitudinal dispersion length	Triangular	0.5 - 1.0 - 2.0	0
ConvFak: Variation factor for sheeting	Uniform	0 - 2.0	1.0
PorDebris: Porosity of debris from sheeting	Uniform	0.25 - 0.5	0.4
C14Inv: Variation factor for C-14 inventory	Uniform	0 - 2.5	1.0

SALT LILW MODEL (20 PARAMETERS): UNCERTAINTY ANALYSIS

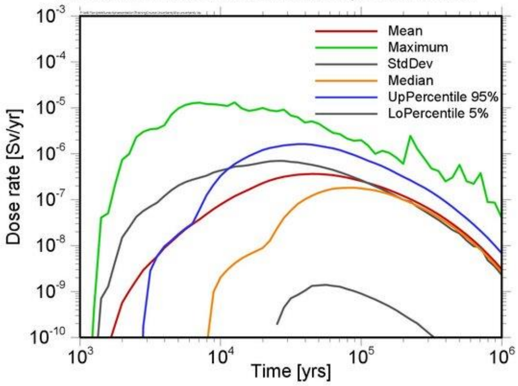
4096 runs



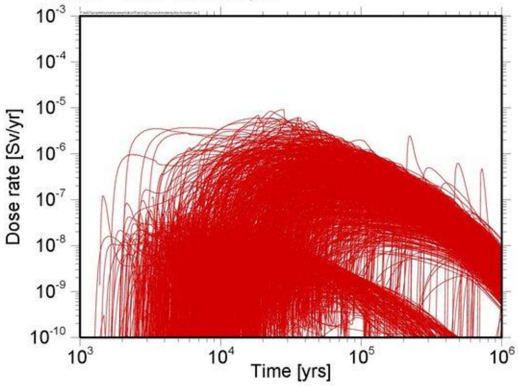
- **Maximum scatterplot:**
  - For each individual model run the absolute maximum over time is plotted against its time of occurrence.
  - An additional piece of information can be coded via dot colour. Here: the second most important radionuclide (as the most important one is always Sn-126).
- **One can see**
  - The total span of maxima is between $2 \cdot 10^{-10}$ Sv/yr and $2 \cdot 10^{-5}$ Sv/yr
  - Two clouds of dots:
    - lower and earlier maxima (seal has not failed by the end of scenario),
    - higher and later maxima (occur after seal has failed).
  - Cl-36 is important for most runs in the lower cloud, while Tc-99 dominates the upper cloud.

SALT LILW MODEL (20 PARAMETERS): UNCERTAINTY ANALYSIS

4096 runs: statistical measures of output distribution

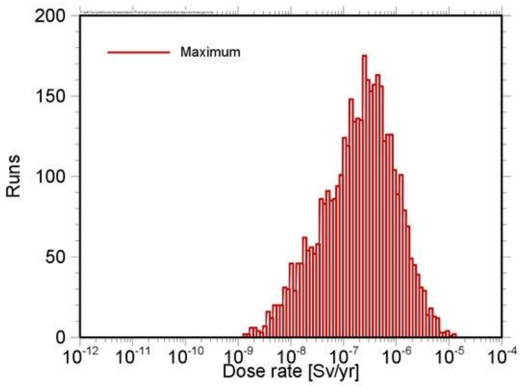


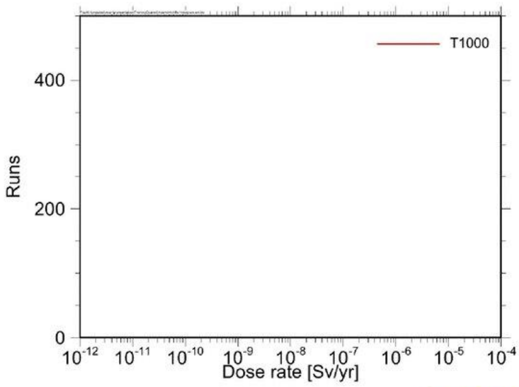
runs 1 – 1000: "horsetail plot"



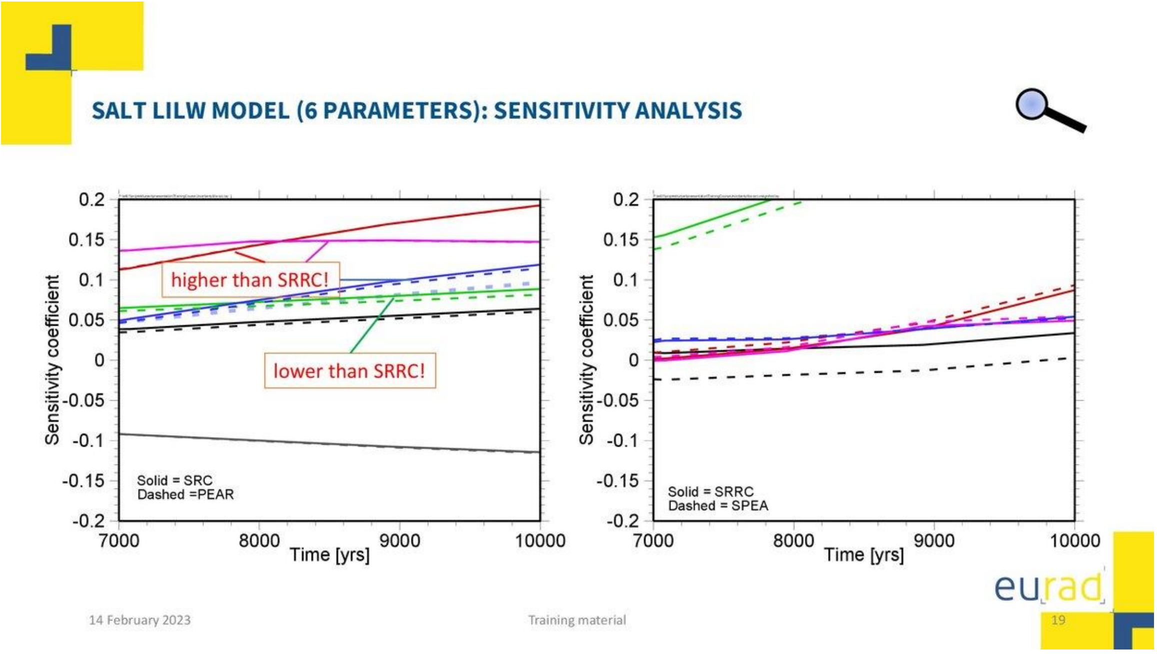
14 February 2023 Training material eurad 17

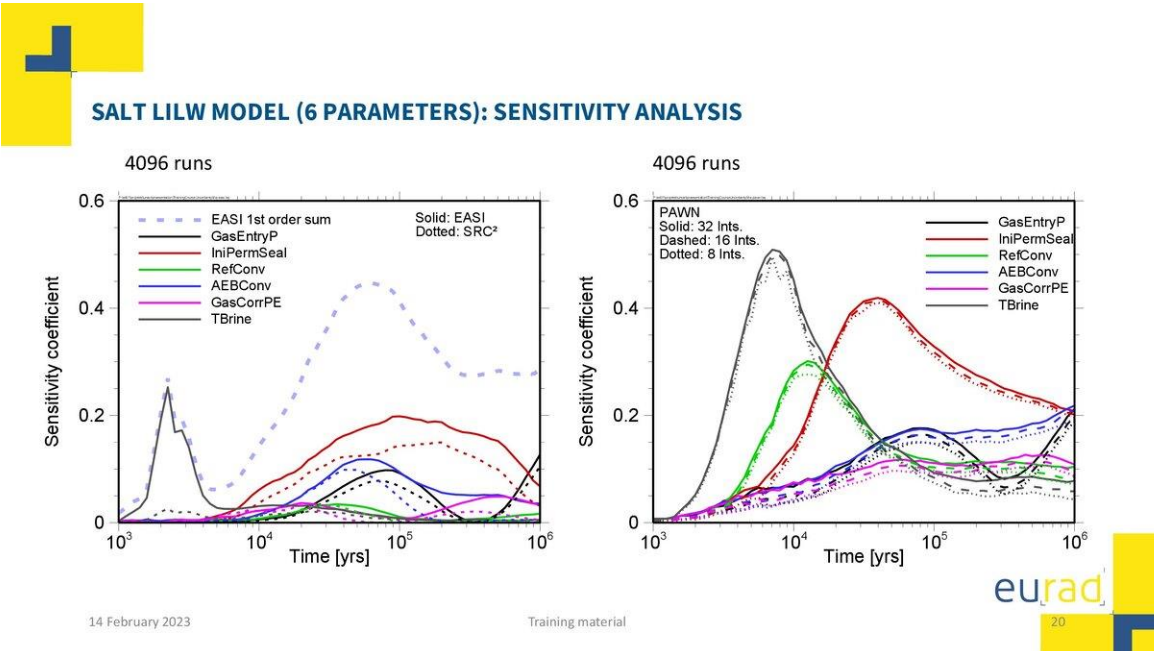
SALT LILW MODEL (20 PARAMETERS): UNCERTAINTY ANALYSIS





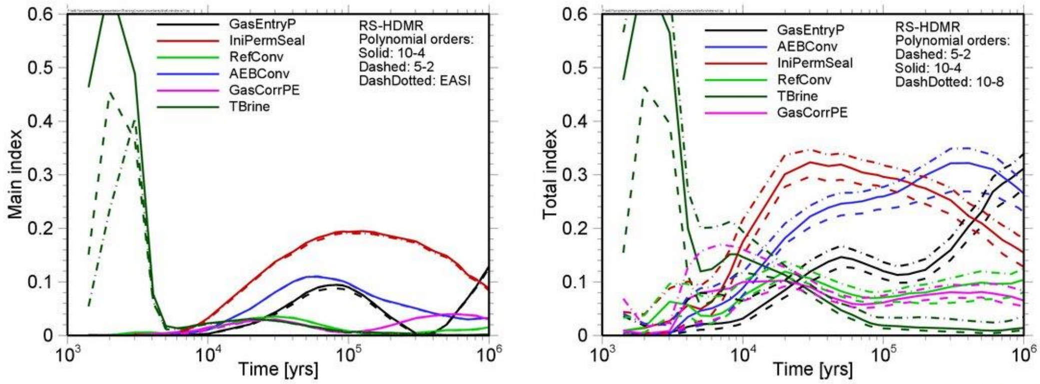
14 February 2023 Training material eurad 18


SALT LILW MODEL (6 PARAMETERS): SENSITIVITY ANALYSIS
Sensitivity coefficient
Time [yrs]
higher than SRRC!
lower than SRRC!
Solid = SRC
Dashed =PEAR
Solid = SRRC
Dashed = SPEA
14 February 2023
Training material
eurad
19


SALT LILW MODEL (6 PARAMETERS): SENSITIVITY ANALYSIS
4096 runs
4096 runs
EASI 1st order sum
GasEntryP
IniPermSeal
RefConv
AEBConv
GasCorrPE
TBrine
Solid: EASI
Dotted: SRC²
PAWN
Solid: 32 Ints.
Dashed: 16 Ints.
Dotted: 8 Ints.
Sensitivity coefficient
Time [yrs]
14 February 2023
Training material
eurad
20

SALT LILW MODEL (6 PARAMETERS): METAMODEL ANALYSIS

8192 runs 8192 runs



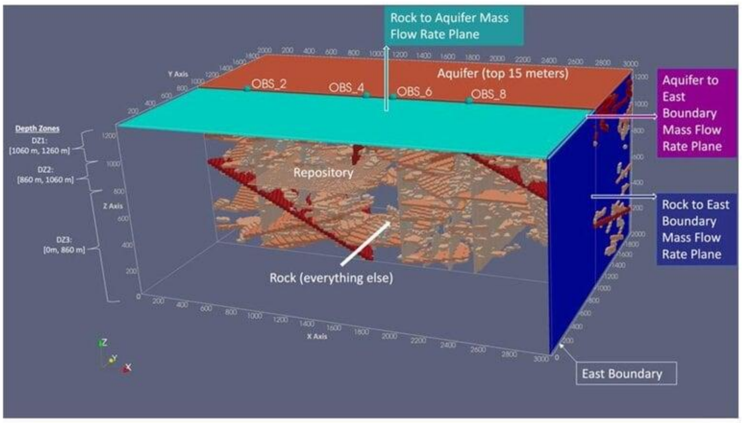
14 February 2023 Training material 21

SALT LILW MODEL (6 PARAMETERS): SENSITIVITY ANALYSIS OUTCOME

- **Despite its nonlinearity the model can be analysed with linearising methods:**
  - mostly fair agreement between SRC and EASI,
  - except: AEBConv at > 200000 years
    - positive and negative linear influences compensate but
    - variance does not become 0.
- **Differences between SRC and SRRC:**
  - SRC > SRRC indicates that the parameter acts mainly on the highest values,
  - SRC < SRRC indicates that the parameter acts mainly on the lowest values.
- **PAWN yields (in part) considerably different results than EASI:**
  - more pronounced dominance of IniPermSeal,
  - much higher sensitivity of TBrine and RefConv,
  - this is a hint to sensitivities that are not well captured by regression or variance:
    - RefConv acts on low values.
- **Metamodeling (RS-HDMR) results are**
  - robust against choice of polynomial orders and well in line with EASI for 1st order,
  - less robust for higher and total order.

14 February 2023 Training material 22

PRACTICAL EXAMPLE 2: CRYSTALLINE REFERENCE CASE (SNL)

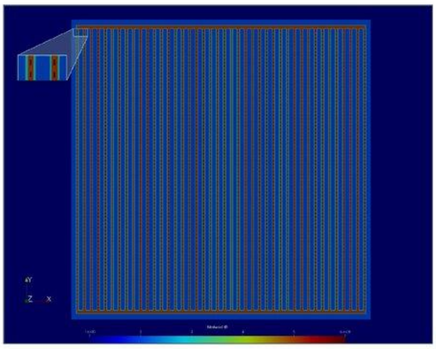


14 February 2023 Training material

eurad 23

CRYSTALLINE REFERENCE CASE: MODEL DESCRIPTION

- **Generic repository for Spent Nuclear Fuel (SNF) in fractured crystalline rock**
- **The model describes**
  - Radionuclide release from waste package
  - Migration through buffer material
  - Transport through damaged rock zone (DRZ)
  - Transport through connected fractures to the biosphere
- **Effects**
  - Advective / diffusive flow
  - Diffusion into and out of pores and fractures
  - Sorption on colloids and immobile mineral surfaces
  - Chemical reactions
  - Dissolution and precipitation
  - Radioactive decay and ingrowth
- **Quantity of interest: peak I-129 concentration in aquifer.**



14 February 2023 Training material

eurad 24

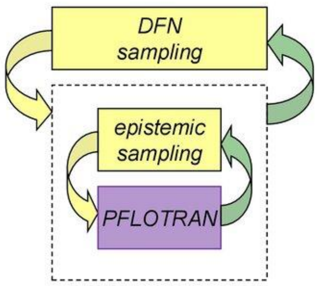
CRYSTALLINE REFERENCE CASE: DISCRETE FRACTURE NETWORK (DFN)

- **The crystalline host rock is disturbed by interconnected fractures.**
- **The network of discrete fractures serves as a transport path for radionuclides.**
- **The exact positions and dimensions of the fractures are unknown.**
- **The fracture network as a whole is characterised by parameters ("graph metrics"):**
  - Average number of intersections per fracture (network connectivity),
  - Number of fractures intersecting the repository (number of potential flow pathways from the repository),
  - Shortest travel time between repository and aquifer (ease of flow from repository to aquifer).
- **The DFN has an aleatory influence on the model results.**

14 February 2023 Training material eurad 25

CRYSTALLINE REFERENCE CASE: PLANNING OF PROBABILISTIC ANALYSIS

- **25 DFN were generated using a specific software:**
  - random fractures,
  - influenced by 3 parameters,
  - numbered 1 – 25:
    - no continuous relation between DFN number and properties,
  - fixed order of waste package breach for each DFN.
- **For each DFN, 40 sets of epistemic parameters were drawn.**
- **A total of 1000 model runs were performed.**
- **Possible evaluations:**
  - Total set without graph metrics (1000 runs),
  - Total set with graph metrics (1000 runs),
  - 25 subsets, one for each DFN (40 runs).



14 February 2023 Training material eurad 26

CRYSTALLINE REFERENCE CASE: PARAMETERS

Epistemic Variables				
Input	**Description**	**Unit**	**PDF type**	**Range**
rateUNF	Fractional dissolution rate of spent (used) nuclear fuel	1/yr	log unif.	$10^{-8} – 10^{-6}$
kGlacial	Glacial till permeability	m²	log unif.	$10^{-15} – 10^{-13}$
pBuffer	Buffer porosity	-	uniform	0.3 – 0.5
permDRZ	DRZ permeability	m²	log unif.	$10^{-19} – 10^{-16}$
permBuffer	Buffer permeability	m²	log unif.	$10^{-20} – 10^{-17}$
meanWPrate	Mean of the truncated log normal distribution on base normalized general corrosion rate (R)	log (1/yr)	uniform	-5.5 – (-4.5)
stdWPrate	Standard deviation of the truncated log normal distribution	log (1/yr)	uniform	0.15 – 0.4
IRF	Instant release fraction	-	uniform	0.038 – 0.156

14 February 2023 Training material

eurad 27

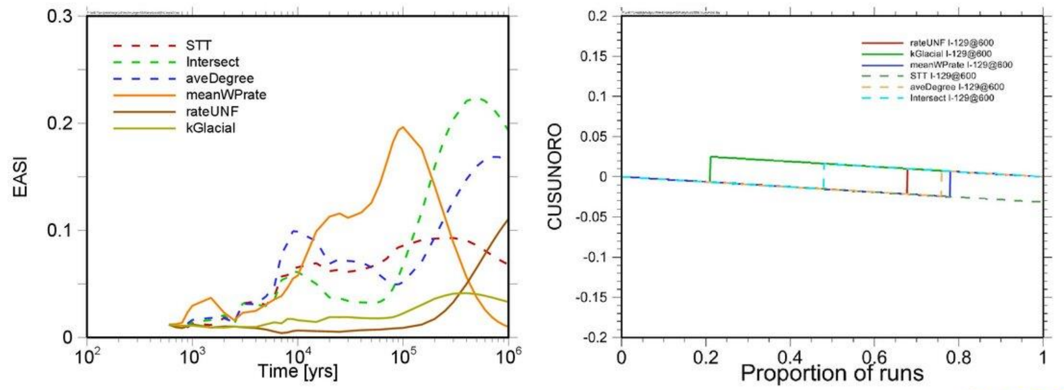
CRYSTALLINE REFERENCE CASE: GRAPH METRIC PARAMETERS

Measures of Spatial Heterogeneity				
Graph Metric	**Description**	**Unit**	**PDF type**	**Range**
STT	The log_{10}-transformed relative shortest travel time between repository and aquifer. Relative shortest travel time computed by scaling shortest travel time for each DFN by the median. A measure of ease of flow between repository and aquifer.	log (yr)	uniform	-2.0 – 2.0
aveDegree	Average number of intersections per fracture. A measure of how connected the network is over the entire domain.	-	uniform	3.4 – 3.6
Intersections	Number of fractures intersecting the repository. A measure of number of potential flow pathways out of the repository region.	-	uniform	63 - 101

14 February 2023 Training material

eurad 28

CRYSTALLINE REFERENCE CASE: TIME-DEPENDENT ANALYSIS



14 February 2023 Training material 29

CRYSTALLINE REFERENCE CASE: TIME-DEPENDENT ANALYSIS

EASI

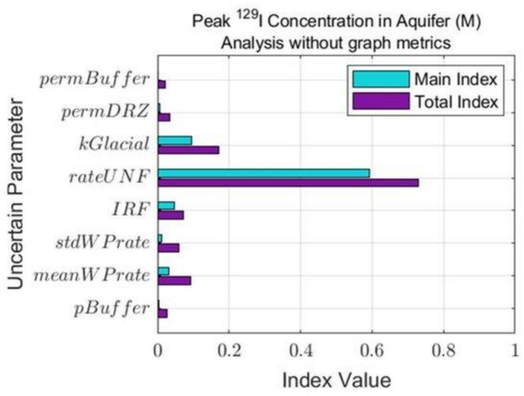
- **meanWPrate**
  - increasing sensitivity for 100000 years,
  - decreasing sensitivity in the later phase
  - dominant during the first 400000 years.
- **rateUNF and kGlacial**
  - start to become sensitive only after 100000 years,
  - rateUNF more dominant in the late phase.
- **graph metric parameters**
  - clear and high influence in the late phase.

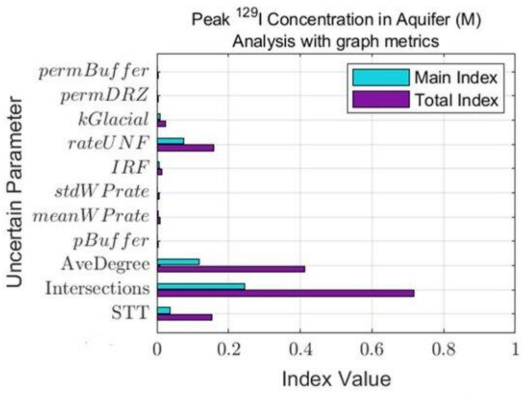
CUSUNORO

- **meanWPrate**
  - increasing sensitivity for 100000 years,
  - decreasing sensitivity in the later phase
  - dominant during the first 400000 years.
- **rateUNF and kGlacial**
  - start to become sensitive only after 100000 years,
  - comparably dominant in the late phase.
- **graph metric parameters**
  - unclear influence at all times.

14 February 2023 Training material 30

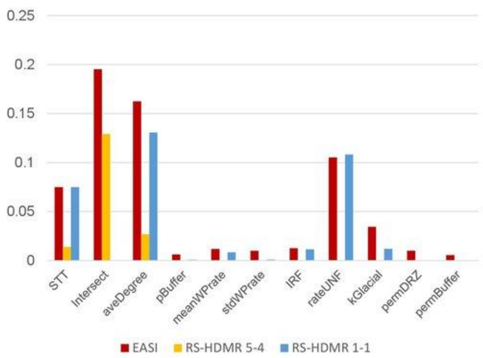
CRYSTALLINE REFERENCE CASE: MAXIMUM ANALYSIS WITH PCE

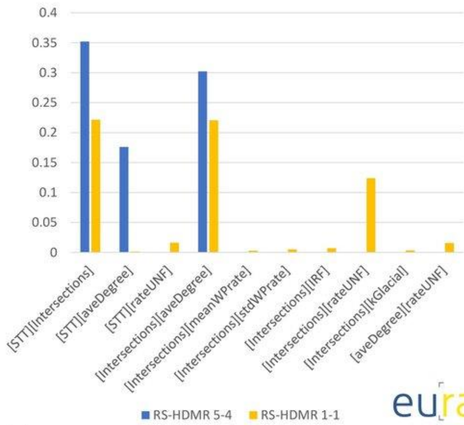




14 February 2023 Training material 31

CRYSTALLINE REFERENCE CASE: MAXIMUM ANALYSIS WITH RS-HDMR





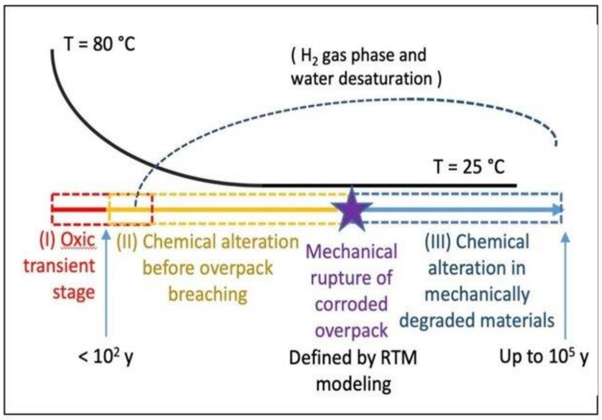
14 February 2023 Training material 32

CRYSTALLINE REFERENCE CASE: VARIANCE-BASED ANALYSIS OUTCOME

- Clear dominance of graph metrics (if taken into account).
- Most influential epistemic parameter: rateUNF.
- Comparable (low) influences of kGlacial and meanWPrate.
- Considerable dependency on choice of polynomial orders.
- Second-order analysis shows relevant interactions only between graph metrics.
- Caution: metamodeling is inadequate for aleatory influence of graph metrics

14 February 2023 Training material 33

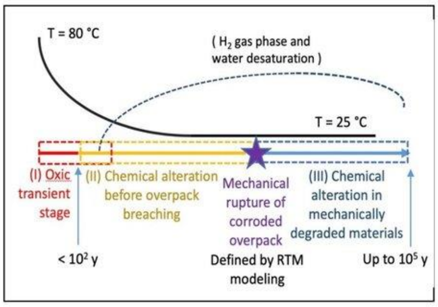
PRACTICAL EXAMPLE 3: REACTIVE TRANSPORT IN A GRANITE REPOSITORY (UDC)



14 February 2023 Training material 34

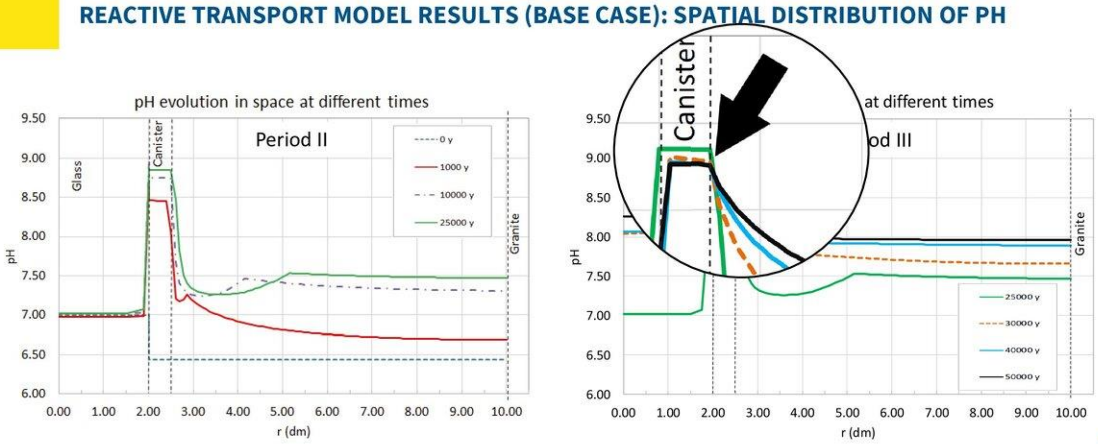
REACTIVE TRANSPORT MODEL: DESCRIPTION

- **Calculation of geochemical and temperature evolution**
- **Three time periods:**
  - Period I: oxidizing unsaturated conditions
  - Period II starts when the buffer is fully saturated
    - Chemical interactions before canister breaching
    - Nonisothermal
    - Anoxic canister corrosion
    - Interactions of corrosion products and buffer material
  - Period III starts after canister failure
    - Glass dissolution & interactions of glass with corrosion products
- **Simulation time horizon: 5·10⁴ years**



14 February 2023 Training material 35

REACTIVE TRANSPORT MODEL RESULTS (BASE CASE): SPATIAL DISTRIBUTION OF PH



14 February 2023 Training material 36

REACTIVE TRANSPORT MODEL: PLANNING OF PROBABILISTIC ANALYSIS

- Reactive transport simulations were performed on a HPC infrastructure (FinisTerrae II cluster from the Galician Supercomputing Center, CESGA, www.cesga.es)
- 27600 simulations
- Output quantity: pH at the canister/bentonite interface (CBI) after $5 \cdot 10^4$ years
- Evaluation with VARS and CUSUNORO

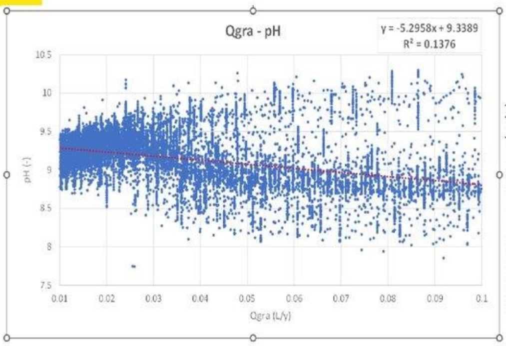
14 February 2023 Training material 37

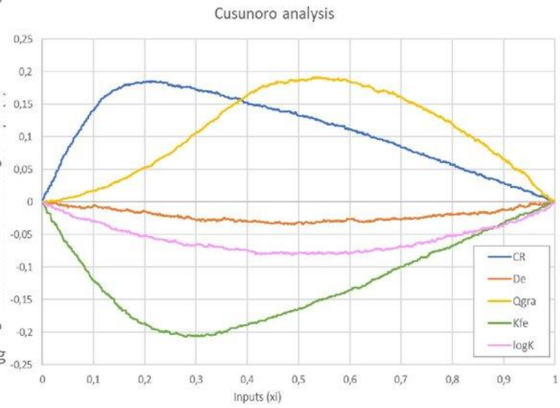
REACTIVE TRANSPORT MODEL: PARAMETERS

Parameter	Name	Range	PDF	Units
CR	Corrosion rate	0.1 – 10	Uniform	µm/y
De	Bentonite dif	0.0631 – 0.631	Log-uniform	dm2/y
Q^{gra}	Granite flow	0.01 – 0.1	Log-uniform	L/y
Fe^{ksel}	Fe selectivity	0.001 – 1	Log-uniform	-
Log(K)	K magnetite	-8.56 – -4.56	Uniform	-

14 February 2023 Training material 38

REACTIVE TRANSPORT MODEL: CUSUNORO ANALYSIS



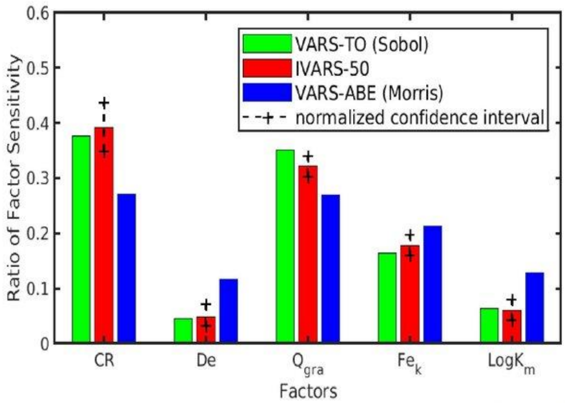


- scatterplot shows bifurcation due to concurring effects of Qgra to pH

14 February 2023 Training material eurad 39

REACTIVE TRANSPORT MODEL: VARS ANALYSIS

- **Three VARS measures**
  - VARS-TO corresponds to total-order Sobol indices
  - VARS-ABE is the mean local influence (derivative)
  - IVARS-50 is “something in between”
- **VARS-TO and IVARS-50 are very similar**
- **VARS-ABE looks more balanced**
- **In contrast to CUSUNORO**
  - logK seems to have a higher influence than De
  - the influence of Kfe is calculated significantly lower than that of CR and Qgra



14 February 2023 Training material eurad 40

DONUT WORK – OVERVIEW

14 February 2023 Training material

eurad 41

SUMMARY AND CONCLUSIONS.

- Level 1 - Inter has ruinarum varietates a Nisibi quam tuebatur accitus Vrsicinus, cui nos obsecuturos iunxerat imperiale praeceptum, dispicere litis exitialis certamina cogebatur abnuens et reclamans.
  - Level 2 - adulatorum oblatrantibus turmis, bellicosus sane milesque semper et militum ductor sed forensibus iurgiis longe discretus, qui metu sui discriminis anxius cum accusatores quaesitoresque subditivos.
    - Level 3 - Sibi consociatos ex isdem foveis cerneret emergentes, quae clam palamve agitabantur, occultis Constantium litteris edocebat inplorans subsidia, quorum metu tumor notissimus Caesaris.
      - Level 4 - Inter has ruinarum varietates a Nisibi quam tuebatur accitus Vrsicinus, cui nos obsecuturos iunxerat imperiale praeceptum
-

14 February 2023 Training material

eurad 42

BIBLIOGRAPHY AND/OR REFERENCES.

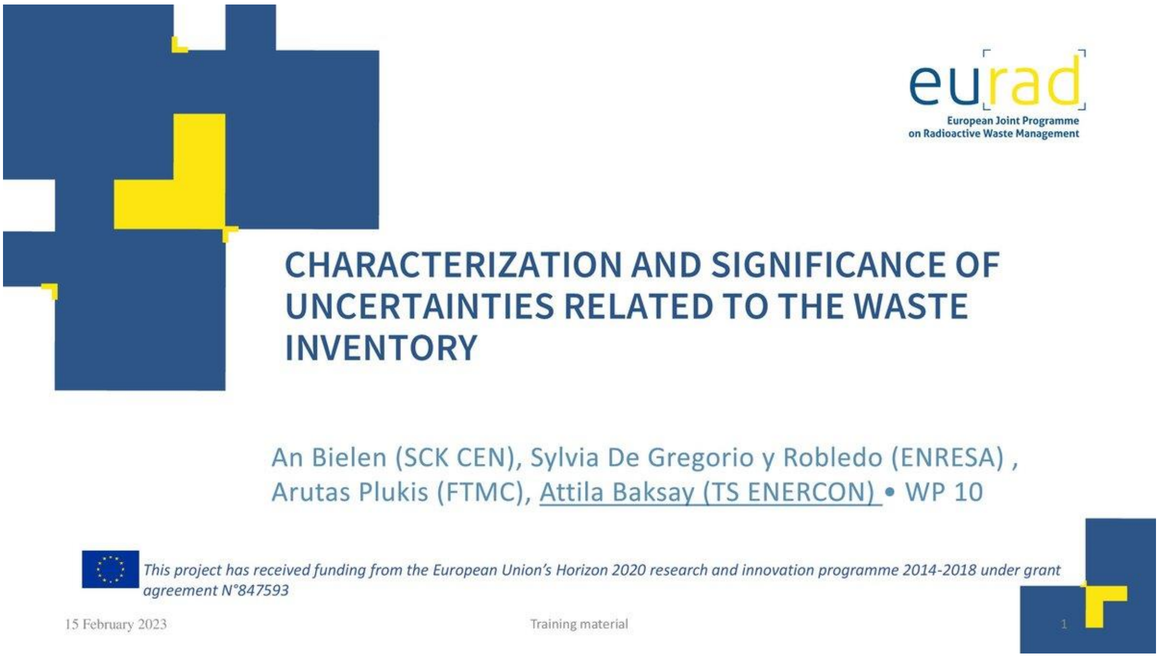
14 February 2023 Training material 43

eurad

Appendix F. Slides of lecture B.1

B.1 Characterization and significance of uncertainties related to the waste inventory

Prepared by Attila Baksay, TSENERCON



CONTENTS

- Introduction
- Radioactive Waste Management and Inventory
  - Radioactive waste management
  - Inventory and its changes during the waste management process
- Uncertainties in Radioactive Waste Inventory
  - Sources of uncertainty in waste inventory
  - Significance and characterization of uncertainties affecting radioactive waste inventory
- Examples of characterization and significance of uncertainties related to radioactive waste inventory
- Summary

15 February 2023 Training material 3

LEARNING OUTCOMES.

After the completion of this training unit/lesson, the students/participants should be able to

- list the elements of radioactive waste management and inventory,
- identify the uncertainties that affect the radioactive waste inventory,
- define the significance of the uncertainties related to radioactive waste inventory,
- assess their own radioactive waste management program from the inventory point of view,
- give examples on the characterization and significance of uncertainties related to the radioactive waste inventory.

15 February 2023 Training material 4

INTRODUCTION

- Problem of radioactive waste starts with its inventory
- Planning steps, shielding, management routes, possible storage and disposal options have roots back to inventory
- Inventory provides the source term for all safety assessment dealing with radioactive waste management
- There are many uncertainties related to the inventory of radioactive waste
- Introduction of radioactive waste and its management
- Identification of points where uncertainties have clear effect on the inventory

15 February 2023 Training material 5

INTRODUCTION -2

- Introduction of uncertainties related to
  - Radiological properties
  - Pysico-chemical properties
  - Waste processing (pre-treatment, treatment, conditioning)
  - Long term behavior of radioactive waste
- Significance of these uncertainties
- What are the plans to reduce uncertaintes, what are their foreseen evolution?
- Examples to illustrate the signifinace of uncertainties regarding their significance and characterization
- Presented information is based on IAEA(1) and EURAD(2,3) sources

15 February 2023 Training material 6

RADIOACTIVE WASTE MANAGEMENT AND INVENTORY

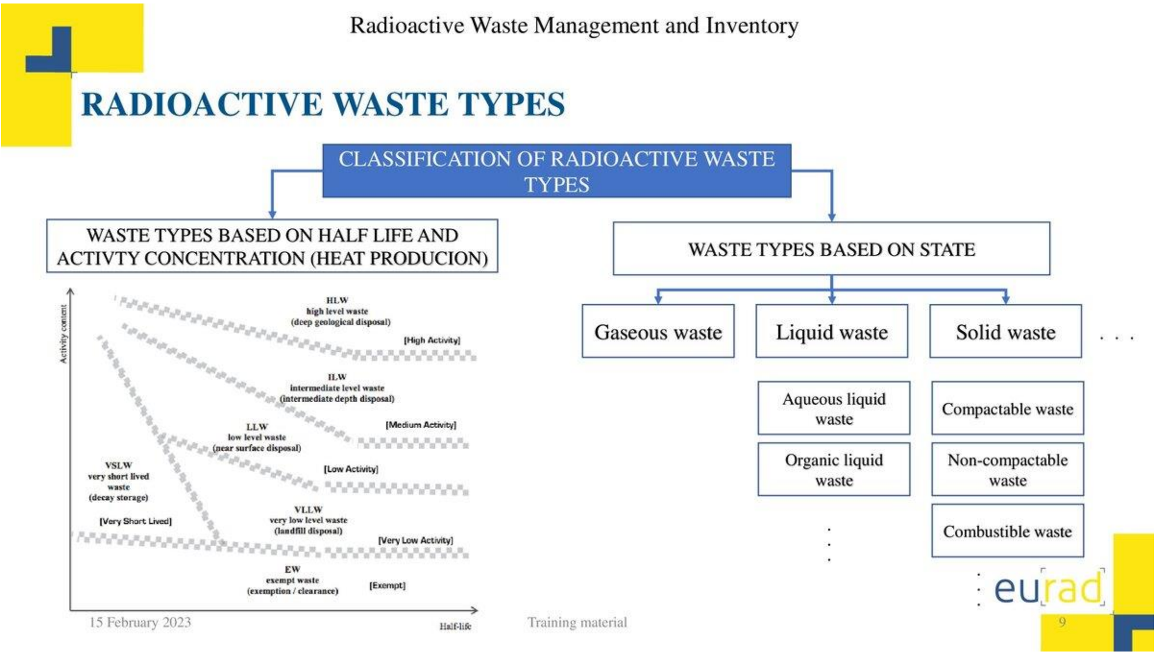
15 February 2023 Training material 7

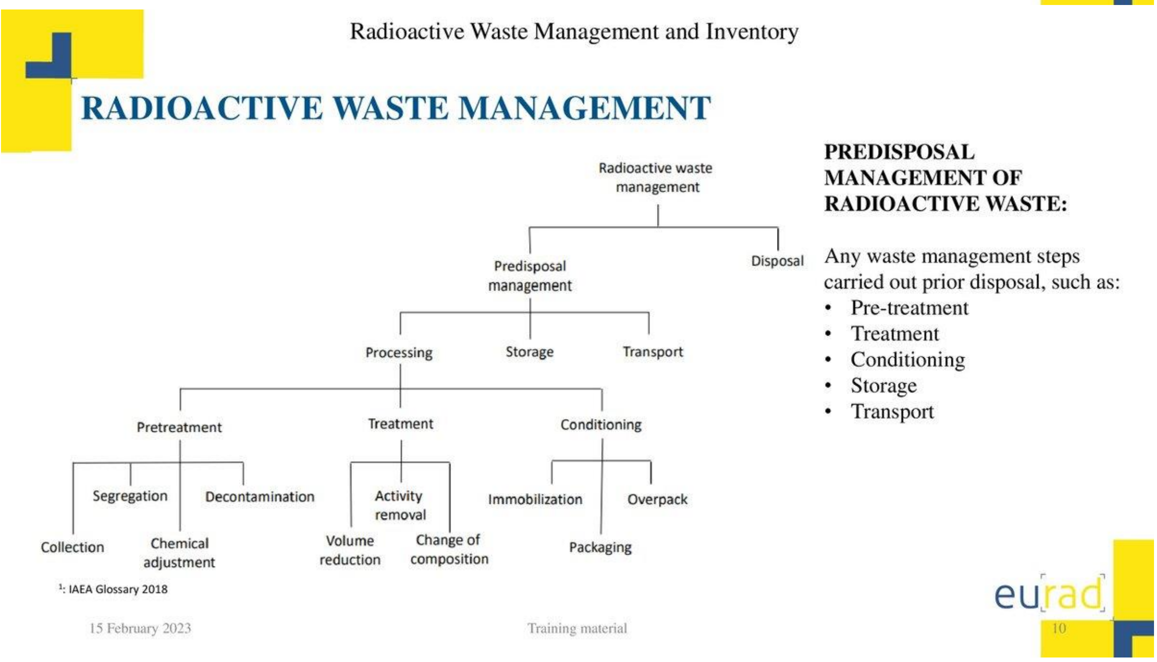
Radioactive Waste Management and Inventory

WHERE IS RADIOACTIVE WASTE COMING FROM?

- Material for which no further use is foreseen that contains, or is contaminated with, radionuclides at activity concentrations greater than clearance levels as established by the regulatory body.[1]
- Operation and Decommissioning of Nuclear Power Plants
- Fuel Cycle Facilities
- Institutional Waste from Industrial, Medical and Research Application
- Legacy waste

15 February 2023 8


Radioactive Waste Management and Inventory
RADIOACTIVE WASTE TYPES
CLASSIFICATION OF RADIOACTIVE WASTE TYPES
WASTE TYPES BASED ON HALF LIFE AND ACTIVTY CONCENTRATION (HEAT PRODUCION)
WASTE TYPES BASED ON STATE
Activity content
HLW
high level waste
(deep geological disposal)
[High Activity]
ILW
intermediate level waste
(intermediate depth disposal)
[Medium Activity]
LLW
low level waste
(near surface disposal)
[Low Activity]
VSLW
very short lived waste
(decay storage)
[Very Short Lived]
VLLW
very low level waste
(landfill disposal)
[Very Low Activity]
EW
exempt waste
(exemption / clearance)
[Exempt]
Half-life
Gaseous waste
Liquid waste
Solid waste
. . .
Aqueous liquid waste
Organic liquid waste
Compactable waste
Non-compactable waste
Combustible waste
15 February 2023
Training material
eurad
9


Radioactive Waste Management and Inventory
RADIOACTIVE WASTE MANAGEMENT
Radioactive waste management
Predisposal management
Disposal
Processing
Storage
Transport
Pretreatment
Treatment
Conditioning
Collection
Segregation
Chemical adjustment
Decontamination
Volume reduction
Activity removal
Change of composition
Immobilization
Packaging
Overpack
1: IAEA Glossary 2018
PREDISPOSAL MANAGEMENT OF RADIOACTIVE WASTE:
Any waste management steps carried out prior disposal, such as:
• Pre-treatment
• Treatment
• Conditioning
• Storage
• Transport
15 February 2023
Training material
eurad
10

WASTE ACCEPTANCE CRITERIA (WAC)

- **Quantitative or qualitative criteria specified by the regulatory body, or specified by an operator and approved by the regulatory body, for the waste form and waste package to be accepted by the operator of a waste management facility.** (1)
  - Waste acceptance criteria specify the radiological, mechanical, physical, chemical and biological characteristics of waste packages and unpackaged waste.
  - Waste acceptance criteria might include, for example, restrictions on the activity concentration or total activity of particular radionuclides (or types of radionuclide) in the waste, on their heat output or on the properties of the waste form or of the waste package.
  - Waste acceptance criteria are based on the safety case for the facility or are included in the safety case as part of the operational limits and conditions and controls.

eurad

15 February 2023 Training material 11

Radioactive Waste Management and Inventory

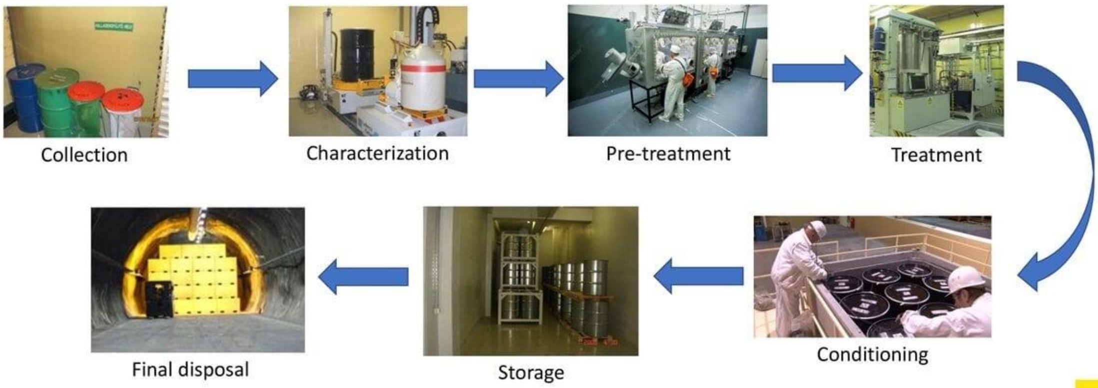
WHAT IS WASTE INVENTORY?

eurad

15 February 2023 Training material 12

Radioactive Waste Management and Inventory

INVENTORY IN THE WASTE LIFECYCLE - 1



eurad

15 February 2023 Training material 13

Radioactive Waste Management and Inventory

INVENTORY IN THE WASTE LIFECYCLE - 2

	Radiological properties	Volume	Mass	Physio-chemical properties
Collection				
Characterization	Difficult-to-measure isotopes			
Pre-treatment	Decay	Volume change	Mass change	Change
Treatment	Decay	Volume change	Mass change	Change
Conditioning	Decay	Volume change	Mass change	Change
Storage	Decay			Possible change
Disposal	Decay		Mass change	Possible change

15 February 2023 Training material 14

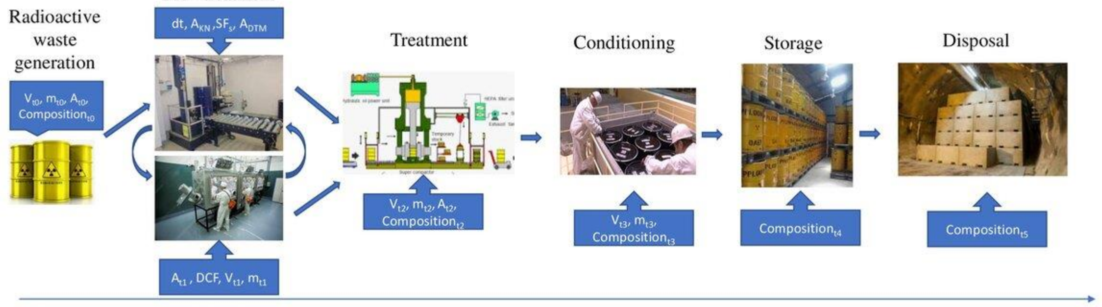
UNCERTAINTY IN RADIOACTIVE WASTE INVENTORY

Date Training material

eurad 15

Uncertainties in Radioactive Waste Inventory

SOURCES OF UNCERTAINTIES IN INVENTORY



- Waste stream identification
- Waste production rate

- Characterization:
  - Radiological properties
  - Physio-chemical prop.
- Pre-treatment:
  - Yield of processes
  - Volume reduction
  - ….

- Volume change
- Composition change
- Yield of process

- Long term behavior:
  - Physio-chemical changes
  - Aging

15 February 2023 Training material

eurad 16

Uncertainty in Radioactive Waste Inventory

LIST OF UNCERTAINTIES ASSOCIATED WITH WASTE INVENTORY(2)

Topical area	Associated uncertainties
Radiological properties	List of critical radionuclides **Radionuclide activity** **Scaling factor**
Physico-chemical properties	Cellulose content Behavior of cementitious waste forms **Chemical composition** Thermal reactivity Swelling Volume, mass Voids
Waste stream identification & management route	Waste streams & associated waste forms WAC's Limited knowledge Not defined routes
Pre-treatment, treatment and conditioning processes	Pre-treatment techniques Treatment techniques Conditioning techniques
Long-term behaviour	**Physico-chemical conditions in the storage or disposal facility** Waste form behaviour and ageing in storage or disposal conditions Storage time

eurad

15 February 2023 Training material 17

Uncertainty in Radioactive Waste Inventory

RADIOLOGICAL PROPERTIES: RADIONUCLIDE ACTIVITY

- **Depending on the focus, the list of the radionuclides can be different**
  - Operational phase of facilities:
    - short lived gamma emitters, neutron emitters (^{60}Co, ^{137}Cs, ^{252}Cf….),
    - isotopes of mobile, volatile elements (^{3}H, ^{14}C, ^{131}I, ^{222}Rn….)
    - fissile isotopes (^{235}U, ^{239}Pu, …)
  - Post closure phase of disposal facilities:
    - Long lived, mobile isotopes add to the list (^{36}Cl, ^{79}Se, ^{135}Cs, …)
- **A variety of measurement and calculation methods can be applied to estimate the activity levels of radionuclides enclosed in a waste package. Uncertainties are associated with each of these methods.**
- **Radiological waste characterization is often based on the determination of the key nuclides gamma-ray emitting radionuclides by a measurement and the estimation of the DTM alpha and beta emitter radionuclides via SF method.**

eurad

15 February 2023 Training material 18

Uncertainty in Radioactive Waste Inventory

RADIONUCLIDE ACTIVITY - SIGNIFICANCE

- **Uncertainties related to radionuclide activity including scaling factor**
  - Proper characterization of RW
    - Proper classification
    - Key information with regard to the dose rate
  - Appropriate and optimal waste management route
    - Underestimated dose rates
    - Limiting choice to suboptimal waste management scenario

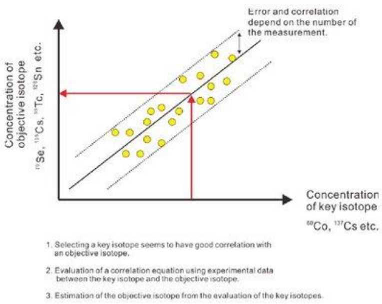
15 February 2023 Training material 19

Uncertainty in Radioactive Waste Inventory

RADIOLOGICAL PROPERTIES: SCALING FACTORS

- **Scaling Factors are determined by detailed multi-step analysis:**
  - Representative samples from the waste stream
  - Radiochemical analysis, determining activity concentrations for gamma emitters as well as beta- and alpha emitters
  - Correlations between activity concentrations of gamma emitters and beta- and alpha emitters

$$AC_{DTM} = b \cdot AC_{KN}^{m}$$



- **Radiological waste characterization is often based on the determination of the easy-to-measure (ETM) gamma-ray emitting radionuclides, called Key-Nuclides (KN).**
- **Determination of alpha and beta emitter (commonly referred as difficult-to-measure (DTM) radionuclides) activities is based on scaling factors (SF)**

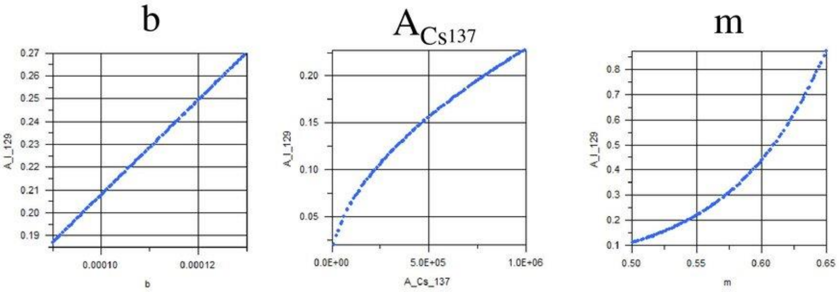
15 February 2023 Training material 20

Uncertainty in Radioactive Waste Inventory

SCALING FACTORS - SIGNIFICANCE

- **Example: Effect of the uncertainties in SF parameters and ^{137}Cs activity concentration on the activity concentration of ^{129}I**

$$AC_{DTM} = b \cdot AC_{KN}{}^{m}$$

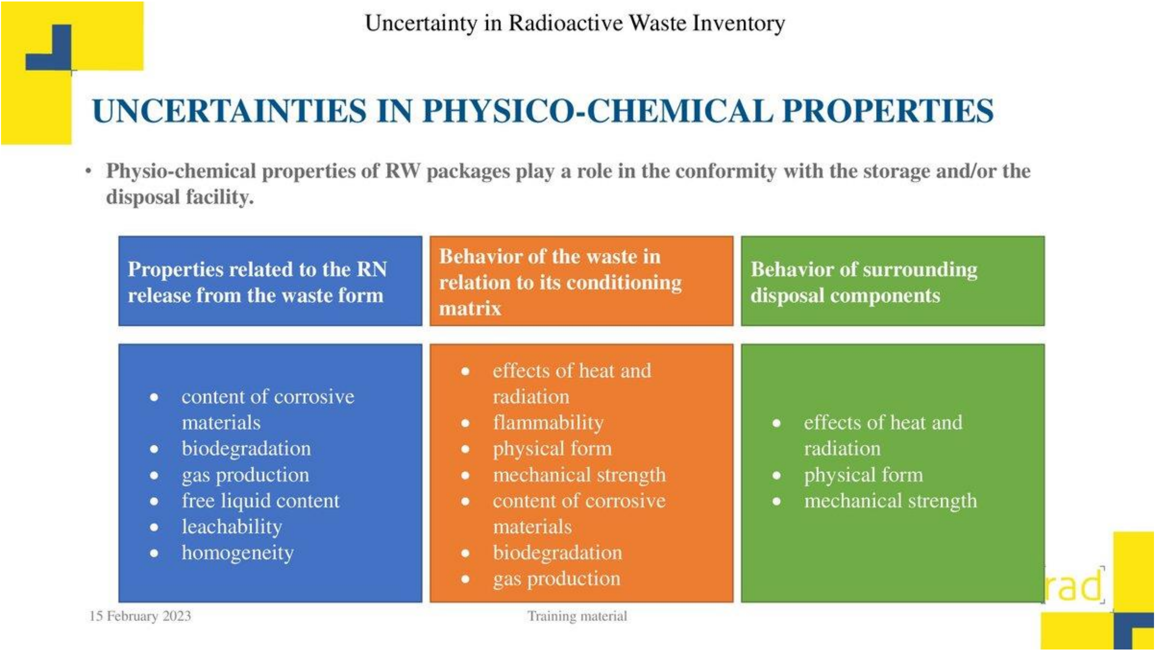


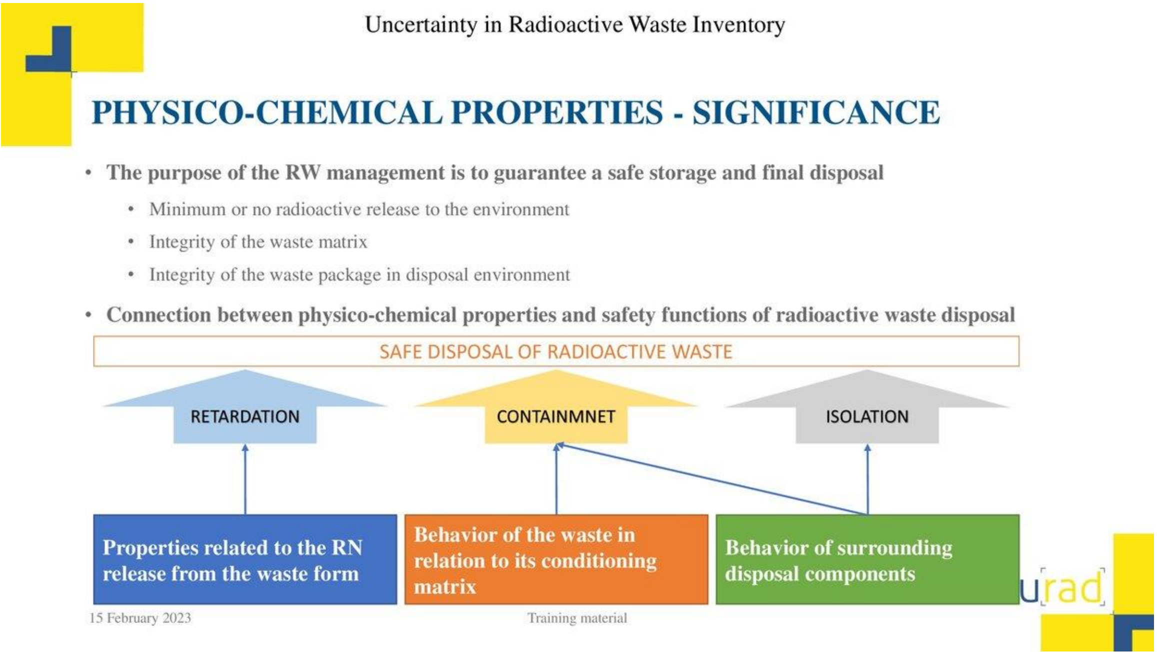
Uncertainty in Radioactive Waste Inventory

CHARACTERIZATION OF UNCERTAINTIES OF RADIOLOGICAL PROPERTIES

- **Uncertainties related to radionuclide activity including scaling factor**
  - Should be implemented at each stage of their management
  - Focus on technical improvements
  - Improve statistical approaches
  - Scaling factors -> narrowing the uncertainty
  - Development of adequate methodology
    - Measurement uncertainties
    - Model uncertainties
- **Evolution:**
  - Decrease of uncertainties because of:
    - Operational experience, which will give more insight and more specific knowledge on the behavior of waste and its activities.
    - Improvement of characterization quality.

15 February 2023 Training material


Uncertainty in Radioactive Waste Inventory
UNCERTAINTIES IN PHYSICO-CHEMICAL PROPERTIES
• Physio-chemical properties of RW packages play a role in the conformity with the storage and/or the disposal facility.
Properties related to the RN release from the waste form
Behavior of the waste in relation to its conditioning matrix
Behavior of surrounding disposal components
• content of corrosive materials
• biodegradation
• gas production
• free liquid content
• leachability
• homogeneity
• effects of heat and radiation
• flammability
• physical form
• mechanical strength
• content of corrosive materials
• biodegradation
• gas production
• effects of heat and radiation
• physical form
• mechanical strength
15 February 2023
Training material


Uncertainty in Radioactive Waste Inventory
PHYSICO-CHEMICAL PROPERTIES - SIGNIFICANCE
• The purpose of the RW management is to guarantee a safe storage and final disposal
• Minimum or no radioactive release to the environment
• Integrity of the waste matrix
• Integrity of the waste package in disposal environment
• Connection between physico-chemical properties and safety functions of radioactive waste disposal
SAFE DISPOSAL OF RADIOACTIVE WASTE
RETARDATION
CONTAINMNET
ISOLATION
Properties related to the RN release from the waste form
Behavior of the waste in relation to its conditioning matrix
Behavior of surrounding disposal components
15 February 2023
Training material

Uncertainty in Radioactive Waste Inventory

CHARACTERIZATION OF UNCERTAINTIES IN PHYSICO-CHEMICAL PROPERTIES

- **Uncertainties related to chemical composition with a special attention to organic content**
  - Research and investments regarding the characterization of chemical composition
  - Mass of overall materials and additives is uncertain
  - WAC
    - Internal safety reviews
    - Revision of legislation
    - More stringent final WAC's
  - Limited accuracy of measurements
  - Waste generation history
  - Evolution of the waste

15 February 2023 Training material

Uncertainty in Radioactive Waste Inventory

EVOLUTION OF UNCERTAINTIES IN PHYSICO-CHEMICAL PROPERTIES

- **Recent answers show mixed picture on the expected evolution of uncertainties in physico-chemical properties**
- **Positive view in improvements will help in reducing uncertainties:**
  - Technical improvemnet
  - Better performance laboratories
  - Development in QA/QC
- **Conservative views:**
  - A lot of uncertianties rely on speculation
  - Difficult, what to measure, how to measure and what is the goal
  - Improvemnts in safety assessments are needed

15 February 2023 Training material

Uncertainty in Radioactive Waste Inventory

PRE-TREATMENT, TREATMENT AND CONDITIONING PROCESSES

- Phases of the radioactive waste processing activities are dedicated to transform raw RW to a waste form that is capable to withstand the conditions of long-term storage and/or final disposal.
- Pre-treatment prepares the waste for further processing and may include sorting and separating different waste materials or waste types, as well as size/volume reduction or shredding to optimize treatment and disposal.
- The aim of waste treatment processes is to transform the waste into a stable and solid physico-chemical form, and to reduce the volume of the waste.
- Conditioning puts the waste in a safe, stable, and manageable form for transport, storage and disposal.

15 February 2023 Training material

Uncertainty in Radioactive Waste Inventory

UNCERTAINTIES IN PRE-TREATMENT, TREATMENT AND CONDITIONING PROCESSES - SIGNIFICANCE

- Waste which is not properly sorted, could have in the end an impact on the physico-chemical properties and volume of the waste.
- Uncertainties related to other pre-treatment processes could have a direct effect on the radionuclide content and physico-chemical form of the waste, as well as an influence on the eventual volume of the waste that shall be produced.
- Uncertainties related to treatment processes could result in more hazardous waste forms from radiation protection point of view.
- Uncertainties associated with conditioning processes could have an impact on the content of radionuclides and dose rate, due to the type of shielding the package offers. Conditioning also has a direct effect on physico-chemical properties and can, in some cases, lead to new uncertainties regarding these properties

15 February 2023 Training material

Uncertainty in Radioactive Waste Inventory

CHARACTERIZATION EVOLUTION EVOLUTION OF UNCERTAINTIES IN PRE-TREATMENT, TREATMENT AND CONDITIONING PROCESSES

- **Technological development**
  - Decontamination strategy and technology developments
  - Characterization technology developments
  - QA/QC developments
- **Evolution**
  - Uncertainties will be reduced thanks to development of new techniques

15 February 2023 Training material

Uncertainty in Radioactive Waste Inventory

LONG-TERM BEHAVIOR OF RADIOACTIVE WASTE

- **Physico-chemical conditions in the storage or disposal facility:**
  - The long-term behavior of the waste package and waste matrix in the surface facility or underground conditions due to uncertainties in the facility, such as pH, presence of aggressive species (chlorides, sulphates,…), mechanical stresses, etc.
- **Degradation rate of the waste:**
  - Uncertainty in changes in matrix, degradation rate and integrity of the waste form/package
  - Uncertainty on release rates of radionuclides and aggressive species in the waste form
  - Uncertainty on waste-induced disturbances of other disposal system components
- **Storage time:**
  - Storage facilities are designed for specific classes of waste packages and therefore their design and implementation must take into account all the operational risks related to these classes of waste including those associated with extended storage times. The storage may be short term to allow for radioactive decay or long-term until the waste can be safely transferred to a suitable disposal site

15 February 2023 Training material

Uncertainty in Radioactive Waste Inventory

LONG-TERM BEHAVIOR OF RADIOACTIVE WASTE - SIGNIFICANCE

- **Physico-chemical conditions in the storage or disposal facility:**
  - Uncertainty in disposal behaviors could produce reactions with the waste form, or result in corrosion, swelling, etc. of the matrix. Influence on the properties of the waste form – degradation rate.
  - Uncertainties in the storage or disposal facility conditions will impact all parameters related to the long-term waste package behavior and can result in leaching out radionuclides, chemicals, by-products, etc. into the environment.
- **Waste form behavior, degradation rate**
  - Reduction of the stability of the waste form will in turn affect those parameters that are responsible for the migration rate of the contaminants, evolving in uncertainty in which way, rate and extent the radionuclides will be released from the facility.
- **Storage time**
  - Uncertainties associated with storage time might arise and may affect the uncertainties on the waste form characteristics due to ageing processes or the occurrence of events like incidents or accidents.

15 February 2023 Training material

Uncertainty in Radioactive Waste Inventory

CHARACTERIZATION OF UNCERTAINTIES IN LONG-TERM BEHAVIOR OF RADIOACTIVE WASTE

- **Uncertainties related to physico-chemical conditions in the storage or disposal facility**
  - Information on
    - Micro-climate indoors
    - Barriers
    - Surroundings
  - Collecting data from experiments
  - Modelling

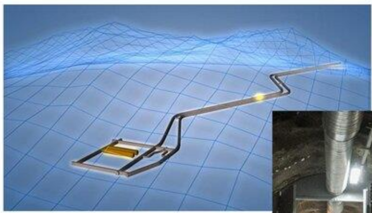
15 February 2023 Training material

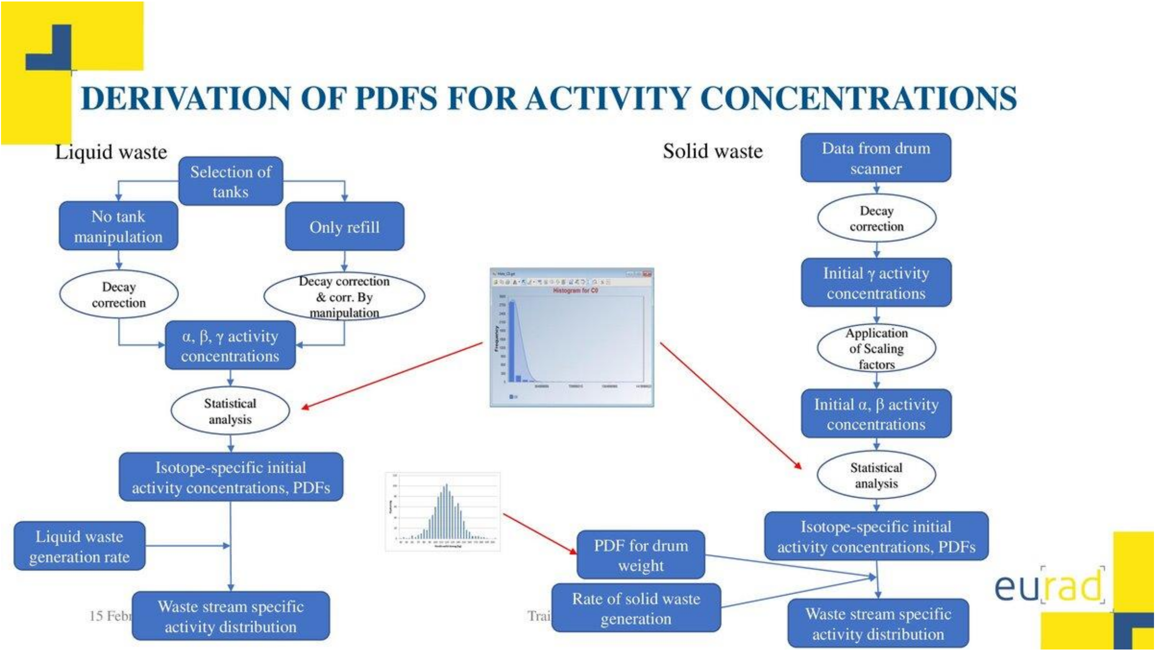
EVOLUTION OF UNCERTAINTIES IN LONG-TERM BEHAVIOR OF RADIOACTIVE WASTE

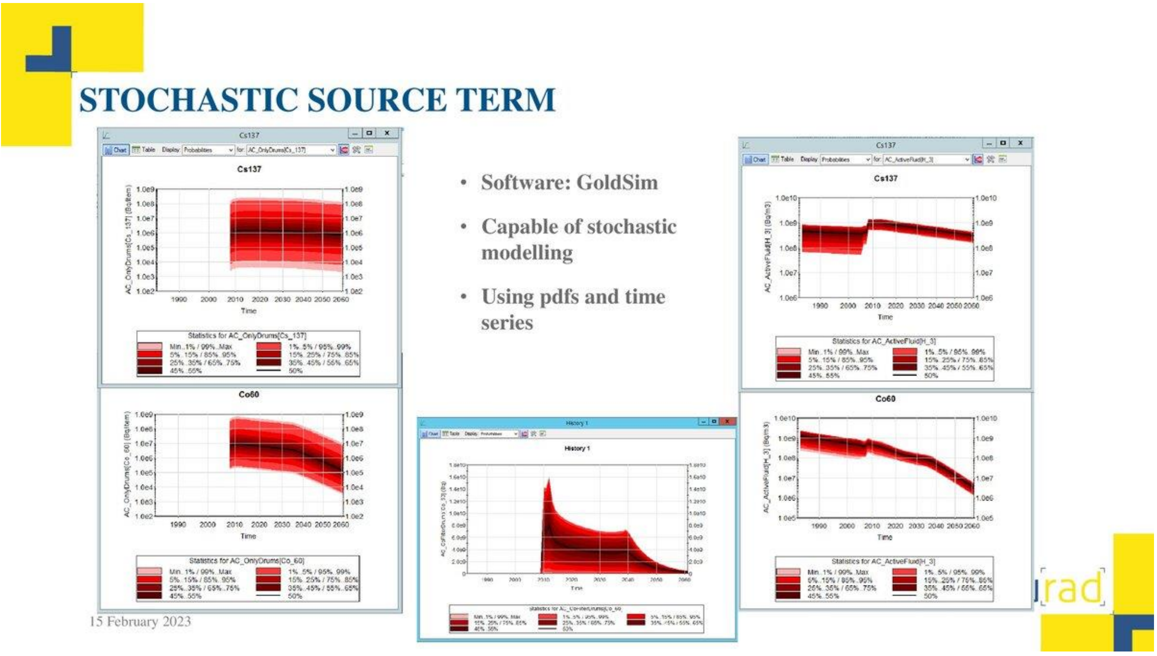
- **New information about the characteristics of the disposal site together with the development and implementation of the disposal program may be responsible for the reduction of this uncertainty.**
- **The progress of siting processes, decisions on possible type(s) of host rock and the implementation of the uncertainty in the safety assessment will decrease the uncertainty over time.**

EXAMPLE 1: STOCHASTIC ISOTOPE INVENTORY FOR BÁTAAPÁTI

- **Bátaapáti National Radioactive Waste Repository**
- **Goal:**
  - Input data for:
    - Post closure safety assessment (GoldSim)
    - Dose assessment for operational phase
  - Assessment for later measurement data
- **Used data:**
  - Waste stream- and isotope specific measured data
  - Generation rate for different waste streams
- **Results:**
  - Activity concentrations for the waste streams during and after the operational period of the NPP

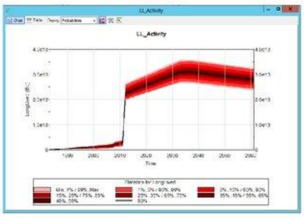


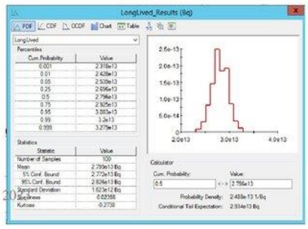

DERIVATION OF PDFS FOR ACTIVITY CONCENTRATIONS
Liquid waste
Selection of tanks
No tank manipulation
Only refill
Decay correction
Decay correction & corr. By manipulation
α, β, γ activity concentrations
Statistical analysis
Isotope-specific initial activity concentrations, PDFs
Liquid waste generation rate
Waste stream specific activity distribution
Solid waste
Data from drum scanner
Decay correction
Initial γ activity concentrations
Application of Scaling factors
Initial α, β activity concentrations
Statistical analysis
Isotope-specific initial activity concentrations, PDFs
PDF for drum weight
Rate of solid waste generation
Waste stream specific activity distribution
eurad


STOCHASTIC SOURCE TERM
Software: GoldSim
Capable of stochastic modelling
Using pdfs and time series
Cs137
Co60
History 1
15 February 2023

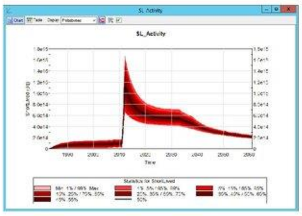
RESULTS OF THE MODELLING

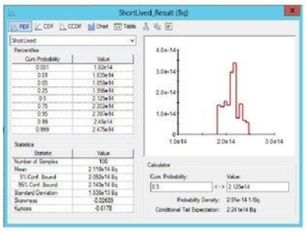
Activity of long-lived isotopes





Activity of short lived isotopes





15 February 20

Training material

eurad

EXAMPLE 2: INCIDENT IN A TREATMENT FACILITY

- **An example for the significance of uncertainty in physico-chemical composition of radioactive waste**
- **Incident took place in Radioactive Waste Treatment Facility**
- **INES 2 incident in 2013**
- **Drums were opened in order to sort and compact the waste**
- **Expected waste form:**
  - Am on electroplated steel discs
  - Paper wipes used in laboratory

15 February 2023

eurad

EXAMPLE 2: INCIDENT IN A TREATMENT FACILITY -2

- Waste contained significant amount of powder, dried salt that contained ^{241}Am, unknown
- Powder got airborne during the compaction of the waste
- Readings taken following the incident showed the worker's hands, clothing, and the waste compactor room were contaminated.
- According to whole-body measurements taken on 12 December 2013, the amounts of incorporated ^{241}Am for the three workers were 0.9 kBq, 1.8 kBq and 9.0 kBq.

15 February 2023 Training material

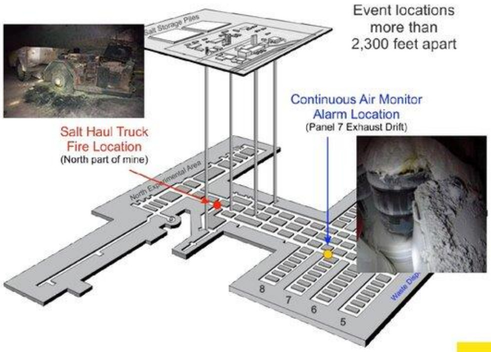
EXAMPLE 3: RADIOLOGICAL RELEASE FROM WIPP -1

- Waste Isolation Pilot Plant in Carlsbad, NM, USA
- Disposal of defense-generated TRU waste from DOE sites
- Waste is disposed of in a set of panels located nearly one-half mile below the surface in a deep geologic salt bed formed 250 million years ago
- Two accidents:
  - A salt haul truck caught fire 05.02.2014
  - Radiological Release Event on 14.02.2014

15 February 2023 Training material

EXAMPLE 3: RADIOLOGICAL RELEASE FROM WIPP -2 [(6)]

- Phase II of the investigation focused on the cause of the radiological release, with the AIB concluding that the release was caused by an exothermic reaction involving the mixture of organic materials and nitrate salts in one drum that was processed at Los Alamos National Laboratory in December 2013
- Example of effect of uncertainty in conditioning and long-term changes in chemical form



15 February 2023 Training material

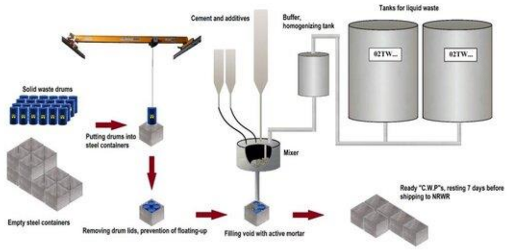
EXAMPLE 4: OPTIMIZATION FOR DISPOSAL 1.

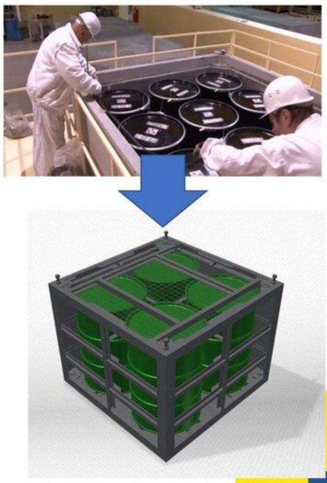
- Safety upgrade of RWTDF
- Old RADON type repository
- One of the major goal was to achieve disposal volume gain
- Optimized usage of waste containers
- Clear effects of uncertainties in
  - waste volume,
  - pre-treatment, treatment and conditioning
- It was difficult to estmate the final disposal volume, the result ws not so satisfying

15 February 2023 Training material

EXAMPLE 5: OPTIMIZATION FOR DISPOSAL 2.

- Geological and economical reasons an optimization project had been carried in Paks NPP
- By changing the pre-treatment, treatment and conditioning methodologies significant volume reduction became possible

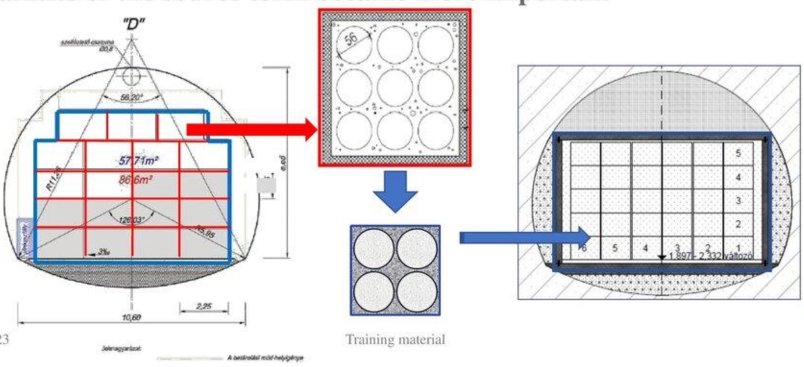




15 February 2023 Training material

CHANGE IN THE WASTE PACKAGE AND IN THE DISPOSAL CONCEPT

- Because of the change of the disposal strategy, radiation protection became significantly more important.
- Uncertainties of the source term became more important



eurad

15 February 2023 Training material

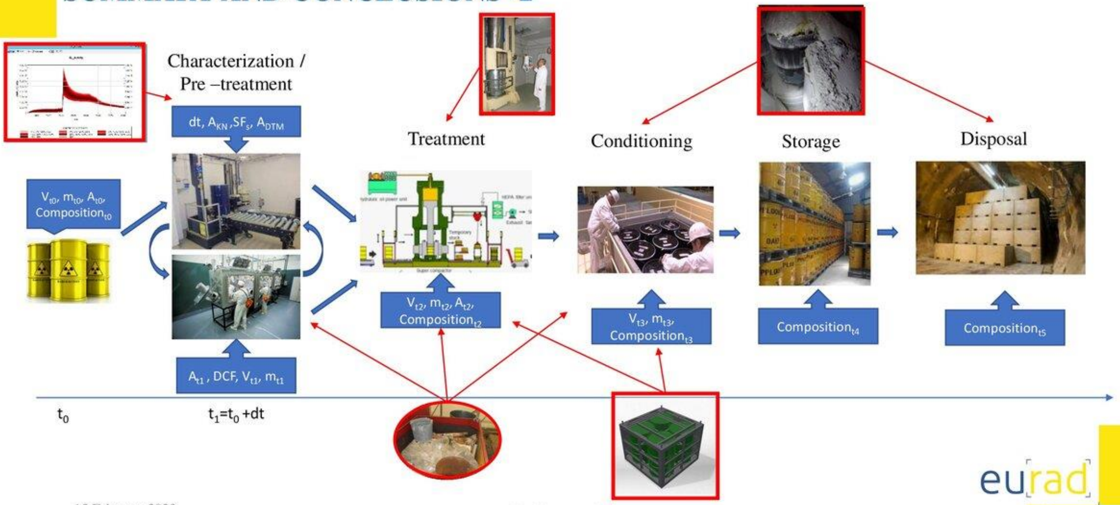
SUMMARY AND CONCLUSIONS.

- Basic information about radioactive waste management was delivered
- Uncertainties discussed:
  - Radiological properties:
  - Physico-chemical properties
  - Waste processing
  - Long term behavior of radioactive waste
- Significance of uncertainties in inventory
  - Safety relevancies (Safety assessments)
  - Role in the optimization
- Characterization
  - Better technologies, methodolgies under development
  - Uncertainties are planned to be diminished

HELP NOTE.
Summary and/or conclusions.
- List of key points in the less
- The purpose of the summary learner understand the lesso
- Organize the ideas in the su relevant to the least importa
- Do not literally copy the sam summarizing.
- Make sure that the writing is text.
- Plan, write, review and edit product.

15 February 2023 Training material eurad 45

SUMMARY AND CONCLUSIONS -2



15 February 2023 Training material eurad 46

BIBLIOGRAPHY AND/OR REFERENCES.

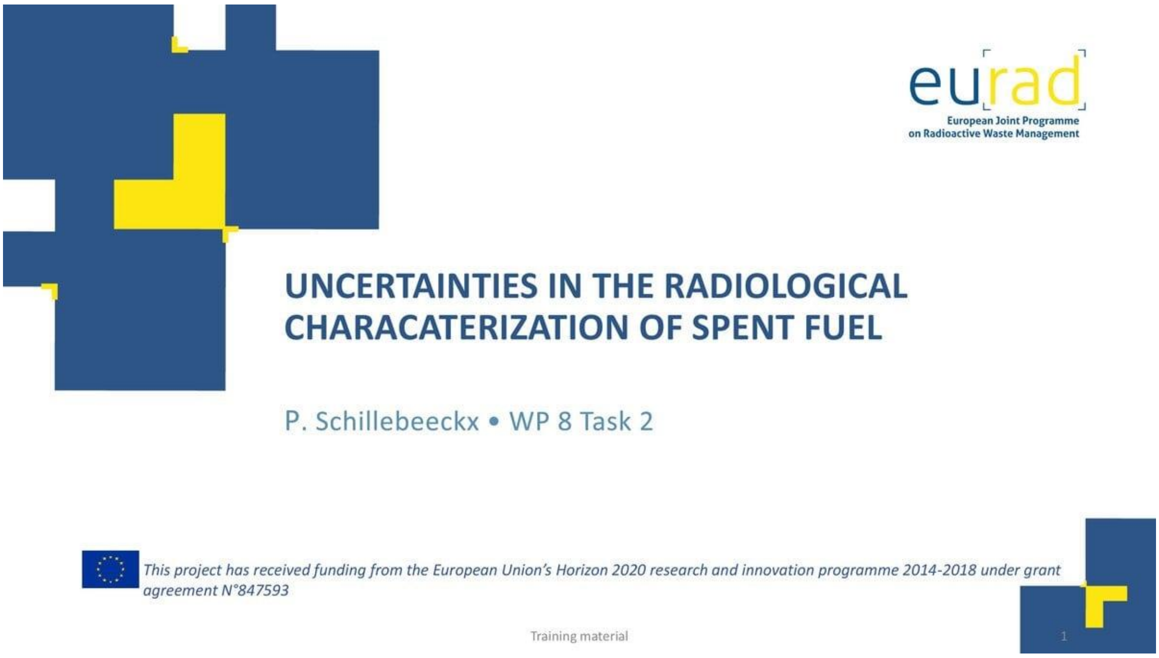
- [1]: IAEA Radioactive Waste Management Glossary, 2003 Edition
- [2]: EURAD Milestone 92: UMAN Preliminary list of uncertainties from Subtask 3.2 as input to Subtask 4.2, WP 10
- [3]: EURAD Deliverable 10.6: Views of the different actors on the identification, characterization and potential significance of uncertainties on waste inventory and on the impact of predisposal steps, WP 10
- [4]: P. Zagyvai: Examination of physico-chemical properties Am-241 pollution, Rad.protection Training, 2014, Hajdúszoboszló
- [5]:https://www.nucnet.org/news/hungary-contamination-incident-gets-provisional-ines-level-2-rating
- [6]:U.S. DoE Office of Environmental Management: Accident Investigation Report Phase 2 Radiological Release Event at the Waste Isolation Pilot Plant, February 14, 2014; April 2015

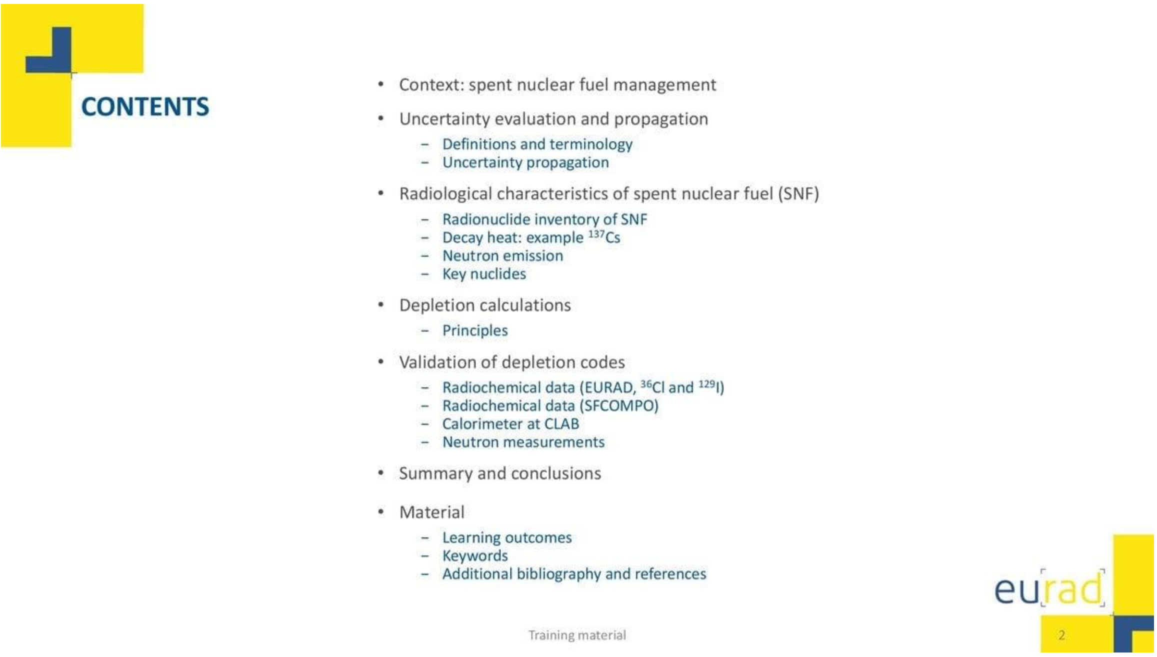
Date Training material eurad 47

Appendix G. Slides of lecture B.2

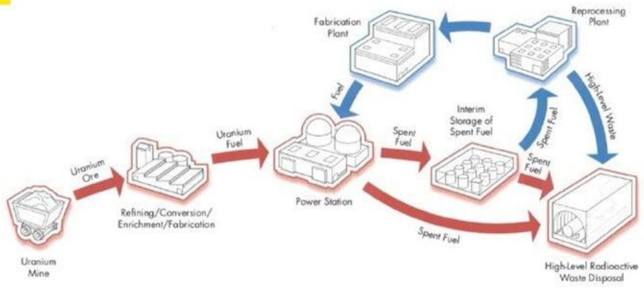
B.2 Uncertainties in the radiological characterization of spent fuel

Prepared by Peter Schillebeeckx, JRC





NUCLEAR FUEL CYCLE

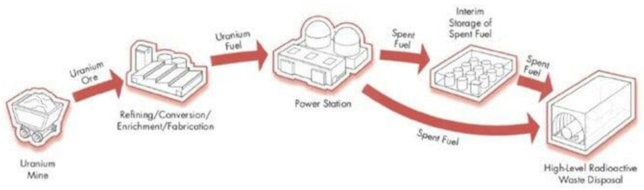


Nuclear fuel cycle
(open or closed)
produces waste

Training material

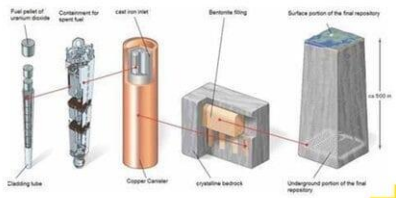
3

NUCLEAR FUEL CYCLE



Open fuel cycle
Sweden : Forsmark
Finland : Onkalo

Three barriers (SKB):
- canister
- buffer (bentonite clay)
- bedrock



Training material

4

SPENT NUCLEAR FUEL (SNF) DISPOSAL EXAMPLE: SWEDISH CONCEPT

CLAB
Central Interim Storage Facility for Spent Nuclear Fuel (SNF)

CLINK
SNF encapsulation plant

SIGRID
SNF carrier

FORSMARK bedrock
SNF disposal

www.skb.com

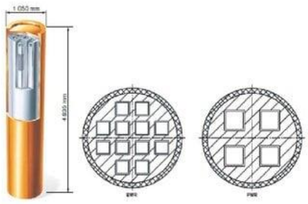
Training material

eurad

5

SNF DISPOSAL EXAMPLE: SWEDISH CONCEPT

- About 1600 canisters
  - 5 m long and 1 m diameter
  - 5 cm thick Cu casing (protect against corrosion)
  - Insert of nodular cast iron (structural integrity)
  - Maximum decay power : 1700 W
- Optimisation of canister loading has a substantial economic and ecological impact
  - Cu- mining and canister production:
    - 1 M€ per extra canister
    - 2 ton Cu per extra canister
  - Repository: tunnel excavation, operation, ...



Training material

eurad

6

OPTIMISING CANISTER LOADING

Reduction of canisters and required disposal volume by

- Improved loading schemes algorithms
  e.g. Solans et al., Nucl. Eng. Des. 370 (220) 110897, reduction of 2% in number of canisters
- Improved decay power estimation
  Reduction of uncertainty of decay power estimation

  (Seidl et al., submitted to Frontiers in Energy research – Nuclear Energy)

One of the main objectives of EURAD WP8 Task 2

“Spent nuclear fuel characterisation and related uncertainty analysis”

eurad

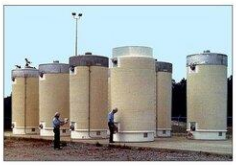
Training material 7

OFFLOADING OF THE FUEL FROM POOL: OPTIMISE REQUIRED COOLING TIME

Electronic Power Research Institute (EPRI)
“Phenomena Identification and Ranking Table (PIRT) for Decay Heat”,
Final Report, July 2020

“…, there is a desire to offload the fuel as early as possible for economic reasons, since maintaining a Spent Fuel Pool is very costly.”

⇒



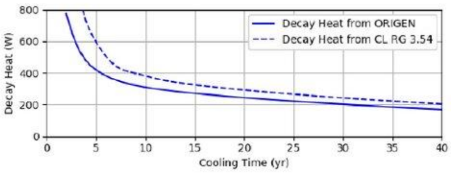
eurad

Training material 8

OFFLOADING OF THE FUEL FROM POOL: OPTIMISE REQUIRED COOLING TIME

Electronic Power Research Institute (EPRI)
"Phenomena Identification and Ranking Table (PIRT) for Decay Heat",
Final Report, July 2020

Difference between regulatory guidelines and SNF specific calculations



Training material

9

SNF MANAGEMENT : STORAGE, TRANSPORT, REPROCESSING AND DISPOSAL

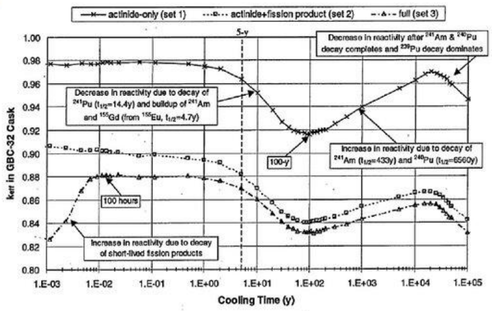


Figure 3 Reactivity behavior in the GBC-32 cask as a function of cooling time for the three classifications of burnup credit (defined in Table 1). The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.

Wagner and Parks, NUREG/CR-6781 (January 2003)
"Recommendations on the credit for cooling time in PWR burnup credit analysis"

Nuclear Criticality Safety (reactivity)

NEA: Woking Party (WPNCS)

- Must be guaranteed based on reliable methods
- Burn-Up Credit (NEA: Expert group EGBUC)
  - Reactivity decreases as fuel BU proceeds: reduction of fissile material and increase of neutron absorbing fission products (FP)
  - Account for this reactivity decrease for criticality safety assessments

⇒ Requires **inventory of key nuclides** and accurate neutron **absorption cross sections**

Training material

10

EURAD WP8: SPENT NUCLEAR FUEL CHARACTERIZATION

- **Nuclide inventory** and related **radiological characteristics** of **SNF** are observables (or measurands) that are determined with an uncertainty
- **Reliable** estimate of the **uncertainty** is required, e.g.
  - to respect the constraint of total decay power < 1700 W
  - to define reliable criticality safety margins

The Orano La Hague reprocessing facility (Photo: Orano)
www.iaea.org

www.skb.com

Training material

11

UNCERTAINTY EVALUATION AND PROPAGATION

Basis: Guides in metrology published by BIPM https://www.bipm.org/en/committees/jc/jcgm/publications

- **GUM: Guide to the expression of Uncertainty in Measurement**
  - **Evaluation of measurements data** **(JCGM 100:2008(E))**
  - Supplement 1 – Propagation of distribution using a Monte Carlo method (JCGM 101:2008)
  - Supplement 2 – Extension to any number of quantities (JCGM 102:2011)
  - An introduction to the "GUM" and related documents (JCGM 104:2009)
  - Guide to the expression of uncertainty in measurement Part 6: Developing and using measurement models (JCGM GUM-6:2020)
- **VIM: International Vocabulary of Metrology**
  - **VIM – Basic and general concepts and associated terms** **(JCGM 200:2012)**

Bureau International des Poids et Mesures

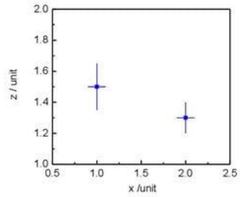
Training material

12

MEASUREMENT UNCERTAINTY

- **Result** of a measurement
  is only an approximation or **estimate of** the value of the **measurand (quantity of interest)** and thus is complete only when **accompanied by** a statement of the **uncertainty** of that estimate

- **Uncertainty** of a measurement
  parameter, associated with the result of a measurement, that characterizes the **dispersion** of the **values** that could reasonably be **attributed** to the **measurand**

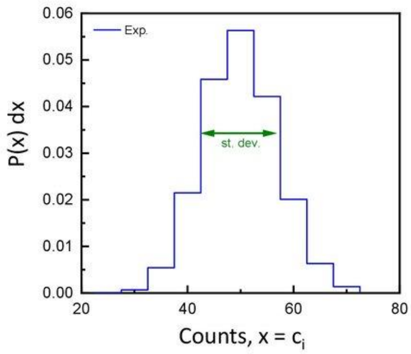


Training material

eurad 13

EXAMPLE: COUNTING EXPERIMENT

c_i : result of a single counting experiment to estimate the counts C

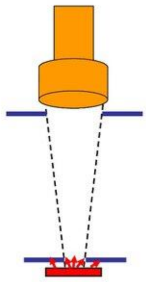


Mean : $c = \frac{1}{m}\sum_{i=1}^{m} c_i$

Variance of mean : $s_c^2 = \frac{s^2(c_i)}{m}$

Variance of a single observation : $s_{c_i}^2 = \frac{1}{m-1}\sum_{i=1}^{m}(c_i - c)^2$

Standard uncertainty is expressed as the standard deviation

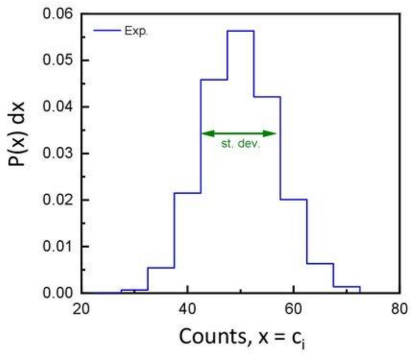


Training material

eurad 14

EXAMPLE: COUNTING EXPERIMENT

c_i : result of a single counting experiment to estimate the counts C



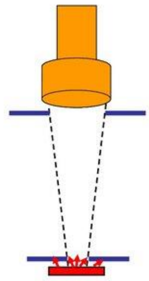
Mean : $c = \frac{1}{m}\sum_{i=1}^{m} c_i$

Variance of mean : $s_c^2 = \frac{s^2(c_i)}{m}$

Variance of a single observation : $s_{c_i}^2 = \frac{1}{m-1}\sum_{i=1}^{m}(c_i - c)^2$

Standard uncertainty of c_i : $u_{c_i} = s_{c_i}$

Standard uncertainty of c : $u_c = \frac{s_{c_i}}{\sqrt{m}}$

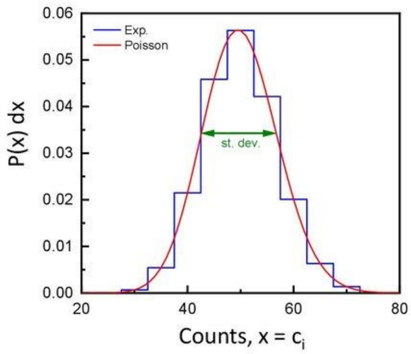


Training material

eurad 15

EXAMPLE: COUNTING EXPERIMENT

c_i : result of a single counting experiment to estimate the counts C



Poisson distribution

$P(c, \mu) = e^{-\mu}\frac{\mu}{c!}$

Mean : μ

Variance : $\sigma^2 = \mu$

Standard deviation : $\sigma = \sqrt{\mu}$

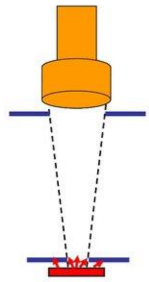
Result of a single counting experiment

Counts : c_i

Uncertainty : $u_{c_i} = \sqrt{c_i}$

$\frac{u_{c_i}}{c_i} = \frac{1}{\sqrt{c_i}}$

Uncertainty due to counting statistics



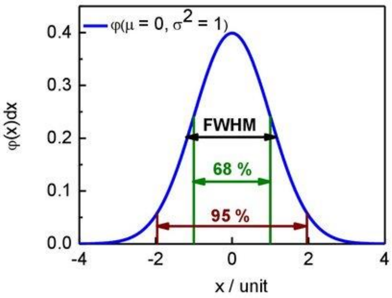
Training material

eurad 16

REPORTING OF UNCERTAINTIES

- Standard (k = 1) or expanded (k > 1) uncertainty (x, u_x) with $u_x = k\ s_x$
  - Standard uncertainty
    k = 1 ⇒ 0.68 %
  - Expanded uncertainty
    k > 1
    e.g. k = 1.96 ⇒ 0.95 %
    k = 2.58 ⇒ 0.99 %
- Reporting example: x = 10.21 with u_x = 0.25
  - k = 1 10.21 (25) or 10.21 (0.25)
  - k > 1 10.21 ± 0.25 (specify k, mostly k = 2)

Note: physicists mostly report a standard uncertainty (k = 1)
chemists mostly report an expanded with k = 2.



Training material

eurad 17

UNCERTAINTY PROPAGATION: INDEPENDENT VARIABLES

(y, u_y), (b, u_b) and (k, u_k) **independent** input quantities ⇒ **estimate** of **(z,u_z)**

$z = y + b \qquad u_z^2 = u_y^2 + u_b^2$

$z = y - b \qquad u_z^2 = u_y^2 + u_b^2$

$z = k\,y \qquad u_z^2 = k^2 u_y^2 + y^2 u_k^2 \qquad \frac{u_z^2}{z^2} = \frac{u_y^2}{y^2} + \frac{u_k^2}{k^2}$

(y, u_y) and constant K ⇒ estimate of Z

$z = K\,y \qquad u_z^2 = K^2 u_y^2 \qquad \frac{u_z^2}{z^2} = \frac{u_y^2}{y^2}$

Training material

eurad 18

LINEAR FUNCTION OF INDEPENDENT VARIABLES

Z : linear function of independent random variables $X_{i=1,\dots,n}$ with a normal PD with (μ_i, σ_i^2)

$$z = \sum_{i=1}^{n} c_i\, x_i \qquad c_i = \left.\frac{\partial f}{\partial x_i}\right|_{\mu_i}$$

$\Rightarrow$ PD of Z = f(X_i; i,...,n) is a normal distribution with

- Mean $E(Z) = \mu_z = \sum_{i=1}^{n} c_i\, \mu_i$
- Variance $V(z) = \sigma_z^2 = \sum_{i=1}^{n} c_i^2\, \sigma_i^2$

eurad

Training material 19

NON-LINEAR FUNCTION OF INDEPENDENT VARIABLES

Z : non-linear function of independent random variables $X_{i=1,\dots,n}$ with a normal PD with (μ_i, σ_i^2)

1[st] order Taylor development

$$z \approx f(\mu_1,\dots,\mu_n) + \sum_{i=1}^{n} g_i\,(x_i - \mu_i) \qquad g_i = \left.\frac{\partial f}{\partial x_i}\right|_{\mu_i}$$

$\Rightarrow$ PD of Z = f(X_i; i,...,n) is a normal distribution with

- Mean $E(Z) = \mu_z \approx f(\mu_1,\dots,\mu_n)$
- Variance $V(z) = \sigma_z^2 \approx \sum_{i=1}^{n} g_i^2\, \sigma_i^2$

eurad

Training material 20

SENSITIVITY ANALYSIS AND UNCERTAINTY PROPAGATION

Z : non-linear function of independent random variables $X_{i=1,\ldots,n}$ with a normal PD with (μ_i, σ_i^2)

1st order Taylor development

$$z \approx f(\mu_1,\ldots,\mu_n) + \sum_{i=1}^{n} g_i\,(x_i - \mu_i) \qquad g_i = \left.\frac{\partial f}{\partial x_i}\right|_{\mu_i}$$

Sensitivity analysis based on partial derivatives: study how the output Z depends on the variables X_i

$$\frac{u_z}{z} = R_{x_i}\,\frac{u_{x_i}}{x_i} \qquad R_{x_i} = \frac{g_i}{\frac{z}{x_i}}$$

$\Rightarrow$ PD of $Z = f(X_i; i,\ldots,n)$ is a normal distribution with

- Mean $E(Z) = \mu_z \approx f(\mu_1,\ldots,\mu_n)$
- Variance $V(z) = \sigma_z^2 \approx \sum_{i=1}^{n} g_i^2\,\sigma_i^2$

Training material

21

SENSITIVITY ANALYSIS AND UNCERTAINTY PROPAGATION: DEPENDENT VARIABLES

Z : non-linear function of dependent random variables $X_{i=1,\ldots,n}$ with a normal PD with $(\vec{\mu}, V_{\vec{x}})$

$$z \approx f(\vec{\mu}_x) + G_{\vec{x}}(\vec{x} - \vec{\mu}_x)$$

$G_{\vec{x}}$: gradient matrix of f

$$g_k = \frac{\partial f}{\partial x_k}$$

- Mean $\mu_z \approx f(\vec{\mu}_x)$
- Variance $V_z \approx G_{\vec{x}}\,V_{\vec{x}}\,G_{\vec{x}}^T$

$\Rightarrow$ basis of General Law of Uncertainty Propagation (GLUP)

(sandwich formula, $V_z = G\,V_x\,G^T$)

Based on normal distributions

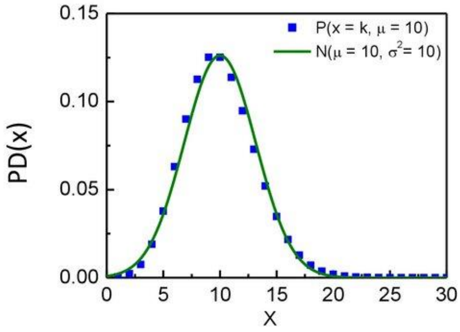
Training material

22

NORMAL DISTRIBUTION ASSUMPTION

(1) Poisson distribution to account for uncertainty due to counting statistics

For large μ the distribution approaches a normal distribution



Poisson : $P(x = k, \mu) = e^{-\mu}\frac{\mu}{k!}$

Normal : $N(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$

Training material

eurad 23

NORMAL DISTRIBUTION ASSUMPTION

(1) Poisson distribution to account for uncertainty due to counting statistics

For large μ the distribution approaches a normal distribution

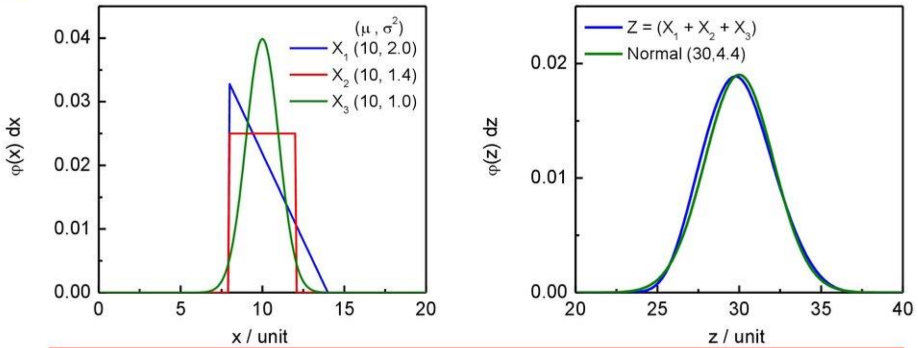
(2) Central limit theorem (CLT)

The sum of a large number of independent random variables with a similar distribution (i.e. width) will be approximately normally distributed

Training material

eurad 24

NORMAL DISTRIBUTION ASSUMPTION: CENTRAL LIMIT THEOREM

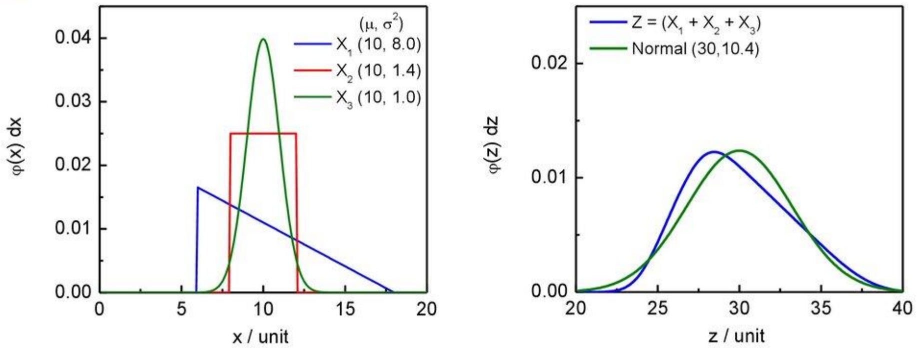


$$Z = \sum_{i=1}^{n} X_i \quad \text{normal distribution with} \quad \mu_Z = \sum_{i=1}^{n} \mu_i \quad \text{and} \quad \sigma_Z^2 = \sum_{i=1}^{n} \sigma_i^2$$

Training material

25

NORMAL DISTRIBUTION ASSUMPTION: CENTRAL LIMIT THEOREM



$\sigma_1 > (\sigma_2 \text{ and } \sigma_3)$ ⇒ combination deviates from a normal distribution

Training material

26

NORMAL DISTRIBUTION ASSUMPTION

(1) Poisson distribution to account for uncertainty due to counting statistics

For large μ the distribution approaches a normal distribution

(2) Central limit theorem (CLT)

The sum of a large number of independent random variables with a similar distribution (i.e. width) will be approximately normally distributed

(3) Principle of maximum entropy (ME)

If only the mean and standard deviation is given, the optimal probability distribution for further inference is the normal distribution

$\Rightarrow$ in most cases normal distribution can be assumed

Training material

eurad 27

ERROR AND UNCERTAINTY

- Measurement error : **difference** between **two values**

  *"**result** of a measurement **minus** a **true value** of the measurand "*

  can be + or -

- Measurement uncertainty : **dispersion** of a distribution

  *"**non-negative parameter** characterizing the **dispersion** of the values being attributed to the measurand"*

  always > 0

  determined by the width of the PD of the uncertainty component(s)

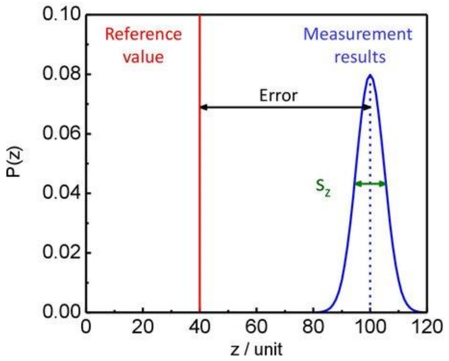
error ≠ uncertainty

Training material

eurad 28

ERROR AND UNCERTAINTY

z : result of a measurement to estimate the value of quantity Z



- Measurement error
  Difference between values
  \+ or -

- Uncertainty
  Derived from the standard deviation (width) of a distribution
  \> 0

Training material

eurad

29

RANDOM AND SYSTEMATIC ERROR

- Random error

  "Result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions."

- Systematic error (bias)

  "Mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand."

  Bias: estimate of a systematic error with respect to a reference value of the same measurand

Training material

eurad

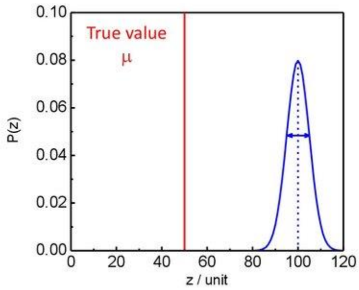
30

$(Y_1, \ldots, Y_N, B) \Rightarrow$ ESTIMATE OF Z = Y - B

Z : measurand, i.e. quantity of interest, with true value μ

y_i : result of a single experiment to estimate true value of Z
all measurements in same conditions (e.g. measurement time,…)

b : correction for background, z = y - b



$$y = \frac{1}{m}\sum_{j=1}^{m} y_j \qquad u_y = \frac{s_{y_j}}{\sqrt{m}}$$

$$s_{y_j}^2 = \frac{1}{m-1}\sum_{i=1}^{m}(y_j - y)^2$$

eurad

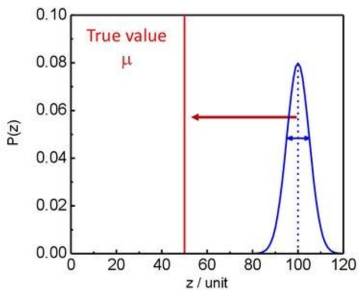
Training material 31

$(Y_1, \ldots, Y_N, B) \Rightarrow$ ESTIMATE OF Z = Y - B

Z : measurand, i.e. quantity of interest, with true value μ

y_i : result of a single experiment to estimate true value of Z
all measurements in same conditions (e.g. measurement time,…)

b : correction for background, z = y - b



$$y = \frac{1}{m}\sum_{j=1}^{m} y_j \qquad u_y = \frac{s_{y_j}}{\sqrt{m}}$$

$$s_{y_j}^2 = \frac{1}{m-1}\sum_{i=1}^{m}(y_j - y)^2$$

z = y - b

$\Rightarrow$ Not correcting for the background results in a systematic error b

eurad

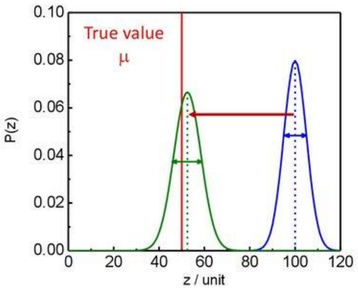
Training material 32

$(Y_1, \ldots, Y_N, B) \Rightarrow$ ESTIMATE OF Z = Y - B

Z : measurand, i.e. quantity of interest, with true value μ

y_i : result of a single experiment to estimate true value of Z
all measurements in same conditions (e.g. measurement time,…)

b : correction for background, z = y - b



$$y = \frac{1}{m}\sum_{j=1}^{m} y_j \qquad u_y = \frac{s_{y_j}}{\sqrt{m}}$$

$$s_{y_j}^2 = \frac{1}{m-1}\sum_{i=1}^{m}(y_j - y)^2$$

$$z = y - b \qquad u_z = \sqrt{\frac{s_{y_j}^2}{m} + u_b^2}$$

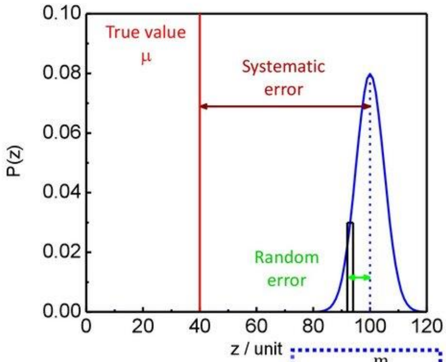
After correction for the systematic effect (e.g. background)
$\Rightarrow$ Additional uncertainty u_b due to a systematic effect

eurad

Training material 33

RANDOM AND SYSTEMATIC ERROR

z_j : result of a single measurement to estimate the value of quantity with true value μ



$$z = \frac{1}{m}\sum_{j=1}^{m} z_j$$

$z_i = \mu + \beta_s + \varepsilon_{r,i}$

- Systematic error : β_s

  $\beta_s = z - \mu$

- Random error : $\varepsilon_{r,i}$

  $\varepsilon_{r,i} = z_i - z$

eurad

Training material 34

MEASUREMENT ACCURACY AND PRECISION

- **Measurement precision**

  *"**Closeness of agreement between** indications or **measured quantity values** obtained by replicate measurements on the same or similar objects under specified conditions"*

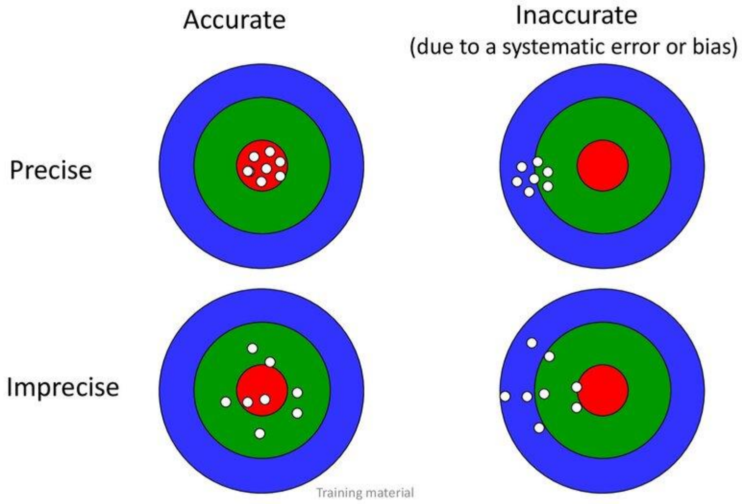
- **Measurement accuracy**

  *"**Closeness of agreement between** a **measured quantity value** and a **true quantity value** of a measurand"*

Training material

35

MEASUREMENT ACCURACY AND PRECISION



Training material

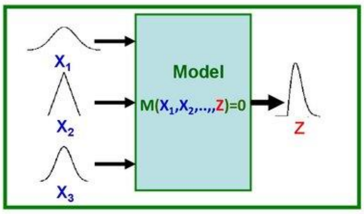
36

ASSUMPTION OF NORMAL DISTRIBUTIONS

Input quantities (X_1, X_2, X_3, …) → Model → Output quantity (measurand) Z

Input

- experimental data
- calibration constants
- influencing quantities
- physics constants, e.g. N_A



Ideally : define Probability Distribution (PD) of (X_1,X_2,X_3, …) and transform into PD of Z by Monte Carlo simulations (stochastic)

Common practice: GLUP (sandwich formula based on normal distributions) in most cases fulfilled, even if the model includes parameter adjustments

⇒ Requires a good understanding of the measurement/calculation process (try always to start from independent input quantities)

Training material

eurad

37

UNCERTAINTY EVALUATION AND PROPAGATION

- Importance of the use of proper definitions and terminology
  e.g. in this work all uncertainties are reported as standard deviations (≈ 68 % confidence limit)
- Methods (statistical analysis) to evaluated and propagate uncertainties are will understood
- Uncertainty evaluation and propagation requires
  - Separation of random and systematic effects
  - Correlated and uncorrelated uncertainty components

⇒ Requires a good understanding of the measurement/calculation process

Training material

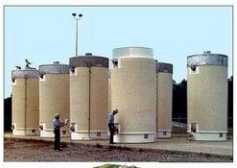
eurad

38

SNF CHARACTERISATION

An accurate characterisation of **Spent Nuclear Fuel** (SNF) is required for a **safe**, **ecological** and **cost effective** operation of the facilities involved in **SNF management** (transport**,** storage, handling, reprocessing and disposal):

- Decay heat
- Neutron emission
- γ-ray emission
- Reactivity (Burn Up Credit (BUC), i.e. Fission Product (FP), actinides)
- Fissile material (Nuclear Safeguards, i.e. ^{235}U, ^{239}Pu)
- Specific nuclides (Long term safety)
  i.e. ^{14}C, ^{36}Cl, ^{79}Se, ^{94}Nb, ^{99}Tc, ^{129}I, ^{135}Cs, ^{226}Ra, ^{237}Np



A reliable determination of these observables including **realistic uncertainties** requires a **good understanding** of the underlying physics **process**

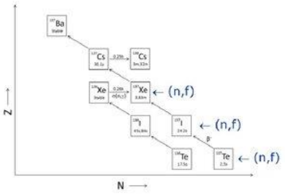
eurad

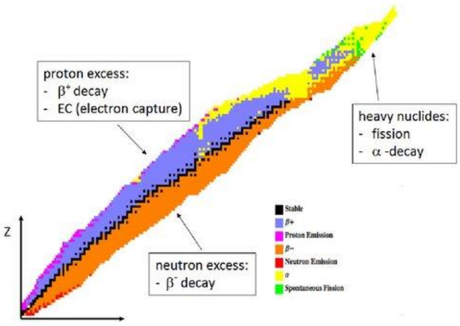
Training material

39

SPENT NUCLEAR FUEL: NUCLIDE INVENTORY

- Fission products (FP): neutron induced fission (n,f)
  e.g. ^{90}Sr, ^{99}Tc, $\mathbf{^{137}Cs}$, ^{154}Eu, …





- Actinides (major and minor): neutron induced capture (n,γ)
  e. g. ^{235}U, $\mathbf{^{238}U}$, $\mathbf{^{239}Pu}$, ^{241}Am, ^{244}Cm, …

$$n + {}^{238}_{92}U \xrightarrow{(n,\gamma)} {}^{239}_{92}U \xrightarrow[23.5\ min]{\beta^-} {}^{239}_{93}Np \xrightarrow[2.36\ d]{\beta^-} {}^{239}_{94}Pu$$

eurad

Training material

40

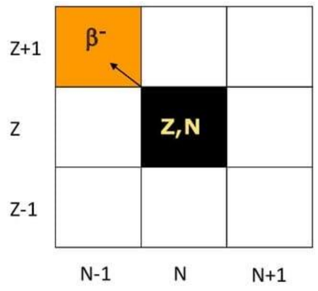
β^- - DECAY BY NEUTRON RICH NUCLIDES

Radioactive decay in which a neutron is transformed into a proton and an electron + anti-neutrino are emitted

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^* + e^- + \bar{\nu}_e$$

$$\downarrow$$

$$^{A}_{Z+1}Y \; + E_\gamma$$

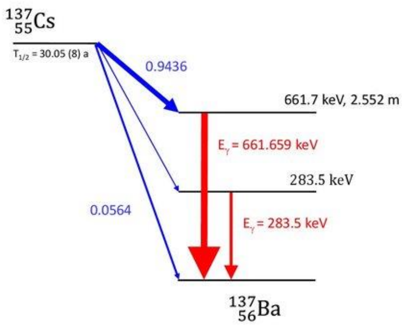


Training material

eurad 41

β^- - DECAY BY NEUTRON RICH NUCLIDES: e.g. ^{137}Cs

- $T_{1/2}$ = 30.05 (8) a
- $Q_{\beta-}$ = 1175.73 (17) keV



$$^{137}_{55}Cs \rightarrow {}^{137}_{56}Ba^* + e^- + \bar{\nu}_e$$

$$\downarrow$$

$$^{137}_{56}Ba \; + E_\gamma$$

Gamma-ray emission probability: P_γ

E_γ	P_γ
661.7 keV	**0.8499 (20)**
283.5 keV	5.8 (8) x 10^{-6}

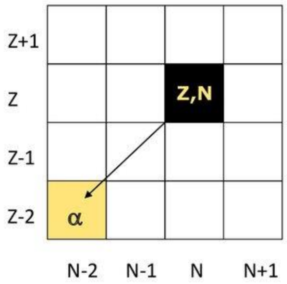
http://www.nucleide.org/DDEP_WG/Nuclides/Cs-137_tables.pdf

Training material

eurad 42

α - DECAY

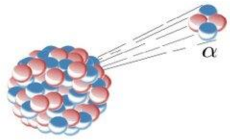
Radioactive decay in which a nucleus **emits** an **α-particle** (^{4}He nucleus) and transforms into a nucleus with 4 less nucleons (2n, 2p)



$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y^{*} + \alpha $$

$$ \downarrow $$

$$ {}^{A-4}_{Z-2}Y + E_{\gamma} $$



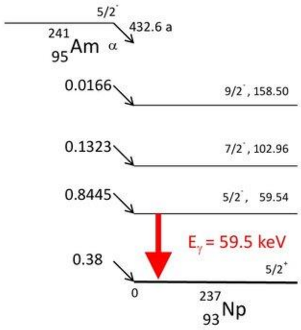
in heavy nuclei

Training material

eurad 43

α - DECAY BY ACTINIDES: e.g. ^{241}Am

- $T_{1/2}$ = 432.6 (6) a
- Q_{α} = 5637.82 (12) keV



$$ {}^{241}_{95}Am \rightarrow {}^{237}_{93}Np^{*} + \alpha $$

$$ \downarrow $$

$$ {}^{237}_{93}Np + E_{\gamma} $$

α -particle emission probability:

E_{α}	$P(E_{\alpha})$
5388.3 keV	0.0166 (3)
5442.9 keV	0.1323 (10)
5485.6 keV	**0.8445 (10)**

http://www.nucleide.org/DDEP_WG/Nuclides/Am-241_tables.pdf

Training material

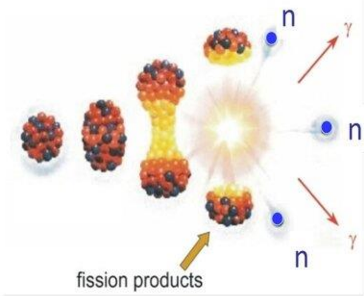
eurad 44

SPONTANEOUS FISSION

Fission: nucleus splits up into fission products (FP)

e.g. ^{238,240,242}Pu(sf), ^{242,244,246}Cm(sf), ^{252}Cf(sf)

- FP : acceleration due to Coulomb repulsion
- FP : strongly excited, emission of
  - Prompt fission neutrons (PFN)
  - Prompt fission γ-rays (PFG)
- Prompt fission neutrons important for Non-Destructive Assay (NDA)



Training material

eurad

45

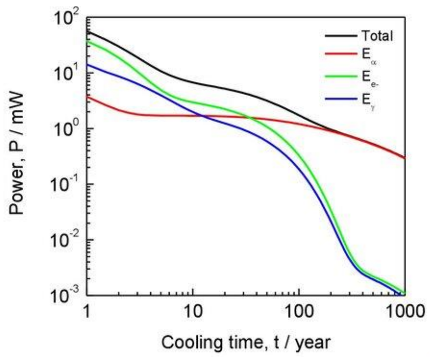
DECAY POWER PRODUCED BY SNF

- Initial enrichment (IE)
  - amount of ^{235}U relative to the total amount of U in the fresh fuel (before irradiation in the reactor)
  - ^{235}U/U mostly expressed in wt%
- Cooling time (CT)
  - Time period since the removal of a reactor (running)
- Burnup (BU)
  - Measure of the total energy production
    $E_{tot} \approx E_{rf} \times N_f$
    E_{tot} : total energy
    E_{fr} : energy per fission
    N_f: total number of fission event
  - Mostly defined as:
    total energy divided by total amount of initial fuel
  - Expressed in MWd/kg
    (time integrated power/amount of initial fuel)

PWR UO_2 pellet (5 g)

^{235}U/U = 4.8 wt%

burnup = 45 MWd/kg



Training material

eurad

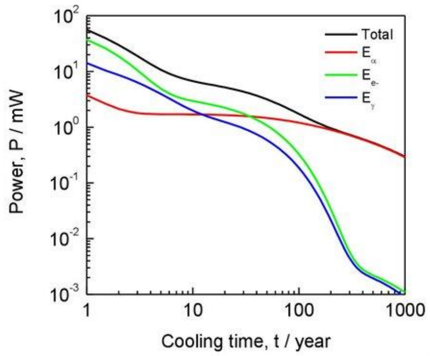
46

DECAY POWER PRODUCED BY SNF

$$P(t) = \sum_k P_k(t)$$

- $P_k(t)$: contribution of radionuclide k
- $P_k(t) = p_k N_k(t)$
  - $N_k(t)$: number of nuclei of nuclide k at time t
  - p_k : specific decay heat rate of nuclide k

PWR UO_2 pellet (5 g)
$^{235}U/U$ = 4.8 wt%
burnup = 45 MWd/kg

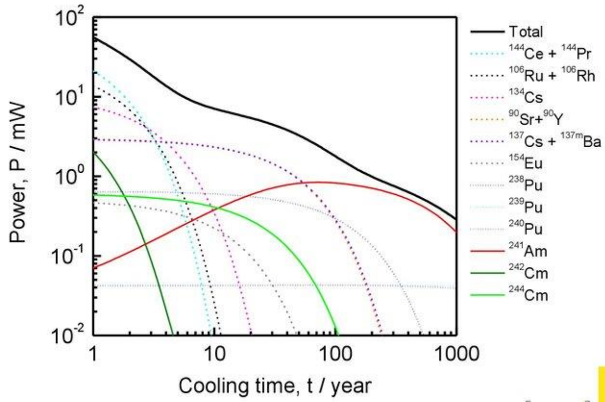


Training material 47

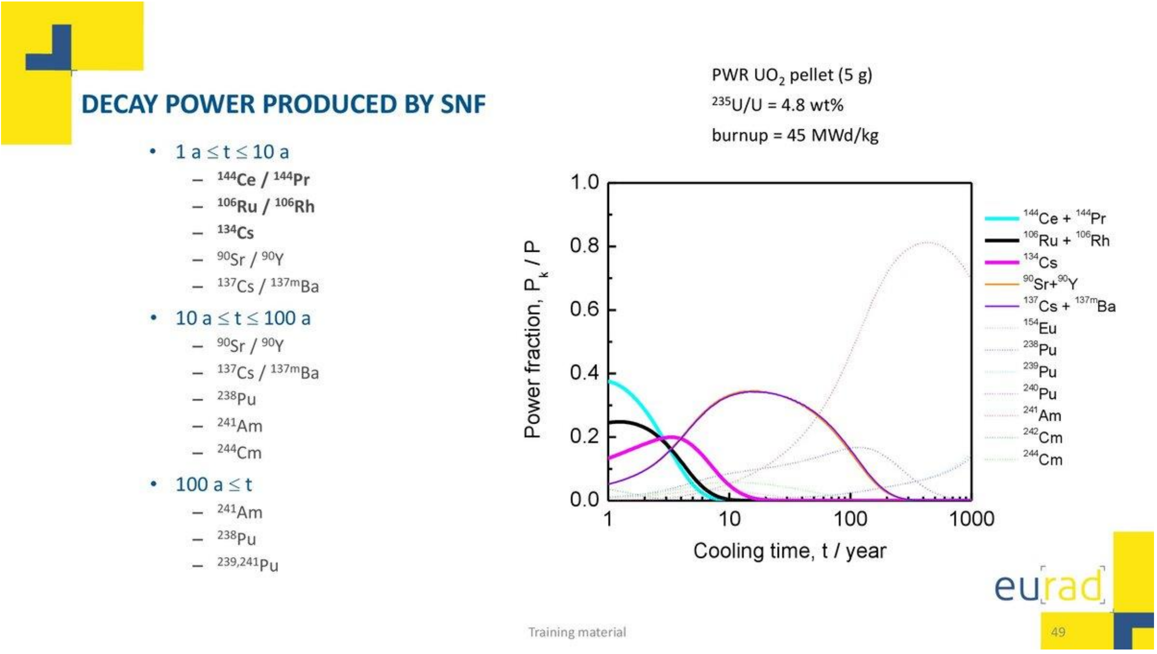
DECAY POWER PRODUCED BY SNF

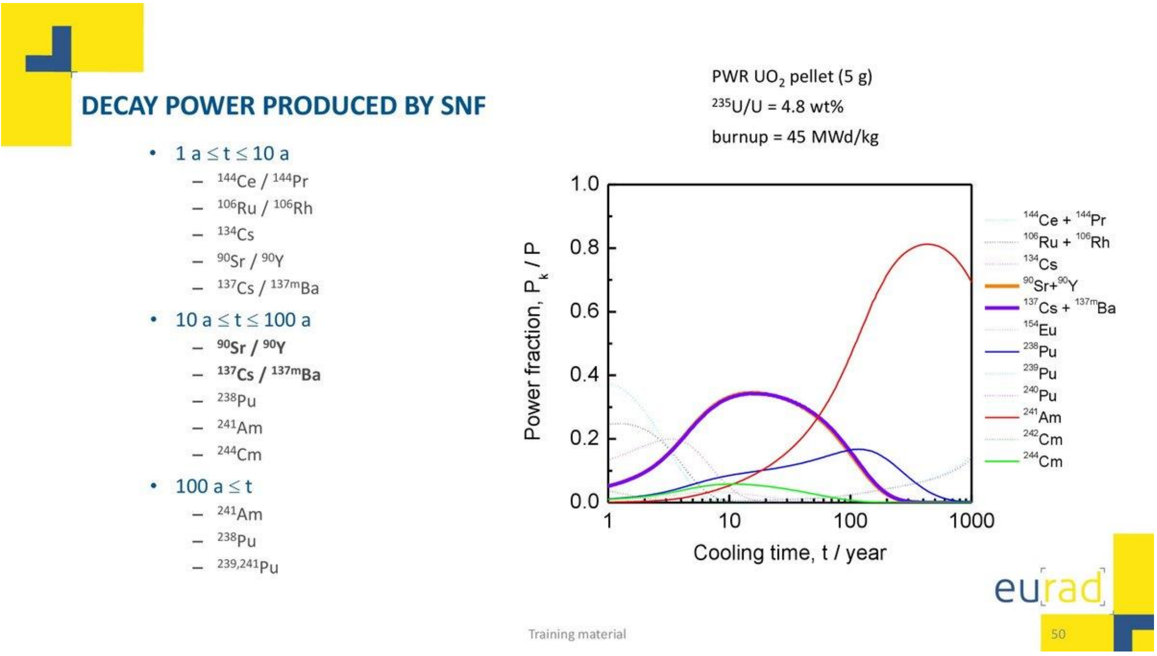
- 1 a ≤ t ≤ 10 a
  - ^{144}Ce / ^{144}Pr
  - ^{106}Ru / ^{106}Rh
  - ^{134}Cs
  - ^{90}Sr / ^{90}Y
  - ^{137}Cs / ^{137m}Ba
- 10 a ≤ t ≤ 100 a
  - ^{90}Sr / ^{90}Y
  - ^{137}Cs / ^{137m}Ba
  - ^{238}Pu
  - ^{241}Am
  - ^{244}Cm
- 100 a ≤ t
  - ^{241}Am
  - ^{238}Pu
  - $^{239,241}Pu$

PWR UO_2 pellet (5 g)
$^{235}U/U$ = 4.8 wt%
burnup = 45 MWd/kg



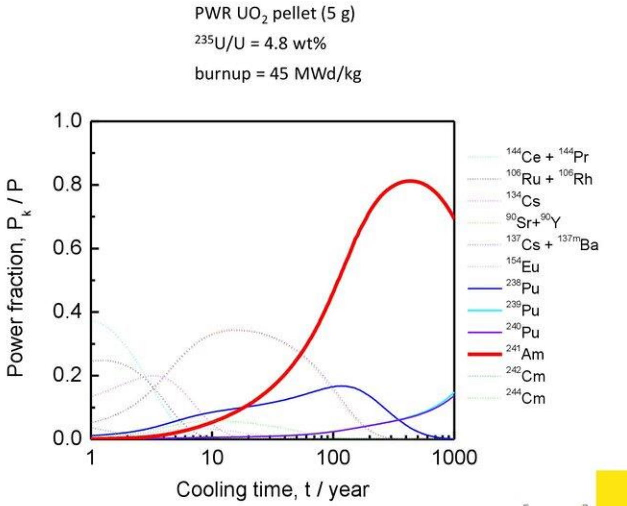
Training material 48


DECAY POWER PRODUCED BY SNF
• 1 a ≤ t ≤ 10 a
– 144Ce / 144Pr
– 106Ru / 106Rh
– 134Cs
– 90Sr / 90Y
– 137Cs / 137mBa
• 10 a ≤ t ≤ 100 a
– 90Sr / 90Y
– 137Cs / 137mBa
– 238Pu
– 241Am
– 244Cm
• 100 a ≤ t
– 241Am
– 238Pu
– 239,241Pu
PWR UO2 pellet (5 g)
235U/U = 4.8 wt%
burnup = 45 MWd/kg
Power fraction, Pk / P
Cooling time, t / year
144Ce + 144Pr
106Ru + 106Rh
134Cs
90Sr+90Y
137Cs + 137mBa
154Eu
238Pu
239Pu
240Pu
241Am
242Cm
244Cm
Training material
eurad
49


DECAY POWER PRODUCED BY SNF
• 1 a ≤ t ≤ 10 a
– 144Ce / 144Pr
– 106Ru / 106Rh
– 134Cs
– 90Sr / 90Y
– 137Cs / 137mBa
• 10 a ≤ t ≤ 100 a
– 90Sr / 90Y
– 137Cs / 137mBa
– 238Pu
– 241Am
– 244Cm
• 100 a ≤ t
– 241Am
– 238Pu
– 239,241Pu
PWR UO2 pellet (5 g)
235U/U = 4.8 wt%
burnup = 45 MWd/kg
Power fraction, Pk / P
Cooling time, t / year
144Ce + 144Pr
106Ru + 106Rh
134Cs
90Sr+90Y
137Cs + 137mBa
154Eu
238Pu
239Pu
240Pu
241Am
242Cm
244Cm
Training material
eurad
50

DECAY POWER PRODUCED BY SNF

- $1\ a \le t \le 10\ a$
  - ^{144}Ce / ^{144}Pr
  - ^{106}Ru / ^{106}Rh
  - ^{134}Cs
  - ^{90}Sr / ^{90}Y
  - ^{137}Cs / ^{137m}Ba
- $10\ a \le t \le 100\ a$
  - ^{90}Sr / ^{90}Y
  - ^{137}Cs / ^{137m}Ba
  - ^{238}Pu
  - ^{241}Am
  - ^{244}Cm
- $100\ a \le t$
  - **^{241}Am**
  - ^{238}Pu
  - $^{239,241}Pu$



eurad

Training material 51

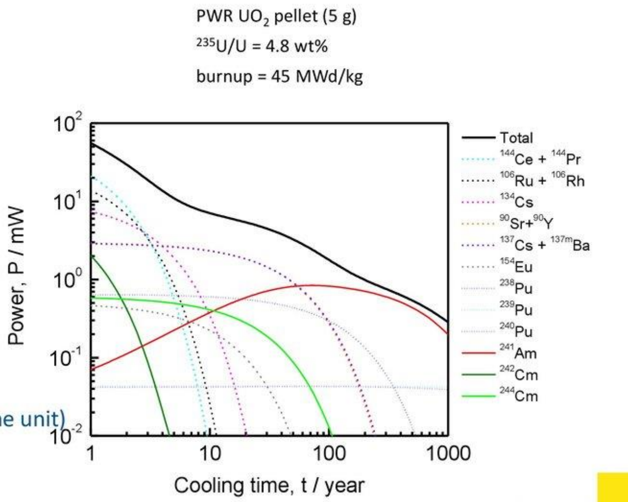
DECAY POWER PRODUCED BY SNF

$$P(t) = \sum_k p_k N_k(t)$$

- $N_k(t)$: number of nuclei at time t
  - $N_k(t_0)$: number of nuclei at time t_0
  - Nuclide vector at $t > t_0$

$$\frac{dN_k}{dt} = \sum_{i \to k} \lambda_i N_i - \lambda_k N_k$$

- $p_k = E_{dk}\ \lambda_k$: specific decay heat rate (nuclear data)
  - λ_k : decay constant (disintegration per time unit)
  - E_{dk} : energy per decay



eurad

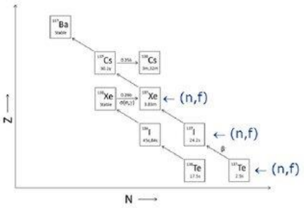
Training material 52

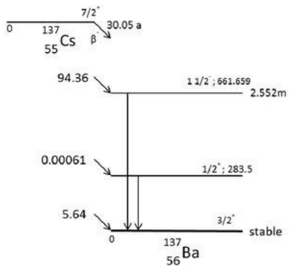
EXAMPLE: ^{137}Cs CONTRIBUTION TO DECAY POWER

Decay power : $P_k(t) = p_k \, Nk(t)$

- Production of ^{137}Cs:
  - (n,f) followed by β^- (decay of short lived precursors)
  - Small neutron capture cross section
  - $\Rightarrow N_k(t_0) \propto$ total number of fission reactions
- Radioactive decay: $p_k = E_{rk} \, \lambda_k$
  - $T_{1/2}$: 30.18 (15) a ($\lambda_k = \ln 2 / T_{1/2}$)
  - Q_{β^-} : 1175.63 (17) keV
  - E_{dk} : recoverable energy
    - Average electron + recoil energy : 247.9 (12) keV
    - $<E_\gamma>$: 565.4 (13) keV

Decay data from DDEP (Decay Data Evaluation Project) : http://www.nucleide.org/DDEP.htm



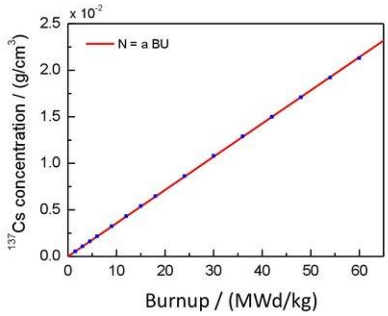


Training material

^{137}Cs: CONTRIBUTION TO DECAY POWER

- Total number of ^{137}Cs nuclei at time t_0: $N_k(t_0) = Y_k \, N_f(t_0)$
  - Y_k : cumulative fission yield
  - $N_k(t_0)$: total number of fission reactions at end of reactor operation
- Burnup, total energy production: $BU = E_{rf} \, N_f(t_0)$
  (BU: time integrated reactor power)
  - $N_f(t_0)$: total number of fission events at end of reactor operation
  - E_{rf} : recoverable energy per fission reaction

$\Rightarrow$ Total number of ^{137}Cs at t_0: $N_k(t_0) \propto BU$



Training material

^{137}Cs : CONTRIBUTION TO THERMAL POWER (UNCERTAINTY EVALUATION)

$P_k(t) = p_k\, N_k(t_0)\, e^{-\lambda_k (t-t_0)}$ $\qquad N_k(t_0) \propto Y_c\, BU$ $\qquad p_k = E_{dk}\, \lambda_k$

$$\Rightarrow \frac{u_{P_k}}{P_k} = = \sqrt{\left(\frac{u_{BU}}{BU}\right)^2 + \left(\frac{u_{Y_c}}{Y_c}\right)^2 + \left(\frac{u_{E_{dk}}}{E_{dk}}\right)^2}$$

- Nuclear data
  - Y_c : cumulative fission yields
  - E_{dk} : recoverable energy
  - λ_k : decay constant (small uncertainty)
- Operational history : BU

Note:

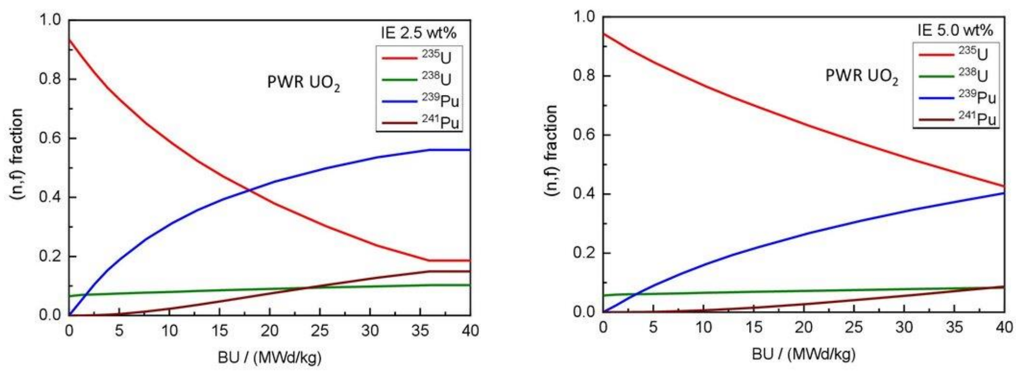
- Contribution of ^{137}Cs and ^{90}Sr: similar
  - simple production path
  - with relatively well determined nuclear data
- Production of e.g ^{134}Cs more complex $\propto BU^b$ with b ~ 2

$$\Rightarrow \frac{u_{N_k}}{N_k} = 2\frac{u_{BU}}{BU}$$

Training material

55

^{137}Cs: CONTRIBUTION OF ^{235}U, ^{239}Pu AND ^{241}Pu



Training material

56

^{137}Cs : NUCLEAR DATA (Y_c,E_d) FOR $^{235}U(n,f)$ AT THERMAL ENERGY

Library	E_d / keV	Ratio	^{137}Cs 100 x Y_c	Ratio	(Y_c x E_d) / keV	Ratio
DDEP/IAEA	811.8 (18)	1	6.221 (69)	1	50.5 (6)	1
JEF-2.2	812.0 (69)	1.000 (8)	6.244 (54)	1.004 (9)	50.7 (6)	1.004 (12)
JEFF-3.1.1	**810.1 (23)**	**0.998 (3)**	**6.221 (69)**	**1.000 (11)**	**50.4 (6)**	**0.998 (11)**
JEFF-3.3	**801.8 (23)**	**0.988 (3)**	**6.090 (63)**	**0.979 (10)**	**48.8 (5)**	**0.967 (10)**
ENDF/B-VI.8	813.4 (41)	1.002 (5)	6.188 (31)	0.995 (5)	50.3 (4)	0.997 (7)
ENDF/B-VII.0	805.7 (16)	0.992 (2)	6.188 (31)	0.995 (5)	49.9 (3)	0.987 (5)
ENDF/B-VIII.0	**805.8 (18)**	**0.993 (2)**	**6.188 (31)**	**0.995 (5)**	**49.9 (3)**	**0.987 (5)**

DDEP: http://www.nucleide.org/DDEP.htm
Evaluated data libraries: https://www.oecd-nea.org/jcms/pl_39910/janis

Training material

eurad 57

^{90}Sr : NUCLEAR DATA (Y_c,E_d) FOR $^{235}U(n,f)$ AT THERMAL ENERGY

Library	E_d / keV	Ratio	^{90}Sr 100 x Y_c	Ratio	(Y_c x E_d) / keV	Ratio
DDEP/IAEA	1129.4 (14)	1	5.730 (130)	1	64.7 (15)	1
JEF-2.2	1129.6 (7)	1.000 (1)	**5.847 (188)**	**1.020 (33)**	**66.0 (21)**	**1.021 (33)**
JEFF-3.1.1	1107.8 (13)	0.981 (1)	5.729 (132)	1.000 (23)	63.5 (15)	0.981 (23)
JEFF-3.3	1127.3 (13)	0.998 (1)	**5.676 (131)**	**0.991 (23)**	**64.0 (15)**	**0.989 (23)**
ENDF/B-VI.8	1129.9 (12)	1.000 (1)	5.782 (58)	1.009 (10)	65.3 (7)	1.010 (10)
ENDF/B-VII.0	1129.4 (13)	1.000 (1)	5.782 (58)	1.009 (10)	65.3 (7)	1.009 (10)
ENDF/B-VIII.0	1128.8 (11)	0.999 (1)	**5.782 (58)**	**1.009 (10)**	**65.3 (7)**	**1.009 (10)**
Ramthum (Exp. 1967)	**1147.0 (90)**					

DDEP: http://www.nucleide.org/DDEP.htm
Evaluated data libraries: https://www.oecd-nea.org/jcms/pl_39910/janis
H. Ramthum, Proc. Symp. Standardization of radionuclides, Oct. (1966) (IAEA, 1967), p. 589

Training material

eurad 58

^{90}Sr and ^{137}Cs: NUCLEAR DATA (Y_c,E_d) FOR ^{235}U(n,f) AT THERMAL ENERGY

Library	^{90}Sr		^{137}Cs	
	(E_d x Y_c) / keV	Ratio	(Y_c x E_d) / keV	Ratio
DDEP/IAEA	64.7 (15)	1	50.5 (6)	1
JEF-2.2	**66.0 (21)**	**1.021 (33)**	**50.7 (7)**	**1.004 (12)**
JEFF-3.1.1	63.5 (15)	0.981 (23)	50.4 (6)	0.998 (11)
JEFF-3.3	**64.0 (15)**	**0.989 (23)**	**48.8 (5)**	**0.967 (10)**
ENDF/B-VI.8	65.3 (7)	1.010 (10)	50.3 (4)	0.997 (7)
ENDF/B-VII.0	65.3 (7)	1.009 (10)	49.9 (3)	0.987 (5)
ENDF/B-VIII.0	**65.3 (7)**	**1.009 (10)**	**49.9 (3)**	**0.987 (5)**

EPRI, PIRT, July 2020

Table 5-5
Summary of Uncertainty in Calculated Decay Heat [17] for BWR Assembly at 37 GWd/MTU Burnup and 15.6 Years' Cooling Time

Perturbed Parameter Set	Relative Uncertainty (%)
Fuel design data	0.2
Operating history data	0.8
Nuclear cross-section data	0.9
Fission yield data	0.3
Overall uncertainty	***1.3***

Ilas et al., Nucl. Eng. Des. 319 (2017) 176

Data set	Data set	Uncertainty (1σ) (%)
Modeling data	Fuel design	0.20
	Operating data	0.85
	Total	0.87
Nuclear data	Cross sections	0.88
	Fission yields	0.26
	Total	0.92
Overall effect	Total	1.27

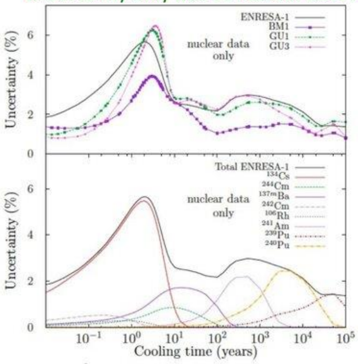
u_P/P = 1.3%, is this realistic?

Training material

59

^{90}Sr and ^{137}Cs: NUCLEAR DATA (Y_c,E_d) FOR ^{235}U(n,f) AT THERMAL ENERGY

Uncertainty only due to nuclear data > 2%



ENRESA-1: BWR
BM1 : MOX
GU1 : PWR
GU3 : PWR

EURAD WP8 Task 2

Rochman et al., Annals of Nuclear Energy 160 (2021) 108539
Rochman et al., EPJ Nuclear Sci. Technolog. 7 (2021) 18
Rochman et al., EPJ Nuclear Sci. Technolog. 8 (2022) 9

EPRI, PIRT, July 2020

Table 5-5
Summary of Uncertainty in Calculated Decay Heat [17] for BWR Assembly at 37 GWd/MTU Burnup and 15.6 Years' Cooling Time

Perturbed Parameter Set	Relative Uncertainty (%)
Fuel design data	0.2
Operating history data	0.8
Nuclear cross-section data	0.9
Fission yield data	0.3
Overall uncertainty	***1.3***

Ilas et al., Nucl. Eng. Des. 319 (2017) 176

Data set	Data set	Uncertainty (1σ) (%)
Modeling data	Fuel design	0.20
	Operating data	0.85
	Total	0.87
Nuclear data	Cross sections	0.88
	Fission yields	0.26
	Total	0.92
Overall effect	Total	1.27

u_P/P = 1.3%, is this realistic? **NO**

Training material

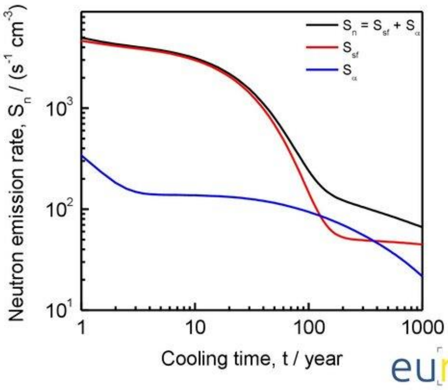
60

NEUTRON EMISSION BY SPENT NUCLEAR FUEL

$$S_n(t) = \sum_k S_{n,k}(t)$$

- $S_{n,k}(t)$: contribution of radionuclide k
- $S_{n,k}(t) = (s_{sf,k} + s_{\alpha n,k})\, N_k(t)$
  - $N_k(t)$: number of nuclei of nuclide k at time t
  - $s_{sf,k}$: specific neutron emission rate of nuclide k due to **spontaneous fission**
  - $s_{\alpha,k}$: specific neutron emission rate of nuclide k due to **(α,n) reactions**

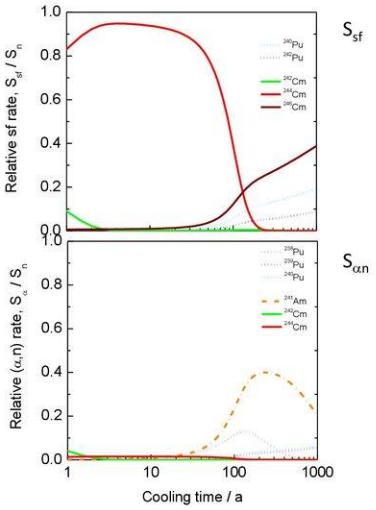
PWR UO_2 pellet (5 g)
$^{235}U/U$ = 4.8 wt%
burnup = 45 MWd/kg



Training material

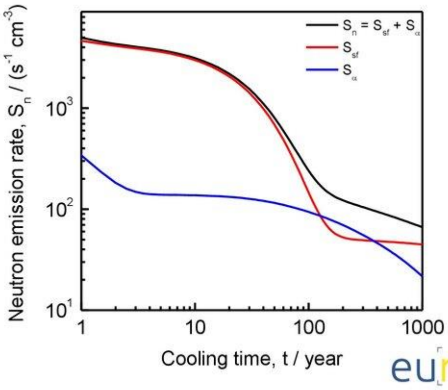
eurad 61

NEUTRON EMISSION BY SPENT NUCLEAR FUEL



PWR UO_2 pellet (5 g)
$^{235}U/U$ = 4.8 wt%
burnup = 45 MWd/kg

⇒ Main contribution from ^{244}Cm(sf)



Training material

eurad 62

^{244}Cm PRODUCTION: COMPLEX PROCESS

$$n + {}^{238}_{92}U \xrightarrow{(n,\gamma)} {}^{239}_{92}U \xrightarrow{\beta^-} {}^{239}_{93}Np + e^- + \bar{\nu}_e$$

$$ {}^{239}_{93}Np \xrightarrow{\beta^-} {}^{239}_{94}Pu + e^- + \bar{\nu}_e$$

$$n + {}^{239}_{94}Pu \xrightarrow{(n,\gamma)} {}^{240}_{94}Pu$$

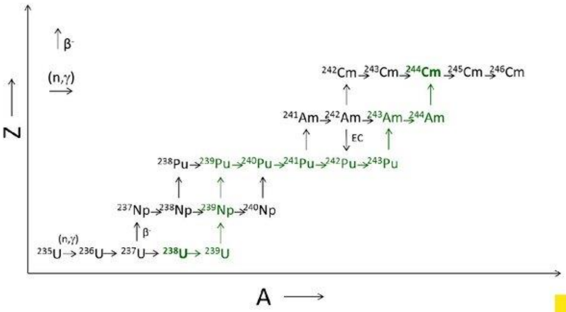
$$n + {}^{240}_{94}Pu \xrightarrow{(n,\gamma)} {}^{241}_{94}Pu$$

$$n + {}^{241}_{94}Pu \xrightarrow{(n,\gamma)} {}^{242}_{94}Pu$$

$$n + {}^{242}_{94}Pu \xrightarrow{(n,\gamma)} {}^{243}_{94}Pu \xrightarrow{\beta^-} {}^{243}_{95}Am + e^- + \bar{\nu}_e$$

$$n + {}^{243}_{95}Am \xrightarrow{(n,\gamma)} {}^{244}_{95}Am \xrightarrow{\beta^-} {}^{244}_{96}Cm + e^- + \bar{\nu}_e$$

Sequence of
- (n,γ) reactions (6)
- β^- decays (4)



SNF SOURCE TERMS

Main **observables** or **source terms** of interest:

- Decay heat : H
- Neutron emission : S_n
- γ-ray emission : S_γ
- Reactivity : ^{235}U, ^{239}Pu, Fission Products (BUC)
- Fissile material : ^{235}U, ^{239}Pu
- Long-term safety : e.g. ^{14}C, ^{36}Cl, ^{79}Se, ^{94}Nb, ^{99}Tc, ^{129}I, ^{226}Ra, ^{237}Np

difficult to be **measured** directly, in particular during **industrial operation**

can not be used to **extrapolate** to evaluate **behaviour** as function of time

SNF SOURCE TERMS: NUCLIDE INVENTORY

Nuclide	Source term	CT
^{90}Sr	H, S_γ	10 a ≤ t ≤ 100 a
^{106}Ru	H	1 a ≤ t ≤ 10 a
^{134}Cs	H	1 a ≤ t ≤ 10 a
^{137}Cs	H, S_γ	10 a ≤ t ≤ 100 a
^{144}Ce	H	1 a ≤ t ≤ 10 a
^{148}Nd	*Burn-up*	*stable*
^{149}Sm	*Power*	*stable*
^{154}Eu	H, S_γ	1 a ≤ t ≤ 10 a

Nuclide	Source term	CT
^{235}U	R, S_γ	10^5 a ≤ t
^{238}U	R, S_γ	10^5 a ≤ t
^{238}Pu	H, S_γ	10 a ≤ t
^{239}Pu	R, S_γ	100 a ≤ t ≤ 10^4 a
^{240}Pu	R, S_γ	100 a ≤ t ≤ 10^4 a
^{241}Pu	H, S_γ	10 a ≤ t ≤ 100 a
^{241}Am	H	10 a ≤ t
^{242}Cm	H, S_n	1 a ≤ t ≤ 10 a
^{244}Cm	H, S_n	10 a ≤ t ≤ 100 a

H : thermal power or decay heat
S_n : neutron emission
S_γ : γ-ray emission
R : reactivity (criticality safety)

Criticality safety (Burn Up Credit, BUC):

^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{143}Nd, ^{147,149,150,151,152}Sm, ^{155}Gd

Long term safety:

^{14}C, ^{36}Cl, ^{79}Se, ^{94}Nb, ^{99}Tc, ^{129}I, ^{135}Cs, ^{226}Ra, ^{237}Np

⇒ Requires **complex nuclide inventory** which can only be obtained by **theoretical calculations**

Training material

65

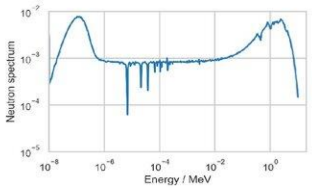
DEPLETION CALCULATIONS/CODES

Coupled neutron transport – nuclide depletion/creation

Neutron transport

↓

Bateman equation



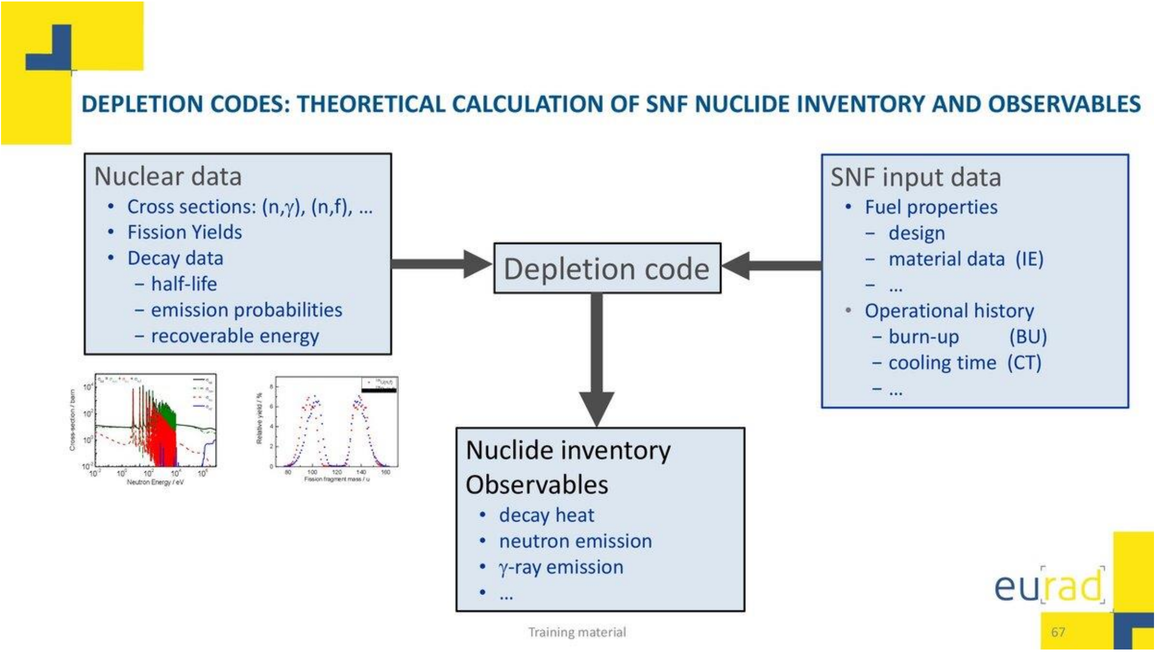
$$\frac{dN_k}{dt} = Y N_f \sigma_f \varphi + \sum_{i \to k} \lambda_i N_i + \sum_{j \to k} \sigma_j N_j \varphi - (\lambda_k + \sigma_{k,a}\varphi) N_k$$

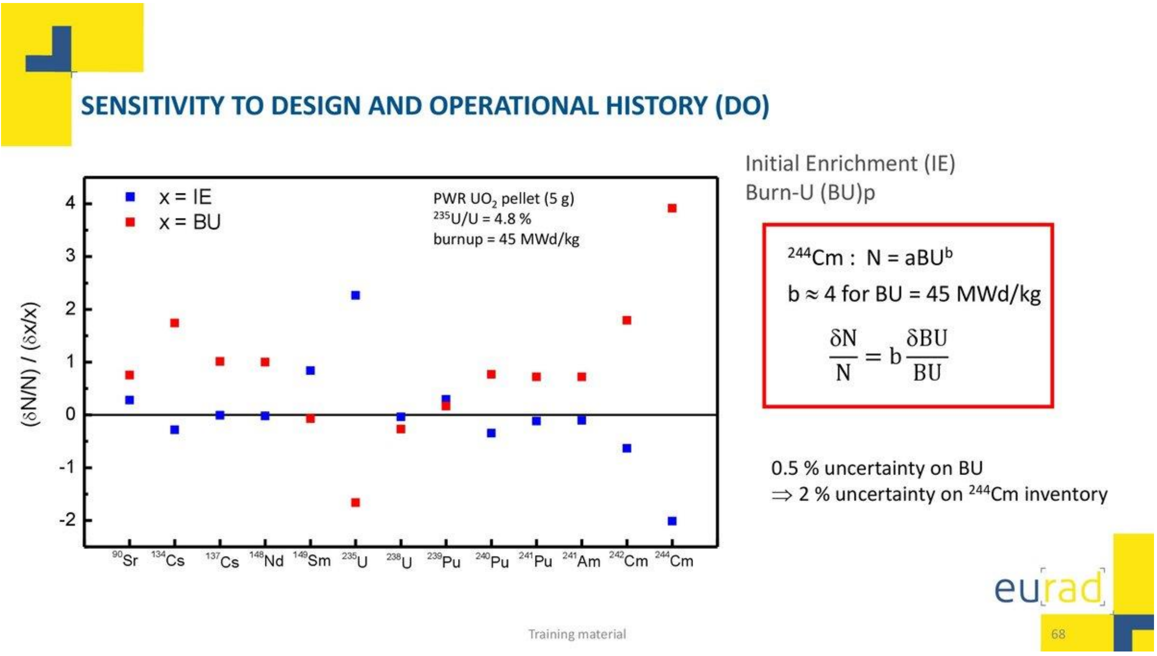
Update nuclide vector

ALEPH2	(SCK CEN)
CASMO	(STUDSVIK)
DARWIN	(CEA)
EVOLCODE	(CIEMAT)
SERPENT	(VTT)
SCALE	(ORNL)
STREAM	(UNIST)
VESTA	(IRSN)

Training material

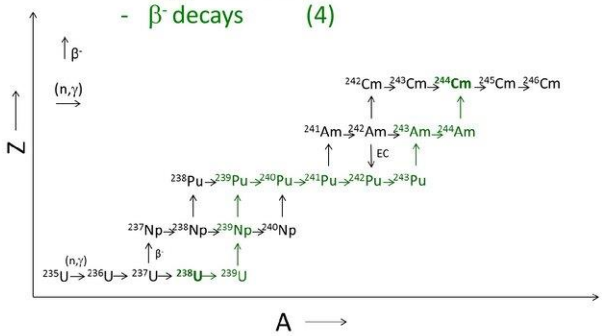
66


DEPLETION CODES: THEORETICAL CALCULATION OF SNF NUCLIDE INVENTORY AND OBSERVABLES
Nuclear data
• Cross sections: (n,γ), (n,f), …
• Fission Yields
• Decay data
– half-life
– emission probabilities
– recoverable energy
Depletion code
SNF input data
• Fuel properties
– design
– material data (IE)
– …
• Operational history
– burn-up (BU)
– cooling time (CT)
– …
Nuclide inventory
Observables
• decay heat
• neutron emission
• γ-ray emission
• …
Training material
eurad
67

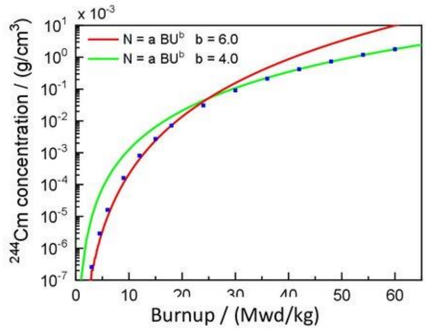

SENSITIVITY TO DESIGN AND OPERATIONAL HISTORY (DO)
x = IE
x = BU
PWR UO2 pellet (5 g)
235U/U = 4.8 %
burnup = 45 MWd/kg
(δN/N) / (δx/x)
90Sr 134Cs 137Cs 148Nd 149Sm 235U 238U 239Pu 240Pu 241Pu 241Am 242Cm 244Cm
Initial Enrichment (IE)
Burn-U (BU)p
244Cm : N = aBU^b
b ≈ 4 for BU = 45 MWd/kg
δN/N = b δBU/BU
0.5 % uncertainty on BU
⇒ 2 % uncertainty on 244Cm inventory
Training material
eurad
68

^{244}Cm PRODUCTION: COMPLEX PROCESS

Sequence of
- (n,γ) reactions (6)
- β^- decays (4)



^{244}Cm : $N = aBU^b$ $\quad \frac{\delta N}{N} = b\frac{\delta BU}{BU}$



DEPLETION CODES/CALCULATIONS

- Nuclide vector $N(t_0)$ at time t_0 after irradiation : burn-up code

Nuclear Data (ND)
- Cross sections
- Fission yields
- Neutron emission probabilities
- Decay data

Fuel History (FH)
- Fuel fabrication data (design, composition) e.g. Initial enrichment (IE)
- Reactor operation and irradiation conditions e.g. Burnup (BU)
- Cooling time (CT)

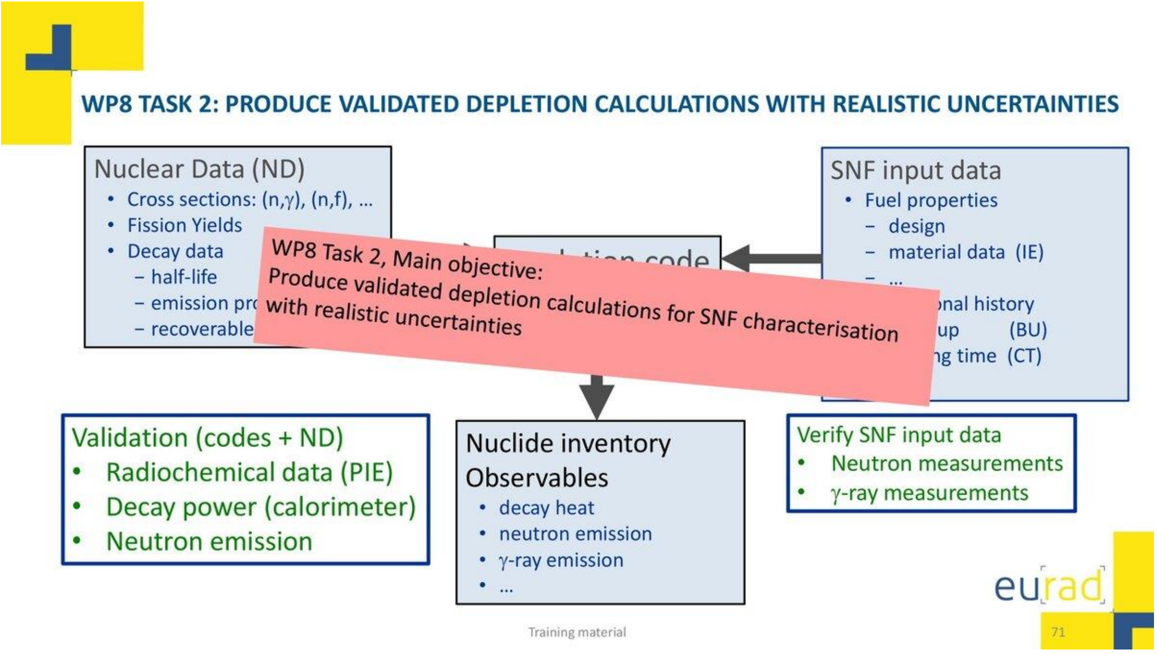
- Nuclide vector at $t > t_0$

$$\frac{dN_k}{dt} = \sum_{i \to k} \lambda_i N_i - \lambda_k N_k$$

- Source terms at $t > t_0$

e.g. $P(t) = \sum_k p_k N_k(t)$

Depends on **decay data** (with relatively low uncertainties)



EXPERIMENTAL DATA TO VALIDATE DEPLETION CODES

⇒ Compare experimental and calculated data

⇒ Identify bias effects in the calculated data:
high quality experimental (reference) data with reliable and low uncertainties are required

$$B = C - E \qquad u_B = \sqrt{(u_C)^2 + (u_E)^2}$$

$$R = \frac{C}{E} \qquad \frac{u_R}{R} = \sqrt{\left(\frac{u_C}{C}\right)^2 + \left(\frac{u_E}{E}\right)^2}$$

Experimental data : E
Calculated data : C

Experimental data (E) can only be used to identify **bias effects** and define realistic confidence limits of calculated results (C) if the experimental value is **a reference value** (based on a reference method)

Training material

eurad 72

EXPERIMENTAL DATA TO VALIDATE DEPLETION CODES

- Results of analytical methods
  (destructive chemical and radiochemical analysis)
- Calorimetry data (assembly)
- Neutron emission measurements

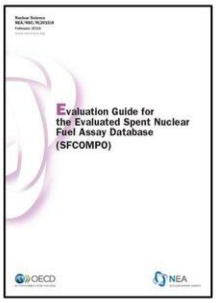
In addition, an accurate knowledge of the design and operational history is required

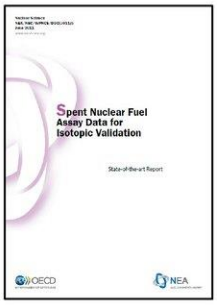
Training material

eurad

73

ANALYTICAL METHODS FOR SNF ASSAY DATA





Post-Irradiation Experiments (PIE)

Complex process including different steps:

- Sampling and sample dissolution
- Separation
  linked to measurement technique, e.g. ICPMS)
- Measurement
  - Radiometric
    (α- and γ-spectrometry, Liquid Scintillation Counting (α- and β-emitters))
  - Mass spectrometry

$\Rightarrow$ Data collected in SFCOMPO data base

Training material

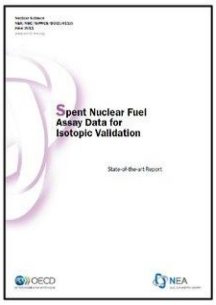
eurad

74

ANALYTICAL METHODS UNCERTAINTIES

Combined uncertainty of

- **Sampling and sample dissolution**
- Separation
- Measurement



eurad

Training material 75

ANALYTICAL METHOD UNCERTAINTIES: EXAMPLES

M: method   % : relative uncertainties   Gauld et al., NUREG/CR-7012, January 2011

Nuclide	PNNL		JAEA		GE-VNC		ANL		Studsvik		SCK CEN		JRC KA		CEA		PSI	
	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%
^{90}Sr	LSC	5.7									LSC	8.0	ICPMS	0.4	TIMS	3.1	ICPMS	3.1
^{137}Cs	γ-sp	3.5	γ-sp	3.0	γ-sp	1.75	γ-sp	4.8	γ-sp	6.4	γ-sp	2.5	ICPMS	1.5	TIMS	3.2	ICPMS	1.9
^{148}Nd			IDMS	0.1	TIMS	0.75	ICPMS	7.1	ICPMS	4.5	TIMS	0.3	ICPMS	6.7	TIMS	3.0	ICPMS	5.0
^{235}U	IDMS	1.6	IDMS	0.1	TIMS	0.5	ICPMS	3.7	ICPMS	8.7	TIMS	1.0	TIMS	1.2	TIMS	3.0	ICPMS	1.9
^{239}Pu	IDMS	1.6	IDMS	0.3	TIMS	0.6	ICPMS	5.7	ICPMS	5.8	TIMS	0.3	TIMS	0.3	TIMS	3.1	ICPMS	4.5
^{244}Cm			MS, α	2.0	TIMS, α	2.75			ICPMS	10.0	α-sp	1.8	ICPMS	6.4	TIMS	3.1	ICPMS	1.5

Methods

- LSC : Liquid scintillation counting(β)
- α : α-spectrometry
- γ-sp : γ-spectrometry
- IDMS : Isotope dilution mass spectrometry
- ICPMS : Inductively coupled plasma mass spectrometry
- MS : mass spectrometry
- TIMS : Thermal ionisation mass spectrometry

Laboratories

- PNNL
- JAEA
- ANL:
- Studsvik
- JRC Karslruhe
- CEA
- PSI

eurad

Training material 76

ANALYTICAL METHOD UNCERTAINTIES: EXAMPLES

M: method   % : relative uncertainties   Gauld et al., NUREG/CR-7012, January 2011

Nuclide	Min	Max
^{90}Sr	0.4 %	8.0 %
^{137}Cs	1.5 %	6.4 %
^{148}Nd	0.1 %	7.1 %
^{235}U	0.1 %	8.7 %
^{239}Pu	0.3 %	5.8 %
^{244}Cm	1.5 %	10.0 %

Uncertainty strongly depends on method and laboratory

Methods
- LSC : Liquid scintillation counting(β)
- α : α-spectrometry
- γ-sp : γ-spectrometry
- IDMS : Isotope dilution mass spectrometry
- ICPMS : Inductively coupled plasma mass spectrometry
- MS : mass spectrometry
- TIMS : Thermal ionisation mass spectrometry

Laboratories
- PNNL
- JAEA
- ANL:
- Studsvik
- JRC Karslruhe
- CEA
- PSI

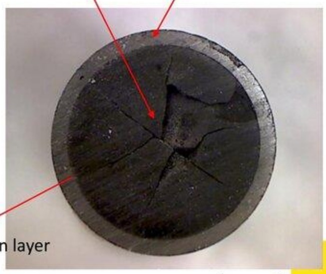
eurad

Training material 77

CLADDING INVENTORY

Cladding composition: important to study fuel integrity (PhD Tobias Köning, August 2022)

- Selection of Zircaloy samples irradiated in a PWR Gösgen (CH) (done)
  (UO2, 50.4 GWd/t, 4 cycles, 3.8%, 32 years cooling time)
  - Zircaloy-4 of UO_x fuel rod segment
  - Zircaloy-4 plenum of UO_X fuel rod segment
  - UO_X fuel fragment
- Experiments using various techniques at KIT
  - Scanning Electron Microscopy (SEM)
  - Wave Length X-ray spectroscopy (WDX)
  - Energy Dispersive X-ray spectroscopy (EDX)
  - X-ray Photo-electron spectroscopy (XPS)
  - Radiochemical analysis (α-spec,γ-spec, LSC, HR-ICP-MS)



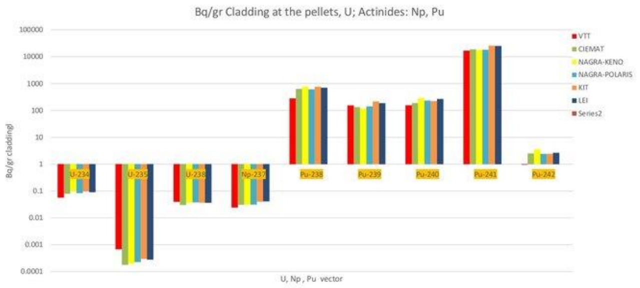
eurad

Training material 78

CLADDING INVENTORY

Code validation

- Calculations
  - MCNP/EVOLCODE CIEMAT,
  - MCNP/CINDER KIT
  - SCALE (TRITON) LEI
  - SCALE (KENO) NAGRA
  - SCALE (POLARIS 2D) NAGRA
  - VTT SERPENT2



- Interpretation of data (in progress)
  - Good agreement for the cladding of the plenum and the cladding around the pellets
  - Singular deviations are being checked for their origin (input issues, code deficiencies, source of uncertainties, …)
  - Comparison with experimental data used to assess how much fuel is adherent to the inner surface of the cladding during manufacturing: important to estimate the risk of radiation damage during interim storage

eurad

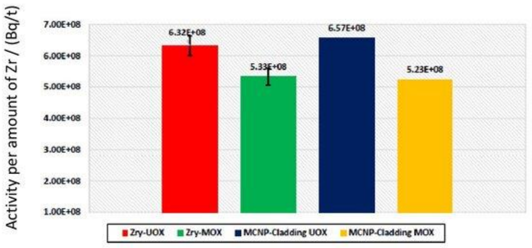
Training material

79

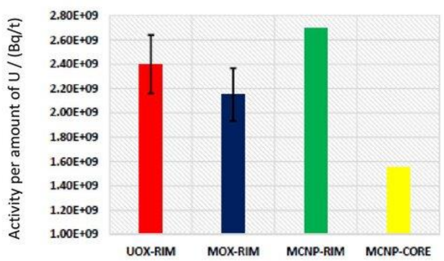
INVENTORY OF ^{36}Cl AND ^{129}I

(PhD Tobias Köning, August 2022)

^{36}Cl activity in Zry-UOx, Zry – MOX
Experimental and calculated (MCNP/CINDER)



^{129}I activity (inventory)
Experimental and calculated (MCNP/CINDER)



- First ever analysis of ^{36}Cl in PWR fuel rod components
- Calculations: 15 ppm ^{35}Cl in fuel and zircaloy
  (Häkkinen, Impurities in LWR fuel and structural materials, Finland 2019)

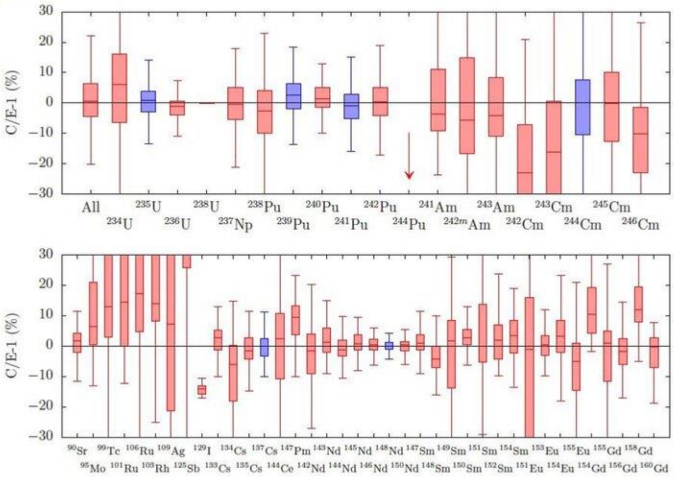
[HÄK19] S. Häkkinen, *Impurities in LWR fuel and structural materials*, VTT, Finland (2019).

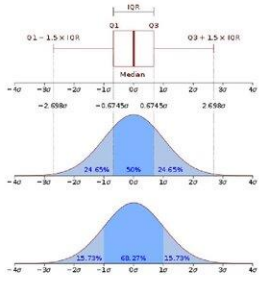
eurad

Training material

80

RADIOCHEMICAL ANALYSIS: ANALYSIS OF PUBLISHED DATA





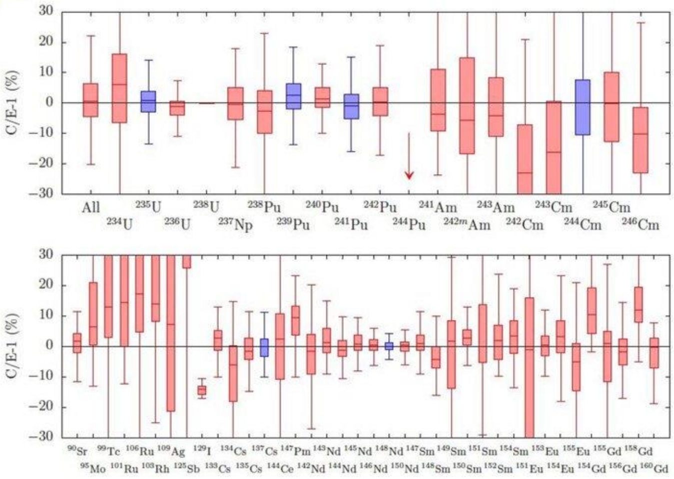
Boxplot: wikipedia

EURAD
Rochman et al., accepted in EPJ Nuclear Sci. Technol.

Training material

81

RADIOCHEMICAL ANALYSIS: ANALYSIS OF PUBLISHED DATA



- C : calculated inventory
- E : experimental inventory

(without any selection criterion)

	<C/E>	Std. x 100
^{90}Sr	0.992	8.2
^{137}Cs	0.996	5.2
^{148}Nd	*0.999*	*2.9*
^{235}U	1.002	7.9
^{239}Pu	1.025	7.9
^{244}Cm	1.020	24.0

EURAD
Rochman et al., accepted in EPJ Nuclear Sci. Technol.

Training material

82

RADIOCHEMICAL ANALYSIS: ANALYSIS OF PUBLISHED DATA

Most of the data are normalised to the ^{148}Nd inventory

- C : calculated inventory
- E : experimental inventory

(without any selection criterion)

	<C/E>	Std. x 100
^{90}Sr	0.992	8.2
^{137}Cs	0.996	5.2
^{148}Nd	*0.999*	*2.9*
^{235}U	1.002	7.9
^{239}Pu	1.025	7.9
^{244}Cm	1.020	24.0

EURAD
Rochman et al., accepted in EPJ Nuclear Sci. Technol.

Training material

eurad 83

RADIOCHEMICAL ANALYSIS: ANALYSIS OF PUBLISHED DATA

Data without any selection criterion

- Experimental data that can be biased and have large uncertainties have the same contribution compared to accurate data with low uncertainties
- Presence of dependent calculated data based on e.g. the same
  - Nuclear data library
  - Model assumptions
  - ...

- C : calculated inventory
- E : experimental inventory

(without any selection criterion)

	<C/E>	Std. x 100
^{90}Sr	0.992	8.2
^{137}Cs	0.996	5.2
^{148}Nd	*0.999*	*2.9*
^{235}U	1.002	7.9
^{239}Pu	1.025	7.9
^{244}Cm	1.020	24.0

EURAD
Rochman et al., accepted in EPJ Nuclear Sci. Technol.

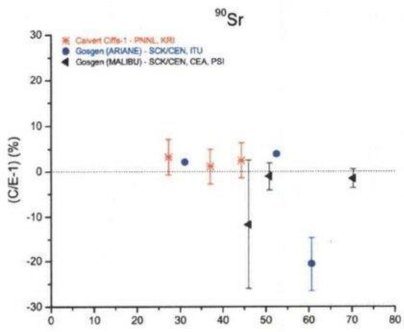
Training material

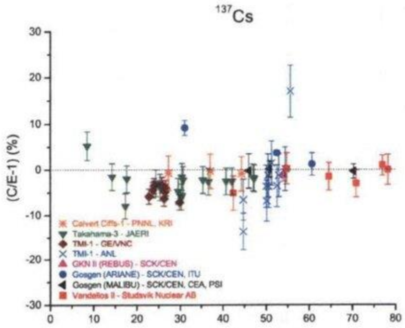
eurad 84

DETAILED STUDY ORNL

Gauld et al., NUREG/CR-7012, January 2011

- Selection of high quality experimental data
- One calculation code and library:
  SCALE 5.1 (TRITON/NEW) & ENDF/B-V





Training material

85

RADIOCHEMICAL ANALYSIS: ANALYSIS OF PUBLISHED DATA

	<C/E>	Std. x 100	<C/E>	Std. x 100
^{90}Sr	0.975	8.4	0.992	8.2
^{137}Cs	0.978	4.4	0.996	5.2
^{148}Nd			*0.999*	*2.9*
^{235}U	1.015	6.4	1.002	7.9
^{239}Pu	1.058	6.1	1.025	7.9
^{244}Cm	0.976	11.1	1.020	24.0

Gauld et al., NUREG/CR-7012
SCALE 5.1, ENDF/B-V

EURAD
Rochman et al.,
accepted in EPJ Nuclear Sci. Technol.

Training material

86

RADIOCHEMICAL ANALYSIS: ANALYSIS OF PUBLISHED DATA

	<C/E>	Std. x 100	<C/E>	Std. x 100	<C/E>	Std. x 100
^{90}Sr	0.975	8.4	0.991	6.9	0.992	8.2
^{137}Cs	0.978	4.4	0.993	3.1	0.996	5.2
^{148}Nd			*1.006*	*1.4*	*0.999*	*2.9*
^{235}U	1.015	6.4	1.012	3.5	1.002	7.9
^{239}Pu	1.058	6.1	1.041	3.5	1.025	7.9
^{244}Cm	0.976	11.1	0.956	11.1	1.020	24.0
	Gauld et al., NUREG/CR-7012 SCALE 5.1, ENDF/B-V		G. Ilas, ORNL/SPR-2019/1143 SCALE 6.1, ENDF/B-VII		EURAD Rochman et al., accepted in EPJ Nuclear Sci. Technol.	

Training material

eurad

87

RADIOCHEMICAL ANALYSIS: ANALYSIS OF PUBLISHED DATA

	<C/E>	Std. x 100	<C/E>	Std. x 100
^{90}Sr	0.975	8.4	0.991	6.9
^{137}Cs	0.978	4.4	0.993	3.1
^{148}Nd			*1.006*	*1.4*
^{235}U	1.015	6.4	1.012	3.5
^{239}Pu	1.058	6.1	1.041	3.5
^{244}Cm	0.976	11.1	0.956	11.1
	Gauld et al., NUREG/CR-7012 SCALE 5.1, ENDF/B-V		G. Ilas, ORNL/SPR-2019/1143 SCALE 6.1, ENDF/B-VII	

Results not consistent with

EPRI, PIRT, July 2020

Table 5-5
Summary of Uncertainty in Calculated Decay Heat [17] for BWR Assembly at 37 GWd/MTU Burnup and 15.6 Years' Cooling Time

Perturbed Parameter Set	Relative Uncertainty (%)
Fuel design data	0.2
Operating history data	0.8
Nuclear cross-section data	0.9
Fission yield data	0.3
Overall uncertainty	***1.3***

Ilas et al., Nucl. Eng. Des. 319 (2017) 176

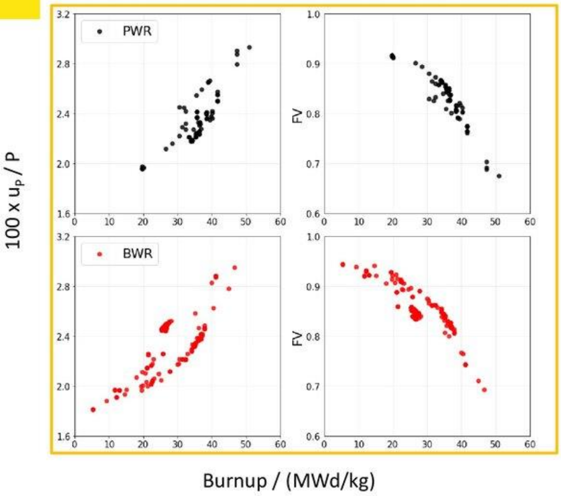
Data set	Data set	Uncertainty (1 σ) (%)
Modeling data	Fuel design	0.20
	Operating data	0.85
	Total	0.87
Nuclear data	Cross sections	0.88
	Fission yields	0.26
	Total	0.92
Overall effect	Total	1.27

eurad

Training material

88

CALCULATED DECAY POWER: UNCERTAINTY EVALUATION



EURAD
Shama et al., Nucl Eng. And Technol. 53 (2021) 2816

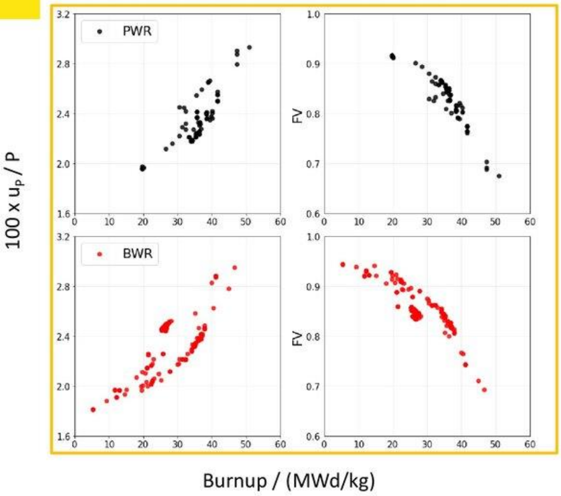
P : calculated decay power
u_P : total uncertainty due to
- Nuclear data (ND)
- Design and operational history (DO)

FV : fraction of variance due to DO

Training material

89

CALCULATED DECAY POWER: UNCERTAINTY EVALUATION



EURAD
Shama et al., Nucl Eng. And Technol. 53 (2021) 2816

Design and operational history
NEA/NSC/R(2015)8
Evaluation Guide for SFCOMPO
- **BU : 1.7 %**
- Others see table

Table 4
Uncertainties in DO variables of the analyzed SFAs, based on [24].

Parameter [a]	Uncertainty/Tolerance [24]	1 σ (this work)
Cladding/tube thickness	±40–50 μm	16.7 μm [c]
Cladding/tube diameter	±200 μm (PWR)/± 300 μm (BWR)	67 μm/100 μm [c]
Fuel pellet density	<2% the theoretical density	0.67% [c]
Fuel pellet diameter	±20 μm	[b]
Enrichment (U-235 wt%)	±0.05%	0.0167% [c]
SFA powers	–	1.67%
Water temp. (PWR only)	±2 °C	2 °C
Water density (PWR only)	±0.005 g/cm³	0.005 g/cm³
Void fraction (BWR only)	±6%	6%
Fuel temp.	±50 °C	50 °C
Boron content (PWR only)	±10 ppm	10 ppm

Training material

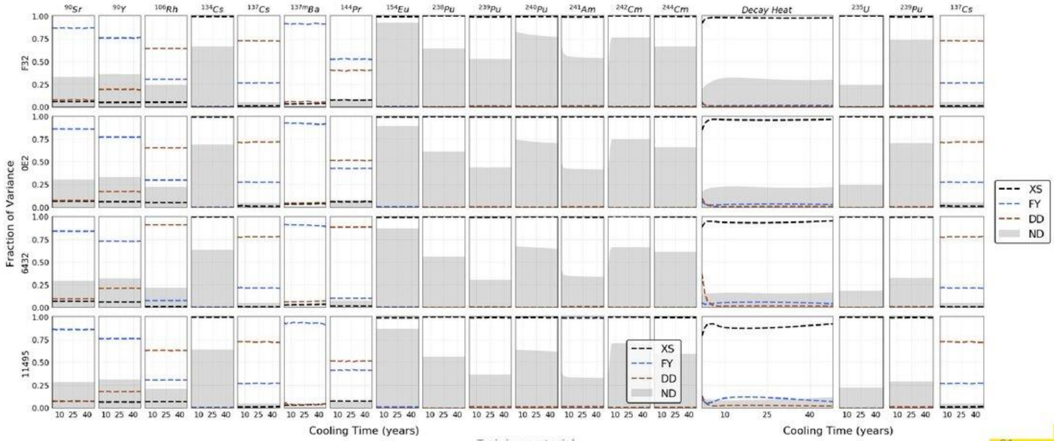
90

CALCULATED DECAY POWER: UNCERTAINTY EVALUATION

Contribution of XS, FY, DD, also contribution of ND and DO parameters

EURAD

Shama et al., Nucl Eng. And Technol. 53 (2021) 2816



Training material

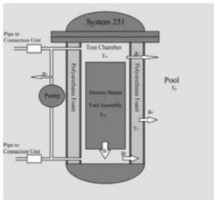
91

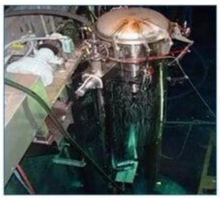
VALIDATION OF CALCULATIONS: CLAB CALORIMETER

- Only operating calorimeter worldwide to determine decay power of SNF assemblies

- Extensively used to validate depletion codes, e.g.
  - Ilas and Burns, Nucl. Tech. 208 (2022) 403 — SCALE 6.2.4
  - Shama et al., Ann. Nucl. Energy 165 (2022) 108758 — ORIGE, CASMO5
  - Ebiwonjumi et al., Ann. Nucl. Energy 124 (2019) 80 — STREAM
  - Yamamoto and Iwahashi J. Nucl. Sci. Techol. 53 (2016) 2108 — ORIGEN2.2, CASMO5
  - Haeck and Ichou, EPJ Web of Conferences 146 (2017) 06012 — VESTA
  - San-Felice et al., Nucl. Technol. 184 (2013) 217 — DARWIN

  Summary in Rochman et al., EPJ Nucl. Sci. Technol. accepted for publication





eurad

Training material

92

DATA FROM CLAB CALORIMETER: SOME RESULTS

Ref.	Year	Code	Library	PWR		BWR	
				<C/E>	St. dev	<C/E>	St. dev
Ilas and Gauld	2008	SCALE 5.1	ENDF/B-V	1.011	0.012	1.003	0.025
Ilas et al.	2014	SCALE 6.1.2	ENDF/B-VII.0	1.002	0.012	0.997	0.024
Ilas and Burns	2021	SCALE 6.2.4	ENDF/B-VII.0	1.013	0.013	1.002	0.012
	2021	SCALE 6.2.4	ENDF/B-VII.1	1.008	0.012	1.009	0.024
Ilas and Burns	2022	SCALE 6.3	ENDF/B-VIII.0	1.006	0.014	1.007	0.024
Shama et al.	2022	SCALE 6.2.3	ENDF/B-VII.1	1.019	0.012	1.003	0.025
		SCALE 6.2.3 (POLARIS)	ENDF/B-VII.1	1.015	0.012	1.010	0.026
Shama et al.	2022	CASMO5		1.009	0.013	1.008	0.025
Yamamoto	2016	CASMO5	JENDL-4.0	1.016	0.013	1.001	0.024
Haeck et al.	2022	VESTA 2.1	JEFF-3.1	0.978	0.012		
		VESTA 2.1	ENDF/B-VII.0	0.996	0.012		
San-Felice et al.	2012	DARWIN	JEFF-3.1.1	0.978	0.011		

Not blind!

Normalisation not specified

Adjustments not excluded

Training material

eurad

93

BLIND TEST CLAB CALORIMETER

NUCLEAR SCIENCE AND ENGINEERING · VOLUME 196 · 1125–1145 · SEPTEMBER 2022
© 2022 The Author(s). Published with license by Taylor & Francis Group, LLC.
DOI: https://doi.org/10.1080/00295639.2022.2053489

ANS

Blind Benchmark Exercise for Spent Nuclear Fuel Decay Heat

- PWR assemblies
- Decay heat rate determined at CLAB

Assembly ID	BU	CT	IE	Decay heat rate	Gamma-escape
BT01	53 MWd/kg	4.5 a	3.95 wt%	1662 W	58 W
BT02	55 MWd/kg	8.6 a	3.95 wt%	1068 W	30 W
BT03	50 MWd/kg	9.8 a	3.95 wt%	895 W	21 W
BT04	51 MWd/kg	13.5 a	3.70 wt%	768 W	15 W
BT05	50 MWd/kg	21.4 a	3.60 wt%	663 W	12 W

Training material

eurad

94

BLIND TEST CLAB CALORIMETER: CODES + LIBRARIES

Code	Library	Appendix Section
ALEPH 2.7.2	ENDF/B-VII.1	A.I.A
APOLLO2.8/DARWIN2.3	JEFF-3.1.1	A.I.B
CASMO-4E + ORIGEN-S	JEF-2.2	A.I.C
CASMO-5 (2.03)	ENDF/B-VII.1	A.I.D
CASMO-5 (2.12.00) + SNF (1.07.02)	ENDF/B-VII.1	A.I.E
DRAGON 4.0.5	ENDF/B-VII.1	A.I.F
EVOLCODE (MCNP + ACAB)	JEFF-3.3	A.I.G
MCNP-CINDER + Nukleonika (2D)	ENDF/B-VII.1	A.I.H
Monteburns v3 + CINDER	ENDF/B-VII.1	A.I.I
MOTIVE (KENO-VI + VENTINA)	ENDF/B-VII.1	A.I.J
MOTIVE (OpenMC + VENTINA)	ENDF/B-VIII	A.I.K
MVP 3	ENDF/B-VII.1	A.I.L
MVP 3	JEFF-3.2	A.I.M
MVP 3	JENDL-4.0	A.I.N
OREST	JEF-2.2 + ENDF/B-VI	A.I.O
SCALE 6.0: ORIGEN-ARP	ENDF/B-V	A.I.P
SCALE 6.1.3: ORIGEN-ARP	ENDF/B-V	A.I.Q
SCALE 6.2.3: ORIGAMI	ENDF/B-VII.1	A.I.P
SCALE 6.2.3: Polaris	ENDF/B-VII.1	A.I.R
SCALE 6.2.3: ORIGEN	ENDF/B-VII.1	A.I.R
SCALE 6.2.3: TRITON/KENO	ENDF/B-VII.1	A.I.S
SCALE 6.2.3: TRITON/NEWT	ENDF/B-VII.1	A.I.T
SEADEP	JEFF-3.1.1	A.I.U
Serpent 2.1.29	ENDF/B-VII.1	A.I.V
Serpent 2.1.29	JEFF-3.1.1	A.I.W
Serpent 2.1.31	JEFF-3.2 + JEFF-3.1.1	A.I.X

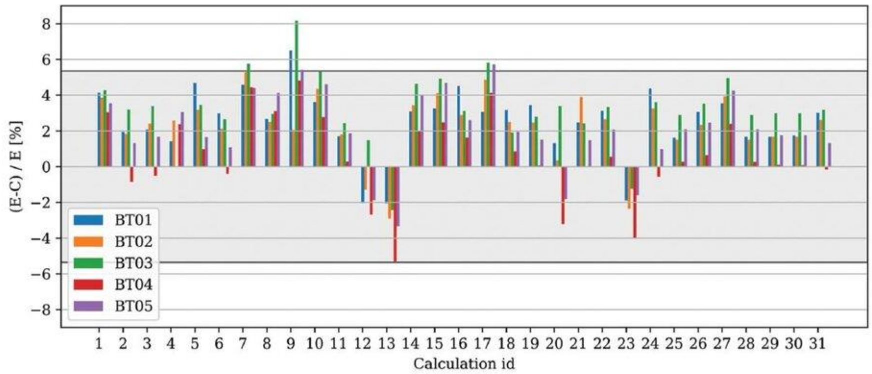
Training material

eurad

95

BLIND TEST CLAB CALORIMETER: RESULTS

Assembly ID	P	CT	<C/E>	St. dev
BT01	1662 W	4.5 a	0.975	0.019
BT02	1068 W	8.6 a	0.977	0.018
BT03 (+ Gd)	895 W	9.8 a	0.967	0.019
BT04	768 W	13.5 a	0.994	0.023
BT05	663 W	21.4 a	0.979	0.021



Training material

eurad

96

DATA FROM CLAB CALORIMETER (R-05-62)

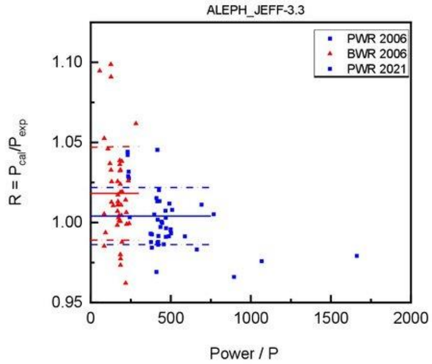
EURAD Task 2: systematic study of published calorimeter data

Compare different codes/libraries

- Total number of fissions
- Inventory of key nuclides
- Calculate decay power using recommended decay data

Paper on preparation
Romojaro et al., SCK CEN, IRSN, JSI, JRC, PSI, NAGRA

Code	Library	PWR		BWR	
		<C/E>	St. dev	<C/E>	St. dev
SCALE	(R-05-62)	1.011	0.012	1.003	0.025
ALEPH2	JEFF-3.1.2	1.001	0.020	1.013	0.031
ALEPH2	JEFF-3.3	1.004	0.018	1.018	0.029
ALEPH2	JEFF-4T0	1.006	0.018	1.020	0.030



EURAD Task 2:

additional blind test exercise using SKB-50 data

eurad

Training material 97

UNCERTAINTY OF CALORIMETRY DATA

- Blind test paper (Jansson et al., Nucl. Sci. Eng. 196 (2022) 1125)

  5% overall uncertainty

- SKB Document R-05-62 (also used in EPRI, PRIT report)
  - PWR

250 W	1.8 %
900 W	1.0 %

  - BWR

50 W	4.2 %
350 W	1.0 %

Only total (combined uncertainties) are given
No separation between

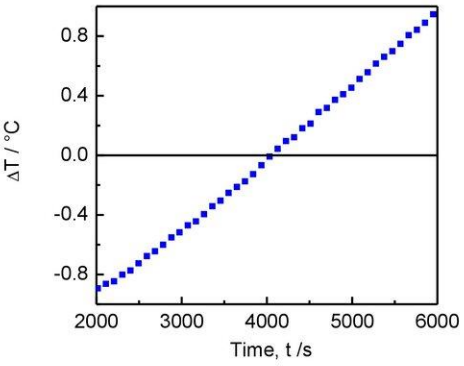
- Systematic and random effects
- Correlated and uncorrelated uncertainty components

⇒ Performance assessment and uncertainty evaluation of CLAB calorimeter is required
⇒ One of the main EURAD objectives of WP8 Task 2

eurad

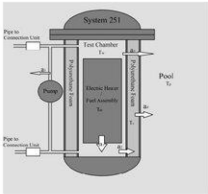
Training material 98

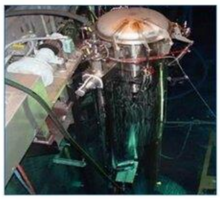
CALORIMETER AT CLAB: DECAY POWER OF FUEL ASSEMBLIES



Experimental observable

- Determine $\Delta T = T_c - T_p$ vs time

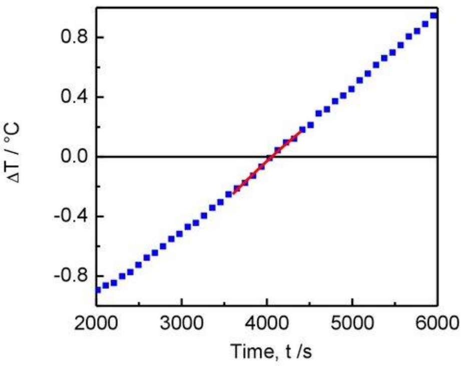




Training material

99

CALORIMETER AT CLAB: DECAY POWER OF FUEL ASSEMBLIES



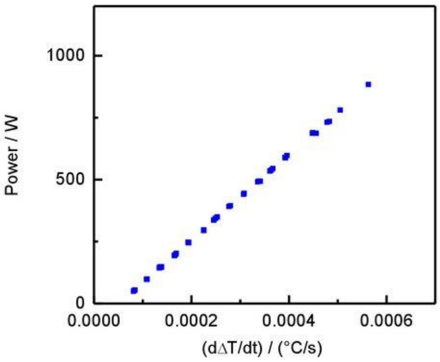
Experimental observable

- Determine $\Delta T = T_c - T_p$ vs time
- Determine $d\Delta T/dt$ for $\Delta T = 0$

Training material

100

CALORIMETER AT CLAB: DECAY POWER OF FUEL ASSEMBLIES



Calibration with an electrical heater

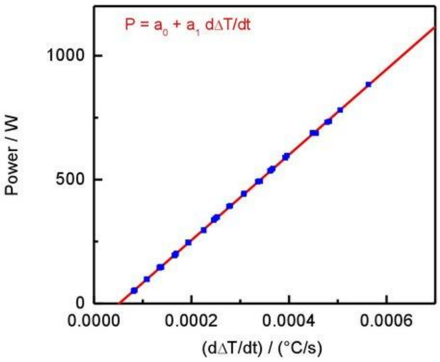
- Determine $\Delta T = T_c - T_p$ vs time
- Determine $d\Delta T/dt$ for $\Delta T = 0$
- Fit to data: $P = a_0 + a_1\, d\Delta T/dt$

Training material

eurad

101

CALORIMETER AT CLAB: DECAY POWER OF FUEL ASSEMBLIES



Calibration with an electrical heater

- Determine $\Delta T = T_c - T_p$ vs time
- Determine $d\Delta T/dt$ for $\Delta T = 0$
- Fit to data: $P = a_0 + a_1\, d\Delta T/dt$

Training material

eurad

102

CALORIMETER AT CLAB: DECAY POWER OF FUEL ASSEMBLIES

Spent nuclear fuel assembly

- Determine $\Delta T = T_c - T_p$ vs time
- Determine $d\Delta T/dt$ when $\Delta T = 0$
- $Q = a_0 + a_1 K\, d\Delta T/dt$
- $P = Q + P_e$
  - K : correction factor due to thermal capacity difference between electrical heater and fuel assembly
  - P_e : heat loss due to γ-rays escaping from the calorimeter

Calibration with an electrical heater

- Determine $\Delta T = T_c - T_p$ vs time
- Determine $d\Delta T/dt$ for $\Delta T = 0$
- Fit to data: $P = a_0 + a_1\, d\Delta T/dt$

Training material

eurad

103

CALORIMETER AT CLAB: DECAY POWER OF FUEL ASSEMBLIES

Spent nuclear fuel assembly

- Determine $\Delta T = T_c - T_p$ vs time
- Determine $d\Delta T/dt$ when $\Delta T = 0$
- $Q = a_0 + a_1 K\, d\Delta T/dt$
- $P = Q + P_e$
  - K : correction factor due to thermal capacity difference between electrical heater and fuel assembly
  - P_e : heat loss due to γ-rays escaping from the calorimeter

Calibration with an electrical heater

- Determine $\Delta T = T_c - T_p$ vs time
- Determine $d\Delta T/dt$ for $\Delta T = 0$
- Fit to data: $P = a_0 + a_1\, d\Delta T/dt$

Result in common uncertainty components for all assemblies measured at CLAB

Training material

eurad

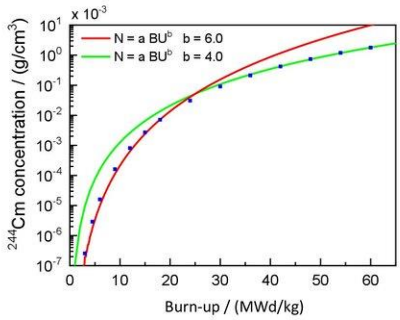
104

IMPORTANCE OF NEUTRON EMISSION ESTIMATION FOR SNF MANAGEMENT

$^{244}Cm: \; N = aBU^b$

$b \approx 4$ for BU = 45 MWd/kg

$$\frac{\delta N}{N} = b\frac{\delta BU}{BU}$$



- Use neutron emission as a BU indicator to improve the operational input for depletion calculations
- For nuclear safeguards authorities using neutron emission as a signature for the fissile material
  - At present : FORK type detectors
  - Innovative detectors being developed for disposal sites in Finland and Sweden, i.e.
    PNAR (Passive Neutron Albedo Reactivity)
    DDSI (Differential Die Away Self-Interrogation)
- Neutron dose

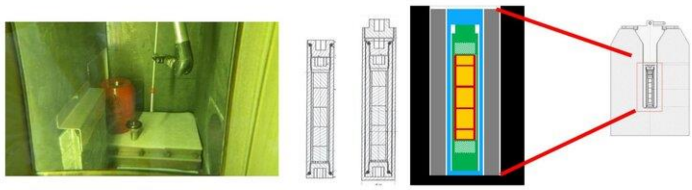
Training material

eurad 105

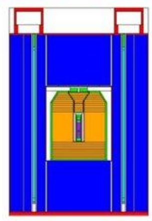
NEUTRON EMISSION: ABSOLUTE MEASUREMENTS OF SNF SEGMENT SAMPLE

EURAD TASK 2:
NDA method to determine the neutron output of a **SNF** sample under **standard controlled area** conditions

Hot cell (LHMA) facility at SCK CEN



Standard controlled area



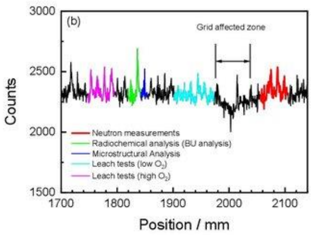
Training material

eurad 106

NEUTRON EMISSION: ABSOLUTE MEASUREMENTS OF SNF SEGMENT SAMPLE

- Irradiation history burnup (REGAL project)

BU indicator	Analysis date	Nuclide Inventory N_X/N_U	BU MWd/kg
^{137}Cs	21/10/2013	2.539 (55) x 10^{-3}	52.6 (11)
$^{143+144}Nd$	05/02/2014	5.701 (60) x 10^{-3}	53.95 (56)
$^{145+146}Nd$	05/02/2014	3.643 (38) x 10^{-3}	53.05 (56)
^{148}Nd	05/02/2014	0.974 (21) x 10^{-3}	53.3 (12)
^{150}Nd	05/02/2014	0.463 (21) x 10^{-3}	52.2 (23)
			Average: 52.78 (37)



- SNF segment sample: characteristics

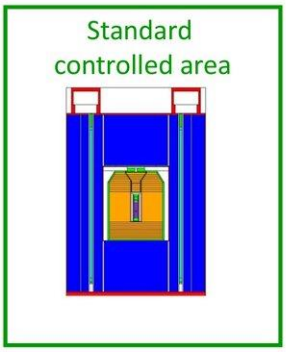
Parameter	Value
Segment length	52.01 (4) mm
Segment weight	42.616 (1) g
Cladding weight	6.71 (4) g
Net fuel weight	35.91 (4) g

⇒ Accurate information about design and operational history

Training material

107

NEUTRON EMISSION: ABSOLUTE MEASUREMENTS OF SNF SEGMENT SAMPLE



S_{sf} = 678 (12) s^{-1} g^{-1}

$S_{\alpha n} / S_{sf}$ = 0.039 (18)

Training material

108

NEUTRON EMISSION: ABSOLUTE MEASUREMENTS OF SNF SEGMENT SAMPLE

⇒ Improve
- detector characteristics
- nuclear data

S_{sf} = 678 (12) s^{-1} g^{-1}

$S_{\alpha n}$ / S_{sf} = 0.039 (18)

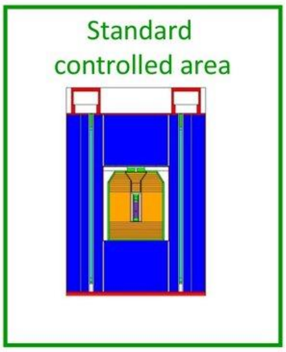
Uncertainty evaluation and sensitivity analysis

Uncertainty component, x_j	$\frac{u_{x_j}}{x_j}$	$\frac{u_{S_{sf},j}}{u_{S_{sf}}}$	$\frac{u_{\alpha,j}}{u_\alpha}$
Totals rate, T	0.0008	< 0.01	0.05
Reals rate, R	0.0027	0.15	0.17
Detection efficiency, ε_{sf}	0.0055	0.60	0.35
Gate fraction, f	0.0071	0.40	0.45
First order factorial moment, $\nu_{sf(1)}$	0.0037	0.20	0.25
Second order factorial moment, $\nu_{sf(1)}$	0.0120	0.67	0.80
Multiplication, M	0.0020	0.01	< 0.01

eurad

Training material 109

NEUTRON EMISSION: ABSOLUTE MEASUREMENTS OF SNF SEGMENT SAMPLE



S_{sf} = 678 (12) s^{-1} g^{-1}

$S_{\alpha n}$ / S_{sf} = 0.039 (18)

Good agreement with:

Radiochemical analysis : S_{sf} = 699 (28) s^{-1} g^{-1}

Note: uncertainty radiochemical analysis > 4%
(> factor 2)

eurad

Training material 110

NEUTRON EMISSION: ABSOLUTE MEASUREMENTS OF SNF SEGMENT SAMPLE

Code	Library	S_{calc}/S_{exp} LIB	S_{calc}/S_{exp} REC
ALEPH2	JEFF-3.3	0.94	0.95
SCALE	ENDF/B-VII.0	0.96	0.96
Serpent2	ENDF/B-VII.0	1.01	1.00
(2.1.29)	ENDF/B-VII.1	1.02	1.01
	ENDF/B-VIII.0	1.02	1.01
	JEFF-3.1.2	0.93	0.92
	JEFF-3.3	0.97	0.96
	JEFF-3.3 (1)	1.09	1.08
	JEFF-3.3 (2)	1.01	1.00
	JEFF-3.3 (3)	1.01	0.99
	JEFF-4T1	0.98	0.97
	JENDL-4.0u (4)		1.06
	JENDL-5.0	1.09	1.08

S_{sf} = 678 (12) s^{-1} g^{-1}

Good agreement with:

Radiochemical analysis : S_{sf} = 699 (28) s^{-1} g^{-1}

Theoretical calculations

Difference between LIB and REC data (~ 1%)

(1) $\sigma(n,\gamma)$ = 0 for ^{147}Nd
(2) $\sigma(n,\gamma)$ for ^{147}Nd from JENDL-4.0u
(3) $\sigma(n,\gamma)$ for ^{147}Nd from JEFF-4T1
(4) No data available to calculate S_{sf}

eurad

Training material 111

NEUTRON EMISSION: ABSOLUTE MEASUREMENTS OF SNF SEGMENT SAMPLE

Code	Library	S_{calc}/S_{exp} LIB	S_{calc}/S_{exp} REC
ALEPH2	JEFF-3.3	0.94	0.95
SCALE	ENDF/B-VII.0	0.96	0.96
Serpent2	ENDF/B-VII.0	1.01	1.00
(2.1.29)	ENDF/B-VII.1	1.02	1.01
	ENDF/B-VIII.0	1.02	1.01
	JEFF-3.1.2	0.93	0.92
	JEFF-3.3	0.97	0.96
	JEFF-3.3 (1)	1.09	1.08
	JEFF-3.3 (2)	1.01	1.00
	JEFF-3.3 (3)	1.01	0.99
	JEFF-4T1	0.98	0.97
	JENDL-4.0u (4)		1.06
	JENDL-5.0	1.09	1.08

S_{sf} = 678 (12) s^{-1} g^{-1}

Good agreement with:

Radiochemical analysis : S_{sf} = 699 (28) s^{-1} g^{-1}

Theoretical calculations

(1) $\sigma(n,\gamma)$ = 0 for ^{147}Nd
(2) $\sigma(n,\gamma)$ for ^{147}Nd from JENDL-4.0u
(3) $\sigma(n,\gamma)$ for ^{147}Nd from JEFF-4T1
(4) No data available to calculate S_{sf}

eurad

Training material 112

NEUTRON EMISSION: ABSOLUTE MEASUREMENTS OF SNF SGMENT SAMPLE

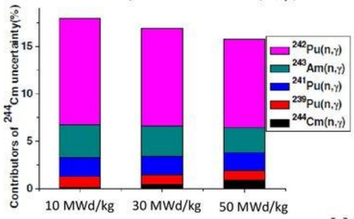
Code	Library	S_{calc}/S_{exp} LIB	S_{calc}/S_{exp} REC
ALEPH2	JEFF-3.3	0.94	0.95
SCALE	ENDF/B-VII.0	0.96	0.96
Serpent2 (2.1.29)	ENDF/B-VII.0	1.01	1.00
	ENDF/B-VII.1	1.02	1.01
	ENDF/B-VIII.0	1.02	1.01
	JEFF-3.1.2	0.93	0.92
	JEFF-3.3	0.97	0.96
	JEFF-3.3 (1)	1.09	1.08
	JEFF-3.3 (2)	1.01	1.00
	JEFF-3.3 (3)	1.01	0.99
	JEFF-4T1	0.98	0.97
	JENDL-4.0u (4)		1.06
	JENDL-5.0	1.09	1.08

S_{sf} = 678 (12) s^{-1} g^{-1}

Uncertainty theoretical estimation

Burnup	Relative uncertainty
10 MWd/kg	12.1 %
30 MWD/kg	11.1 %
50 MWd/kg	10.0 %

Contribution mainly from : $^{241}Pu(n,\gamma)$ & $^{243}Am(n,\gamma)$



Tiejun Zu et al., Annals of Nuclear Energy 94 (2016) 399

Training material

113

NEUTRON EMISSION: ABSOLUTE MEASUREMENTS OF SNF SEGMENT SAMPLE

Code	Library	S_{calc}/S_{exp} LIB	S_{calc}/S_{exp} REC
ALEPH2	JEFF-3.3	0.94	0.95
SCALE	ENDF/B-VII.0	0.96	0.96
Serpent2 (2.1.29)	ENDF/B-VII.0	1.01	1.00
	ENDF/B-VII.1	1.02	1.01
	ENDF/B-VIII.0	1.02	1.01
	JEFF-3.1.2	0.93	0.92
	JEFF-3.3	0.97	0.96
	JEFF-3.3 (1)	1.09	1.08
	JEFF-3.3 (2)	1.01	1.00
	JEFF-3.3 (3)	1.01	0.99
	JEFF-4T1	0.98	0.97
	JENDL-4.0u (4)		1.06
	JENDL-5.0	1.09	1.08

S_{sf} = 678 (12) s^{-1} g^{-1}

Some conclusions:

- Recommended decay data and neutron emission data not always adopted in evaluated data libraries
- $^{147}Nd(n,\gamma)$ cross section in JEFF-3.3 and ENDF/B-VIII.0 are too high (important for normalisation of PIE data)
- Fission yields for ^{148}Nd in JENDL-5.0 are too low
- $^{241}Pu(n,\gamma)$ and $^{243}Am(n,\gamma)$ cross sections require a re-evaluation (use of available experimental data)

Training material

114

SUMMARY AND CONCLUSIONS

- The main observables of interest for a safe handling, transport, storage and disposal of SNF were identified and discussed
- A characterisation of SNF for these observables requires the inventory of some key nuclides with different characteristics
- The inventory of the key nuclides can only be obtained by theoretical calculations using depletion codes
- Uncertainty evaluation and propagation requires a good understanding of the measurement/calculation process
- The quality of the theoretical calculations strongly depends on the quality of the nuclear data and design and operational history of the SNF
- A performance assessment and uncertainty evaluation of the calorimeter installed at CLAB is required to improve its predictive power for the validation of depletion calculations
- Some key nuclear data (including their uncertainties) such as cumulative fission yields and neutron induced capture cross sections need to be improved to allow an accurate estimation of the main observables of interest including reliable confidence limits

Training material

115

LEARNING OUTCOMES

After the completion of this training lesson, the participants should be able to

- understand the basic principles of uncertainty evaluation and propagation
- identify the observables that are important for the transport, handling, storage and disposal of spent nuclear fuel
- identify key nuclides determining these observables
- identify the different components involved in the theoretical calculations of the observables
- understand the importance of nuclear data and design characteristics and operational history of the fuel for an accurate theoretical estimation of the observables
- realise the need of accurate experimental data to validate theoretical calculations

Training material

116

KEY WORDS

- Bias
- Correlation matrix
- Covariance matrix
- Counting statistics
- Expanded uncertainty
- Monte Carlo simulations
- Normal (Gaussian) distribution
- Poisson distribution
- Random effect
- Sandwich formula
- Standard deviation
- Standard uncertainty
- Systematic effect
- Taylor development
- Uncertainty components
- Uncertainty propagation

- Actinides
- Alpha-decay
- Bateman equation
- Beta-decay
- Burnup
- Cooling time
- Cross section
- Decay heat
- Decay power
- Depletion codes
- Disposal
- Fission product
- Fission yields
- Gamma-ray emission
- Initial enrichment
- Irradiation history
- Light water reactor
- Neutron emission
- Neutron reactions
- Neutron induced capture reaction
- Neutron induced fission reaction
- Neutron transport
- Nuclear data
- Pressurised water reactor
- Recoverable energy
- Spent nuclear fuel
- Spontaneous fission

eurad

Training material 117

ADDITIONAL BIBLIOGRAPHY AND REFERENCES

Spent nuclear fuel observables and key nuclides

- Broadhead et al., "Investigation of nuclide importance to functional requirements related to transport and long-term storage of LWR spent fuel", Report ORNL/TM-12742 (1995)
- Gauld et al., "Nuclide importance to criticality safety, decay heating and source terms related to transport and interim storage of high-burnup LWR fuel", Report NUREG/CR-6700, ORNL/TM-2000/284 (2001)
- Žerovnik et al. ,"Observables of interest for the characterisation of Spent Nuclear Fuel", EUR 29301 EN (2018) , JRC112361
- Schillebeeckx et al., "Characterisation of spent nuclear fuel by theoretical calculations and non-destructive analysis", see JRC114178 (2019)

Depletion codes

- Stankovskiy and Van den Eynde, "Advanced method for calculations of core burn-up, activation of structural materials and spallation products accumulation in accelerator driven system", Science and Technology of Nuclear Installations 2012 (2012) 545103
- Álvarez-Velarde, "Validation of the burn-up code EVOLCODE 2.0 with PWR experimental data and with a Sensitivity/Uncertainty analysis", Annals of Nuclear Energy 73 (2014) 175
- Leppänen et al., "The Serpent Monte Carlo code: status, development and applications in 2013", Annals of Nuclear Energy 82 (2015) 142
- Kashima et al., "Validation of burnup calculation code SWAT4 by evaluation of isotopic composition data of mixed oxide fuel irradiated in pressurized water reactor", Energy Procedia 71 (2015) 159
- Rearden and Jessee, "SCALE Code System", ORNL/TM-2005/39 Version 6.2, April 2016
- Gauld et al., "Isotopic depletion and decay methods and analysis capabilities in SCALE", Nuclear Technology 174 (2017) 169
- Ebiwonjumi et al., "Verification and validation of radiation source term capabilities in STREAM", Annals of Nulcear Energy 124 (2019) 80

eurad

Training material 118

ADDITIONAL BIBLIOGRAPHY AND REFERENCES

Radiochemical analysis and validation of depletion codes

- DE Scatena-Wachsel, "Radiochemical analysis methodology for uranium depletion measurements", Report LM-06K140, January 2007
- Gauld et al., "Uncertainties in Predicted Isotopic Compositions for High Burnup PWR Spent Nuclear Fuel", Report NUREG/CR-7012, ORNL/TM-2010/41, January 2011
- OECD/NEA, "Spent Nuclear Fuel Assay Data for Isotopic Validation, State-of-the-art Report", Nuclear Science, NEA/NSC/WPNCS/DOC(2011)5, June 2011
- OECD/NEA, "Evaluation Guide for the Evaluated Spent Nuclear Fuel Assay Database (SFCOMPO)", Nuclear Science, NEA/NSC/R(2015)8, February 2016G. Ilas,"Review of Experimental Assay Data for PWR Spent Fuel", Report ORNL/SPR-2019/1143, April 2019

Non-destructive assay

- SKB, "Measurements of Decay Heat in Spent Nuclear Fuel at the Swedish Interim Storage Facility", Clab, SKB Report R-05-62, December 2006
- B.D. Murphy and I.C. Gauld, "Spent Fuel Decay Heat Measurements Performed at the Swedish Central Interim Storage Facility", Report ORNL/TM-2008/016, Oak Ridge National Laboratory, Feburary 2010
- Schillebeeckx et al., "A non-destructive method to determine the neutron production rate of a sample of spent nuclear fuel under standard controlled area conditions", JRC Technical Report EUR 30379 EN, 2020

Nuclear data

- Nuclear data libraries at JANIS NEA, https://www.oecd-nea.org/jcms/pl_39910/janis
- Decay data, http://www.nucleide.org/DDEP.htm
- Nichols et al., "Handbook of nuclear data for safeguards: database extensions, august 2008", INDC-2453, INDC(NDS) – 0534

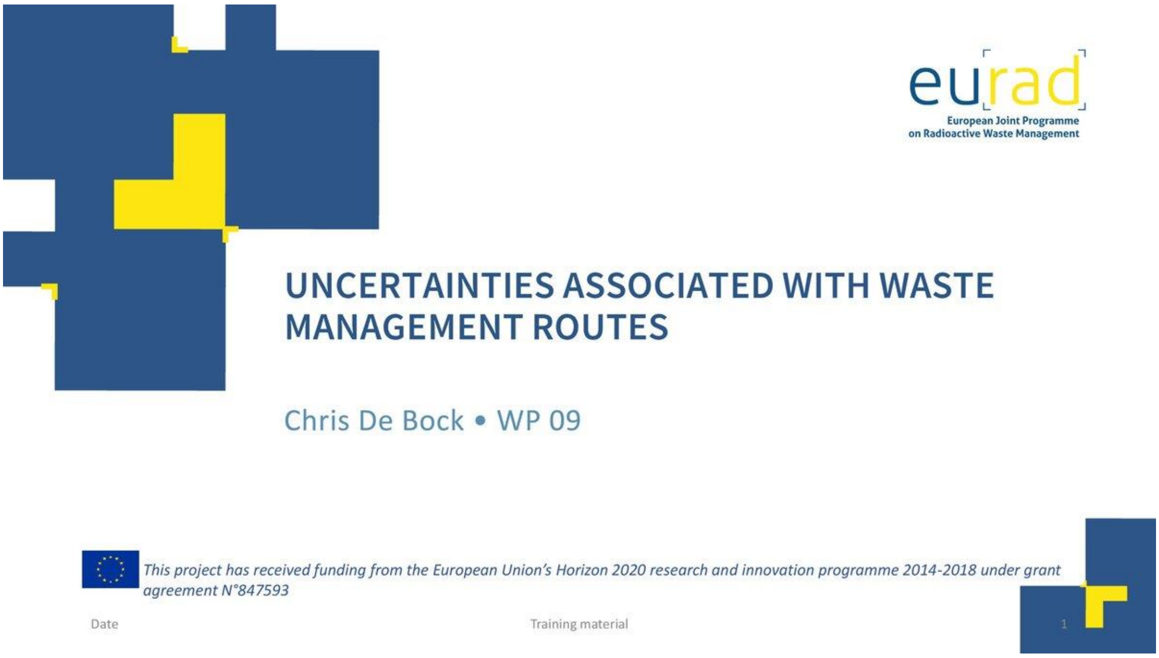
eurad

Training material 119

Appendix H. Slides of lecture B.3

B.3. Uncertainties associated with waste management routes

Prepared by Chris de Bock, ONDRAF/NIRAS



CONTENTS

- Learning outcomes.
- Introduction.
- Challenging wastes: background and waste types
- Legacy waste
- Early or delayed conditioning
- Shared solutions
- Summary and conclusions
- Used acronyms
- Bibliography and/or References.

LEARNING OUTCOMES.

After the completion of this training unit/lesson, the students/participants should be able to:

- Understand why the waste management route of certain waste types is difficult to define
- Be aware of the waste types that are generally considered to be challenging
- Be acquainted with:
  - The double vicious circle entrapping legacy waste
  - The dilemma of early or delayed conditioning
  - The issues related to shared solutions (particularly for SIMS)

INTRODUCTION

The backbone of radioactive waste management is the definition, for each waste type, of a route of activities from the generation of the waste to its disposal.

However, for certain waste types, the definition of a management route may be called *challenging*.

Date Training material 5

CHALLENGING WASTES

- Within EURAD, uncertainties associated with waste management routes are dealt with in WP 9 "ROUTES" (see reference 1)
  - ROUTES focuses on *challenging wastes*
- Challenging wastes = wastes for which it is difficult to define an appropriate management route
- For challenging wastes, no complete management solution is available
  - One or more of the predisposal steps are missing (e.g. characterisation, treatment, conditioning)
  - Disposal strategy is not yet defined
- Reasons for difficulties to define an appropriate management route
  - Intrinsic properties of the waste (e.g. hazardous waste)
  - Uncertainties related to radiological or non-radiological characteristics (e.g. legacy waste)
  - Uncertainties related to waste behavior in certain waste management life-cycle steps (e.g. conditioning, disposal)
    - **No disposal strategy definition in turn impacts characterisation uncertainty (what to characterize + priorities)**
  - Small quantities of waste (typically for SIMS)
    - **Making certain technical options disproportionately expensive**
    - **A solution may be the sharing of infrastructure, mobile equipment or know-how**

Date Training material 6

DIFFICULT MANAGEMENT ROUTE DEFINITION

- Key factors when choosing a waste management route
  - Waste-related factors: waste quantity, radiation level, half-life or radiotoxicity, chemical and physical characteristics (intrinsic and relevant to the interaction between waste and matrix), availability of a suitable treatment technology
  - Broad factors: availability of a repository, well-established WAC, regulatory considerations, public involvement
- Main blocking points for management route definition (from responses to ROUTES questionnaire)
  - Lack of disposal route (31%)
  - Characterization issues (22%)
  - Treatment or Conditioning issues (20%)
- ROUTES has identified 11 wastes types that are generally considered to be challenging wastes
- Per waste type, the areas of uncertainty per life-cycle phase have been investigated
  - Case studies play important role in ROUTES

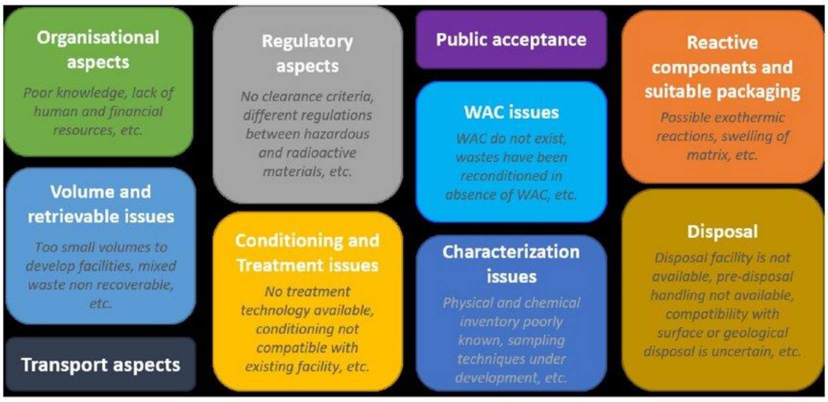
Date Training material eurad 7

CHALLENGING WASTE TYPES

- Following challenging waste types were identified by ROUTES (see reference 2)
  1. Sludges
  2. Spent ion exchange resins
  3. Organic waste
  4. Bituminized waste
  5. Graphite waste
  6. Decommissioning waste
  7. Disused sealed radioactive sources
  8. Radium/Thorium/Uranium-bearing wastes
  9. Spent fuel
  10. Wastes containing reactive metals
  11. Wastes containing chemo-toxic substances

Date Training material eurad 8

UNCERTAINTY AREAS



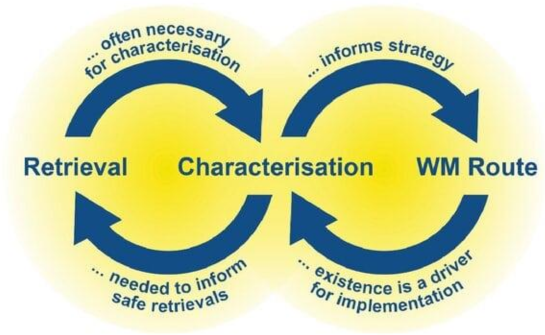
Date Training material 9

ISSUES COMMON TO LEGACY WASTES

- Root cause are characterization uncertainties
  - Missing information about origin
  - Missing information about radionuclide content
  - In some cases, waste streams have been mixed
- Related issues
  - Quantification of specific radionuclides or species
    - Indirect methods (e.g. C-14 in graphite waste)
    - Direct methods (e.g. activation products, complexing substances)
  - Strategy for the retrieval of the unconditioned waste

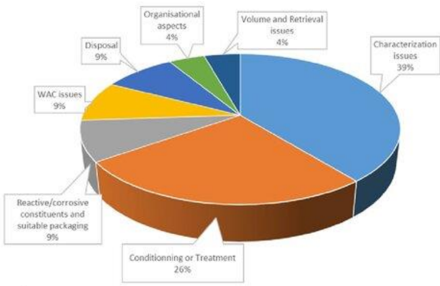
Date Training material 10

THE DOUBLE VICIOUS CIRCLE ENTRAPPING LEGACY WASTES



Date Training material eurad 11

THE EXAMPLE OF LEGACY SLUDGES



- Sludges are a common challenging waste
  - UK: sludge from degradation of Magnox SF in long storage
  - France: sludges from SF reprocessing and liquid effluent treatment
- Approaches to address challenges
  - Characterisation campaigns examining material sampled at different depths
  - In-depth examination of historical records (where available)
  - Requirements to recondition drums of corroded waste offer opportunities for further sampling and characterisation

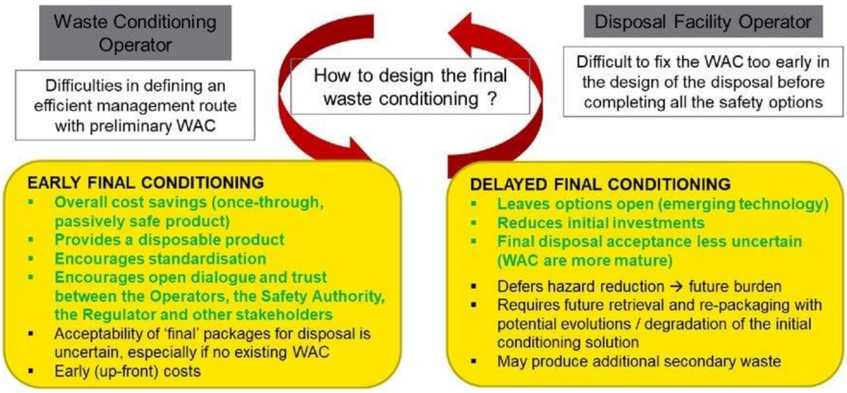
Date Training material eurad 12

CHOOSING BETWEEN EARLY OR DELAYED CONDITIONING

- Root cause of this dilemma is the absence of an established disposal route
- Early conditioning
  - Encourages standardization, thus contributing to cost minimization
  - Requires close dialogue between all stakeholders (producers, WMO, regulator …)
  - Requires stability of WAC
- Delayed conditioning
  - Leave options open, thus reducing the initial investment and the financial risk
  - Requires future retrieval and repackaging of potentially degraded waste

Date Training material eurad 13

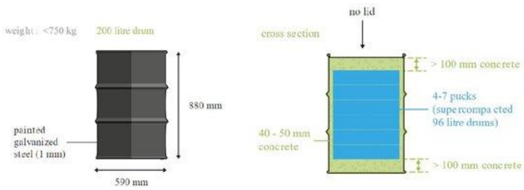
SCHEMATIC REPRESENTATION OF THE DILEMA



Date Training material eurad 14

EARLY OR DELAYED CONDITIONING - NETHERLANDS EXAMPLE CASE (1/3)

- National policy: interim storage ≥100 years followed by geological disposal
- Choice for early conditioning
- LILW in the Netherlands is mostly solid compactable waste
  - Solution based on compaction and cementation in 200-litre galvanized steel drums
  - Concrete for conditioning is made of blast furnace slag, cement, water aggregates and plasticizers
  - Waste characteristics are tentatively assumed based on expert judgement (organics, metals, plastics and others)



Date Training material 15

EARLY OR DELAYED CONDITIONING - NETHERLANDS EXAMPLE CASE (2/3)

- Safety assessment and WAC for storage are stringent and considered to be bounding for safe disposal
  - WAC for transport and waste processing and storage have been established several decades ago
  - Ongoing disposability research to support continued improvements in WAC
  - Waste packages should be ready for disposal after storage period (no additional packaging)
    - National and shared disposal solutions are studied in the research programme. No site location has been identified.
    - Research is further advanced for disposal in clay than disposal in salt formation
  - Approach applied across a wide range of waste classes and categories (except VSLW and exempted waste)

Date Training material 16

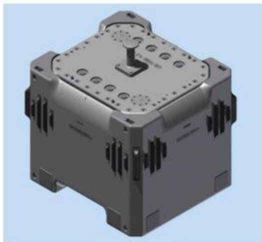
EARLY OR DELAYED CONDITIONING - NETHERLANDS EXAMPLE CASE (3/3)

- Waste packages are stored under dry conditions in a stack
  - Storage conditions considered to be mechanically severer than disposal conditions
  - Packages must also meet requirements for chemical and physical stability in case of flooding of the storage facility
- Monitoring and inspection to confirm stability of packages during storage
  - Every 15-20 years waste packages are checked,
    - Possible defects are repaired
    - Conditioning is adjusted if needed

Date Training material 17

EARLY OR DELAYED CONDITIONING – UNITED KINGDOM EXAMPLE CASE (1/2)

- Sellafield Ltd has developed self-shielded boxes (SSBs) for storage of highly degraded Magnox fuels which have been or will be recovered from the legacy ponds and are not suitable for reprocessing.
  - Packaging of spent fuel in SSBs without matrix conditioning
  - Ductile cast iron walls provide radiological shielding and containment
  - Eight Filters allow hydrogen gas (from radiolysis and corrosion of metallic uranium etc.) to egress and oxygen to ingress
- Sellafield Ltd. has built new Interim Storage Facility, which could potentially hold the SSB-packages
- Packages might be disposed but waste could also be reconditioned relatively easily



Date Training material 18

EARLY OR DELAYED CONDITIONING – UNITED KINGDOM EXAMPLE CASE (2/2)

- Benefits of this strategy:
  - Accelerated hazard reduction (emptying and decommissioning of ageing facilities)
  - Lower upfront capital investment
  - Flexibility in managing such wastes

Date Training material 19

THE CONCEPT OF SHARED SOLUTIONS

- Shared solutions do not have to be purely technical. Shared solutions encompass
  - Research carried out and knowledge used
  - Technology developed and transferred
  - Facilities constructed and operated throughout all the waste life-cycle phases
  - Legal and institutional arrangements established
  - Processes of interaction between the stakeholders, including safety culture and governance issues
- Sharing solutions between countries has benefits
  - Make needed infrastructure available and exchange know-how
  - Share costs
  - However, there are also issues

Date Training material 20

ISSUES RELATED TO SHARED SOLUTIONS

- Prerequisite to developing shared solutions is a common safety culture and a level playing field between participating countries.
  - If not: tendency to shift development and location of shared infrastructure to country with lowest standards
- Transparency must be established
  - Public access to information
  - Evidence-based decision-making
  - Effective public participation and access to justice
- Specific deliberative process should be developed
  - Including proper representation from local, national and multinational actors (not only officials)

Date Training material eurad 21

SHARED SOLUTIONS IN PRACTICE

- Shared solutions for disposal: still in its feasibility phase
  - EC-projects SAPIERR and SAPIERR2 have led to establishment in 2009 of the ERDO working group, transformed in 2021 into the ERDO Association
  - At present, only one agreement for shared disposal: Belgium and Luxembourg
- Shared solutions for characterisation, treatment and/or conditioning:
  - Many examples of implementation
    - Recycling/processing of metals, incineration of Danish waste in Sweden (EDF Cyclife)
    - Reprocessing of SF in France (ORANO)
    - Recycling/processing of metals in Germany (Siemelkamp)
  - Mobile facilities are highly valued (no location issue)
    - Conditioning of ion exchange resins (EDF Cyclife France has two mobile facilities)

Date Training material eurad 22

SHARED SOLUTIONS AND SIMS

- Constraints faced by SIMS:
  - Limited pools of expertise or know-how
  - Limited availability of infrastructure
  - Limited budgets for development of specific new solutions or for radioactive waste management in general
  - Often immature or absent disposal strategy
- Shared solutions would provide best added value for SIMS
  - Needed infrastructure becomes available and know-how is exchanged
  - Costs are shared

Greek case

- ~60 drums of cemented residues from research activities between 1970-1990
- Uncertainty over inventory and approach to characterise
- Evaluating options for deploying mobile characterisation facilities, drawing on experience and capabilities in other MS

Date Training material eurad 23

SUMMARY AND CONCLUSIONS

- Challenging wastes = wastes for which it is difficult to define an appropriate management route
- ROUTES has identified 11 wastes types that are generally considered to be challenging wastes
- Main blocking points for defining a management route
  - Lack of disposal route
  - Characterization issues
  - Treatment or Conditioning issues
- Characterization uncertainties are the root cause of the issues around legacy waste
  - Legacy waste risks being entrapped in a double vicious circle around characterization
- Absence of an established disposal route is the root cause of the early or delayed conditioning dilemma
- Sharing solutions between countries may have substantial benefits, particularly for SIMS
  - Make needed infrastructure available, exchange know-how, share costs
  - However, prerequisite is a common safety culture and a level playing field between participating countries

Date Training material eurad 24

USED ACRONYMS

- SF = spent fuel
- SIMS = small inventory member state
- WAC = waste acceptance criteria
- WMO = waste management organization

Date Training material 25

BIBLIOGRAPHY AND/OR REFERENCES.

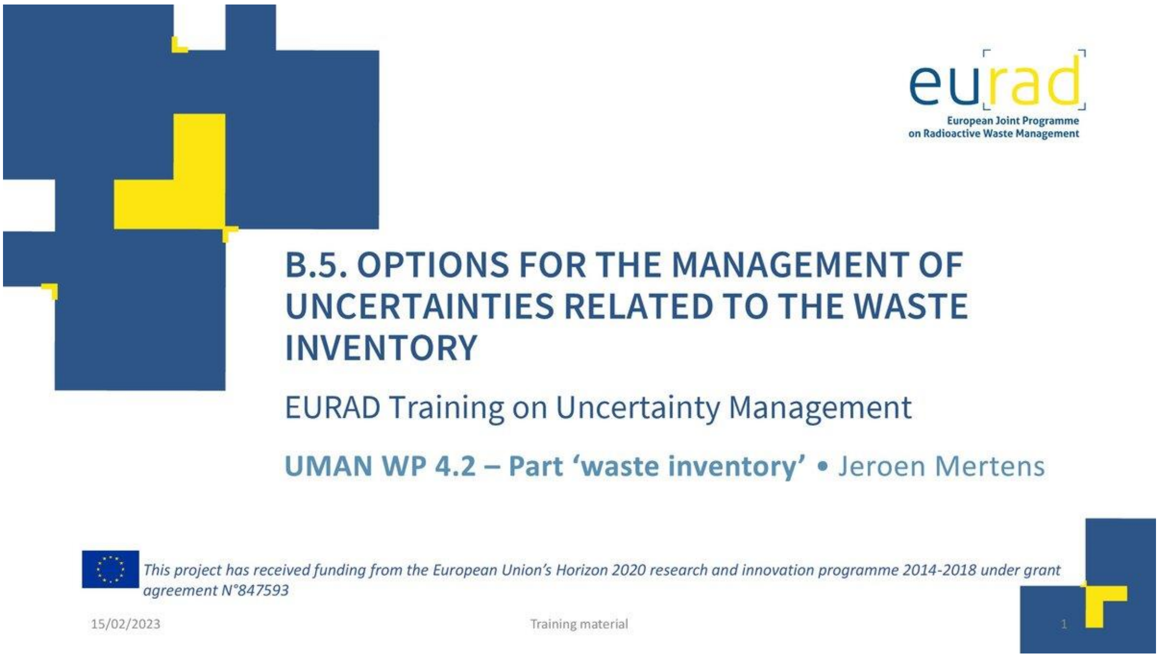
1. F. Marsal et al., *EURAD EC project - overview of the routes work package: identified key issues and open questions about waste management routes in Europe, from cradle to grave*, EPJ Nuclear Sci. Technol. 9, 1 (2023), Published by EDP Sciences, 2023, https://doi.org/10.1051/epjn/2022024
2. V. Wasselin, M. Maitre, I. Kutina, *Overview of issues related to challenging wastes*, Final version as of 18.08.2022 of deliverable D9.5 of the HORIZON 2020 project EURAD. EC Grant agreement no 847593 (2022)

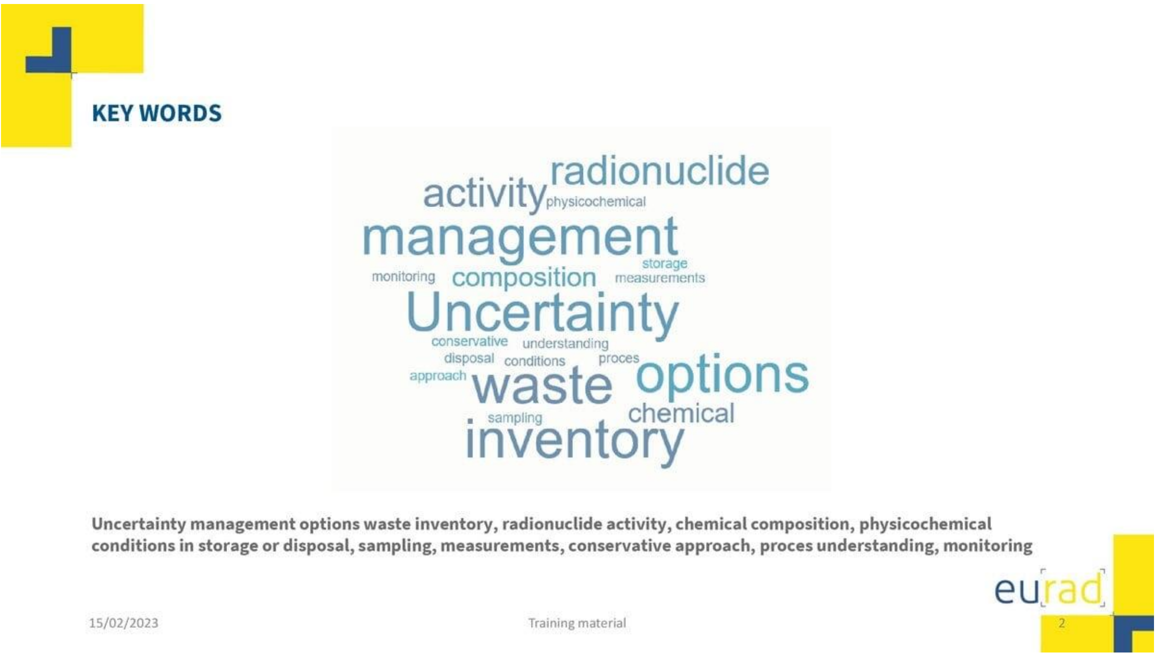
Date Training material 26

Appendix I. Slides of lecture B.4

B.4. Options for the management of uncertainties related to the waste inventory

Prepared by Jeroen Mertens, Bel V





CONTENTS

- Learning outcomes.
- Introduction.
- Uncertainties seen as most important to WMO/TSO/RE (survey)
- Uncertainties related to chemical composition (+ organics)
- Uncertainties related to physicochemical conditions in storage or disposal
- Uncertainties related to radionuclide activity (incl. vector)
- Conclusions.
- Bibliography and/or References.

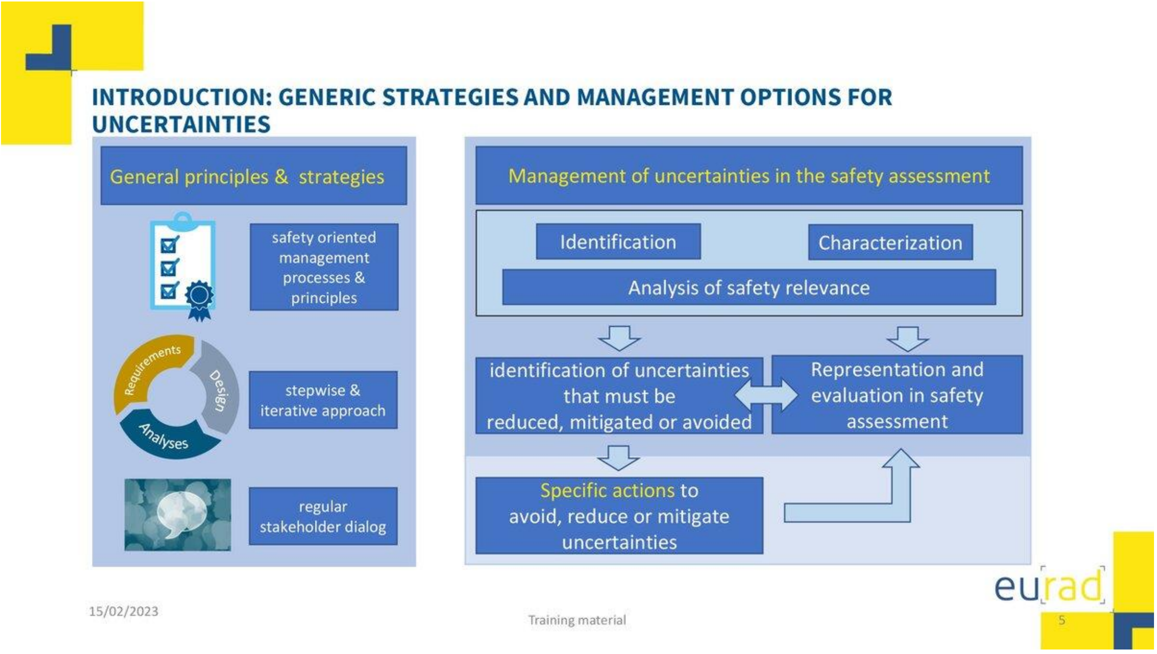
15/02/2023 Training material 3

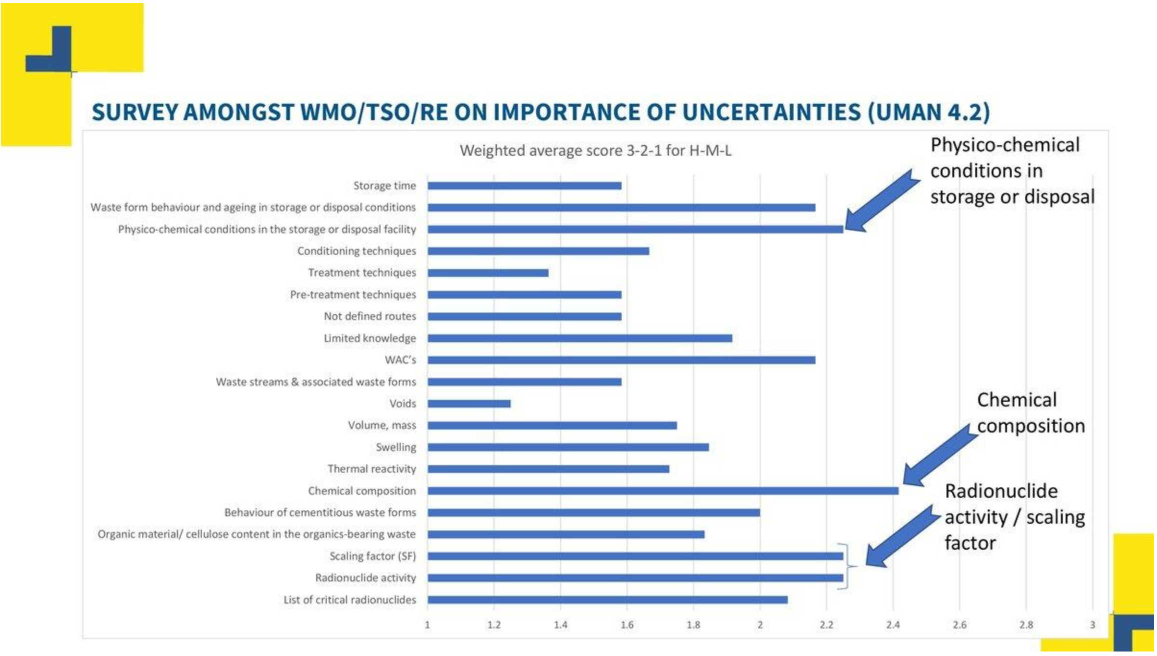
LEARNING OUTCOMES.

After the completion of this training unit, the participants should be able to:

- Understand and explain different ways of managing several of the waste inventory uncertainties; apply the different steps to be able to manage the uncertainty
- Understand the complexity of management of certain of the waste inventory uncertainties
- Be able to take home ideas of how to deal with some of the uncertainties related to waste inventory

15/02/2023 Training material 4


INTRODUCTION: GENERIC STRATEGIES AND MANAGEMENT OPTIONS FOR UNCERTAINTIES
General principles & strategies
safety oriented management processes & principles
Requirements
Design
Analyses
stepwise & iterative approach
regular stakeholder dialog
Management of uncertainties in the safety assessment
Identification
Characterization
Analysis of safety relevance
identification of uncertainties that must be reduced, mitigated or avoided
Representation and evaluation in safety assessment
Specific actions to avoid, reduce or mitigate uncertainties
15/02/2023
Training material
eurad
5


SURVEY AMONGST WMO/TSO/RE ON IMPORTANCE OF UNCERTAINTIES (UMAN 4.2)
Weighted average score 3-2-1 for H-M-L
Storage time
Waste form behaviour and ageing in storage or disposal conditions
Physico-chemical conditions in the storage or disposal facility
Conditioning techniques
Treatment techniques
Pre-treatment techniques
Not defined routes
Limited knowledge
WAC's
Waste streams & associated waste forms
Voids
Volume, mass
Swelling
Thermal reactivity
Chemical composition
Behaviour of cementitious waste forms
Organic material/ cellulose content in the organics-bearing waste
Scaling factor (SF)
Radionuclide activity
List of critical radionuclides
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
Physico-chemical conditions in storage or disposal
Chemical composition
Radionuclide activity / scaling factor

SUMMARY OF THE ANSWERS TO THE QUESTIONNAIRE UMAN 4.2 TASK

Most relevant uncertainties for RE, TSO and WMO according to answers to the survey:

- **Physico-chemical conditions in the storage or disposal facility**
  - Uncertainty in the evolution of the disposal system and its environment
- **Chemical composition (with a special attention to organic content)**
  - Uncertainty associated with initial characteristics
- **Radionuclide activity (including the scaling factor)**
  - Uncertainty associated with initial characteristics

15/02/2023 Training material eurad 7

PHYSICO-CHEMICAL CONDITIONS IN THE STORAGE OR DISPOSAL FACILITY

15/02/2023 Training material eurad 8

PHYSICO-CHEMICAL CONDITIONS IN THE STORAGE OR DISPOSAL FACILITY

Is the history of physico-chemical conditions in storage known?
Are the physico-chemical conditions in the future disposal facility known?

UNCERTAINTY

15/02/2023 Training material 9

PHYSICO-CHEMICAL COND. STORAGE/DISPOSAL - IDENTIFICATION

- Covers large domain:
  - **Many parameters** regarding physico-chemical conditions
  - As well **storage** as **disposal conditions**
  - Behaviour of the waste form in specific physico-chemical storage & disposal conditions dependent on the type of waste form (e.g. cementitious, bituminous), type of disposal,…
  - → **identification might be complex prcess**
- For identification, important to perform exhaustive analysis of the physicochemical conditions:
  - Storage, e.g. uncertainty in temperature (extremes), (relative) humidity, radiation, chemical environment
  - Disposal, e.g. pH, aggressive species, presence of water
- Identification generally done in the safety assessment through:
  - Literature survey/International REX
  - Development of system understanding
  - Features, Events & Processes or 'FEP'-screening

15/02/2023 Training material 10

PHYSICO-CHEMICAL COND. STORAGE/DISPOSAL - CHARACTERIZATION

- Storage conditions:
  - Uncertainties could be characterized through identifying uncertainty on the **indoor climatic environment** (t°, humidity…), radiation field, chemical species that could be present in the storage facilities…
  - Conditions outside of the building (heat waves, cold, humidity) might also be useful to characterize the uncertainty, when they can be combined with knowledge on e.g. building isolation
  - Particular aspect could be past **accidents/incidents** with stored waste that could have an influence on the waste (e.g. fire, leaking roof, chemical issue?)

Picture © BP

What casued this? Humidity? Leaking water through roof? Substance leaking from other drum? Cl in the air? What is the situation inside?

15/02/2023 Training material eurad 11

PHYSICO-CHEMICAL COND. STORAGE/DISPOSAL - CHARACTERIZATION

- Disposal conditions:
  - Function of **disposal type and specific environment**. The conditions are not only determined by EBS or **host rock**, **but also by chemical element**s that are released from the waste that might change the pysico-chemical conditions other wastes are in
  - Characterize the uncertainty through **literature survey**, **lab & demonstration experiments** (and applying statistical models), through **modelling** (scenario, sensitivity analysis) and **FEP analysis**, quantification by **expert judgement**

Disposal gallery @ Onkalo (Finland)

15/02/2023 Training material eurad 12

PHYSICO-CHEMICAL COND. STORAGE/DISPOSAL – ASSESSMENT OF THE SAFETY RELEVANCE

- Safety relevance assessed through different means:
  - Literature survey
  - Expert judgement
  - And mostly cited: **safety/performance assessment**, used e.g. to assess gas generation, pressure build-up, chemical evolution
- Relevance → can result in uncertainties regarding safety related properties and their evolution with time:
  - **Impact on physico-chemical properties** important for safety, such as mechanical stability or permeability of the **waste form**
  - **Impact on radionuclide release** from the waste form (increased leaching or degradation → more release)
  - **Impact on safety functions of the components surrounding the waste** (which could degrade engineered barriers): example is the swelling of the waste as a result of matrix degradation or corrosion of the package, mechanically **damaging the EBS**

15/02/2023 Training material eurad 13

PHYSICO-CHEMICAL COND. STORAGE/DISPOSAL– CLASSIFICATION AND ASSOCIATED ACTIONS (MANAGEMENT OPTIONS!)

Avoided | To be reduced | Mitigated

- Unanimously identified as **to be reduced**
- Storage:
  - **Assuring stable physico-chemically favourable conditions** in the storage facility → uncertainty reduced to level it is not important any more. E.g. through climatic control in the storage facility (low moisture, constant temperature)
  - Reduce the uncertainty by **monitoring** physico-chemical conditions in the facility (t°, humidity…). In case not available, information from outside climatic conditions can be used in combination with knowledge on the building structure and isolation behaviour.

15/02/2023 Training material eurad 14

PHYSICO-CHEMICAL COND. STORAGE/DISPOSAL– CLASSIFICATION AND ASSOCIATED ACTIONS (MANAGEMENT OPTIONS!)

- Unanimously identified as **to be reduced**
- Storage:
  - In case no information is available, or in case waste has been moved and records on previous storage conditions are lost, uncertainty cannot as such be reduced. However, physical conditions of the waste (package) itself might give indication of past physico-chemical conditions and still reduce some of the uncertainty (e.g. presence or not of external corrosion of drums).

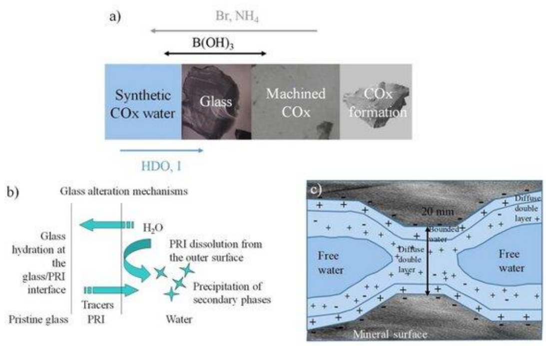
Avoided | To be reduced | Mitigated

15/02/2023 Training material eurad 15

PHYSICO-CHEMICAL COND. STORAGE/DISPOSAL– CLASSIFICATION AND ASSOCIATED ACTIONS

- Unanimously identified as **to be reduced**
- Disposal
  - Reduce through additional experimental research regarding physico-chemical conditions (lab and mock-up), e.g. in situ experiments for a DGR (mock-up installation, corrosion potential experiments,…). For surface disposal, construction of mock-ups of e.g. the cover to identify the chemical composition of water that could percolate through the facility after barrier degradation

Avoided | To be reduced | Mitigated



Debure et al. 2019 – glass corrosion experiment

15/02/2023 Training material eurad 16

PHYSICO-CHEMICAL COND. STORAGE/DISPOSAL– CLASSIFICATION AND ASSOCIATED ACTIONS

- Unanimously identified as **to be reduced**
- Disposal

Avoided	To be reduced	Mitigated

Although not a way of reduction, several respondents marked that **robustness of the waste package and conditioning matrix against all kinds of physico-chemical challenges, reduces the importance of the uncertainty.** (e.g. corrosion resistant package, package that could compensate for a certain swelling of the waste form by using compressible materials, careful selection of materials used for conditioning,…)

15/02/2023 Training material 17

PHYSICO-CHEMICAL COND. STORAGE/DISPOSAL – REPRESENTATION IN THE SAFETY ASSESSMENT

Different ways of representation exist:

- Via a **set of scenarios**, including **normal/reference and altered evolution** with e.g. supposed faster degradation of waste and/or EBS. The set of scenarios covers the range of uncertainties.
- Via carefully chosen **pessimistic (conservative) assessments of the reference scenario** (e.g. supposing oxidizing conditions in the surface disposal facility having the most unfavourable influence on retention properties in the waste form after degradation, or supposing metal drum is not a barrier)
- Via **probabilistic** scenario **assessments** where uncertainty is introduced in a probabilistic manner (e.g. probabilistic density functions)

15/02/2023 Training material 18

CHEMICAL COMPOSITION (WITH A SPECIAL ATTENTION TO ORGANIC CONTENT)

CHEMICAL COMPOSITION - IDENTIFICATION

- Different issues regarding chemical composition:
  - Potential **impact of chemicals on the stability of the waste and waste packages, and EBS**
  - Chemical interaction with radionuclides **might alter transport properties** (e.g. complexing agents)
  - Hazardous materials might **impact waste handling and operational safety**
- Examples: chlorides, sulphates, nitrates, organic content (amongst which e.g. cellulose)
- Identified early in the development of the waste disposal program:
  - Particularly during **inventory development process or while developing WAC**
  - Identified through **systematic FEP-analysis** during safety assessments
  - Can also appear through **observation of absence of declaration** of detailed chemical composition: in particular observed for organic waste

CHEMICAL COMPOSITION


picture © BP

Alkali-Silica reaction in cemented waste

Swelling of bituminous waste


picture © BP

Is the chemical composition known? **UNCERTAINTY**

15/02/2023 Training material eurad 21

CHEMICAL COMPOSITION (+ORGANICS) - CHARACTERIZATION

- Ideally, chemical composition of the waste should be well known, and thus related uncertainty quantitatively well characterized. However:
  - Regularly, **limited data is available** related to the mass of several species such as complexing agents
  - **Overestimated uncertainty** is happening if the **WAC are upper bounds** that need to be respected, and when only this information is available (example: cellulose "< 10kg")
  - **Limited accuracy of measurements**, subsample analysis or the application of statistical methods on data induces uncertainty
  - **Waste generation history** may have varied or may vary, increasing uncertainty
  - (chemical) **evolution of the waste during storage** or in the facility (see also previous uncertainty)


Cellulose (©paragon protection)

15/02/2023 Training material eurad 22

CHEMICAL COMPOSITION (+ORGANICS) - CHARACTERIZATION

- Usually, it is strived for to characterize uncertainty in chemical composition quantitatively, possibly with some additional safety margin
  - In case of limited data, **quantitative estimations based on expert judgement** including knowledge of the waste production could be used.

Homogeneous cementing of sludge from concentration of NPP effluents

© Westinghouse

Cellulose (©paragon protection)

CHEMICAL COMPOSITION (+ORGANICS) – CHARACTERIZATION EXAMPLE

- Example WAC: limit of 15 g sulfates/kg waste form

- Waste drum - > no data on sulfate content
  - But: knowledge that the waste mass is 1206 kg
  - Based on the record, there is 7 kg of PVC in the waste as only potential source of sulfates
  - → so certainly <<< than 7kg sulfates/1206 kg waste or ~6 g/kg → upper bound uncertainty interval

CHEMICAL COMPOSITION (+ORGANICS) – ASSESSMENT OF THE SAFETY RELEVANCE

- **Safety relevance assessed through** (quantitative) phenomenological descriptions of the repository performance (**performance assessment**)
  - E.g. assessment of the degradation of concrete barriers as a result of chloride and sulfate release from the waste form
  - Specific **sensitivity and uncertainty analysis** is used to determine the most relevant parameters and assess safety importance of the remaining uncertainties
- Good agreement across the community that uncertainty with respect to the following topics has the highest relevance for post-closure safety of the disposal facility:
  - Chemicals that lead to **degradation of barriers**, e.g. sulfate attack of cementitious materials, chloride attack of waste drums and concrete reinforcements, Alkali silica reaction
  - **Complexing agents that enhance radionuclide mobility resp. reduce retention**
  - Chemical components that **enhance release** (enhanced corrosion of metallic waste)
  - Chemical components that **influence speciation of nuclides** (e.g. form of C-14 compounds (organic/inorganic))
- Safety relevance of the uncertainty has been noticed to be **different between different repositories** (surface, near surface, deep geological)

15/02/2023 Training material eurad 25

CHEMICAL COMPOSITION (+ORGANICS) – CLASSIFICATION AND ASSOCIATED ACTIONS

- Most uncertainty related to chemical composition → adequately **reduce** before licensing steps and in particular before operational license.

Avoided | To be reduced | Mitigated

- Consensus that **appropriate WAC together with strategies for verification and enforcement** must be put in place to achieve adequate uncertainty reduction
- Furthermore, the following strategies can be used:
  - **analysis of specific waste streams** or specific waste samples to gather more detailed information about specific safety relevant materials
  - assure **best possible description of used materials as soon as possible and *before* conditioning**, and **store the information** accordingly
  - **optimize waste conditioning** and packaging where possible and appropriate. In some countries (e.g, Czech Republic), the WMO has specifically the possibility to control waste conditioning process by waste producer
  - assure that information on waste amounts, radionuclide inventory, and chemical composition is **updated regularly and appropriately**
  - **improve process understanding** e.g., by laboratory measurements on (site specific) sorption of organic and inorganic (C-14) compounds

15/02/2023 Training material eurad 26

CHEMICAL COMPOSITION (+ORGANICS) – REPRESENTATION IN THE SAFETY ASSESSMENT

- Mainly represented by conservative assumptions
- Sometimes specific assumptions are made, or altered evolution scenarios defined, to explore the impact of remaining uncertainty in the safety assessment (e.g. faster waste form degradation, no retention to account for complexing agents)

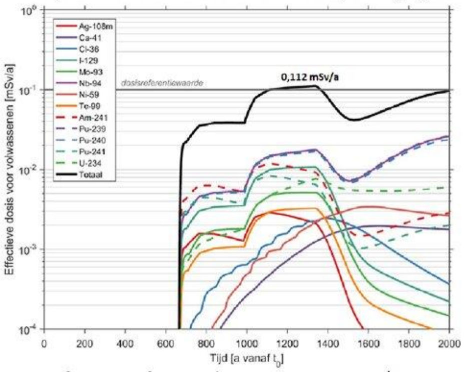
- Examples:
  - Example from Switzerland: For low and intermediate level waste in a cementitious near field → splitting into two waste groups postulated, where for one waste group we can assume better sorption behaviour; for the 2nd group, pessimistic sorption in a conservative way to account for complexing agents.

15/02/2023 Training material eurad 27

CHEMICAL COMPOSITION (+ORGANICS) – REPRESENTATION IN THE SAFETY ASSESSMENT

- Examples:
  - Example from Lithuania: Remaining uncertainties in the program were addressed in safety assessment using a number of conservative assumptions associated with presence of organic C-14 compounds.
  - Example from Belgium: As there are many ways (and maybe even ways that might not be known) in which chemical species might degrade barriers or form complexing agents bypassing the retention barriers, special consideration is given to this in the safety assessment, based on FEP-screening. The assessment considers a specific Altered Evolution Scenario, in which it is supposed that 1% of the waste drums fails and contains complexing agents that had not been detected during verification of waste conformity. This results in a scenario where for 1% of the waste, all retention properties of the engineered barriers are reduced to 0. The results are then compared to the risk criterion to be applied to these scenarios.

Impact Alternative Evolurion – complexing agents



cAt safety case from Belgium, 2019, NIRAS/ONDRAF

15/02/2023 Training material eurad 28

RADIONUCLIDE ACTIVITY (INCLUDING THE SCALING FACTOR)

15/02/2023 Training material eurad 29

RADIONUCLIDE ACTIVITY (INCL. VECTOR) - IDENTIFICATION

- Wide variety of methods for radiological characterization: usually determined by measuring gamma emitters (easy to measure nuclides or ETM), and calculate difficult to measure nuclides (DTM) (mostly alfa/beta) by using scaling factors
- All of these methods subject to uncertainties, linked to:
  - **Representativeness** of samples
  - Measurement **accuracy**
  - **Model** uncertainty
- One more source of uncertainty is associated to the **limited knowledge on historical waste characteristics**
- Uncertainties identified while performing different activities in the development of the disposal program:
  - Conceptual phase: processing waste inventory
  - Performing radiological characterization
  - Updating of the inventory
  - Development of the program for demonstration of compliance with WAC

15/02/2023 Training material eurad 30

RADIONUCLIDE ACTIVITY (INCL. VECTOR) - CHARACTERIZATION

- Two types of uncertainties:
  - Related to measurements
    - Characterized through **statistical methods on data**, multiple measurements to allow identify average, maximum/minimum
    - Aggregation of uncertainty on measurement, on conversion towards activity, and for the "difficult to measure" on the scaling factor
  - Related to models
    - Characterized through **probabilistic modelling**, taking account of sampling locations, or making assumptions (e.g. related to material impurities) to calculate average or maximum values.
- Important to keep in mind when characterizing: comprehensiveness of nuclide list, waste flow estimations, radionuclide composition in the waste, waste production process,…
- Uncertainty can be estimated at different levels: for each waste stream, waste family or for each waste drum/package and this for each radionuclide

15/02/2023 Training material eurad 31

RADIONUCLIDE ACTIVITY (INCL. VECTOR) – ASSESSMENT OF THE SAFETY RELEVANCE

- Impact on conceptual planning, siting, construction, waste emplacement, operational and post closure safety, **WAC derivation, waste acceptance process** and instructions for safe waste management
- Radiological activity → linked to the waste management route → **uncertainty can impact the route**
- Underestimation of the activity → impact to workers dose, release and impact on human/environment in the long term or in case of accidents
- Relevance usually determined by safety assessment
  - If **bounding cases used regarding activity content in the safety assessment : significance is low**
  - If not, and in case of **nuclides that contribute to impact** (e.g. C-14) → medium to high significance
- Averaging effects of uncertainties on radionuclide activity when considering multiple packages (some overestimated, some underestimated) → global activity less uncertain
  - Importance of uncertainty when loading disposal facility → **can there be a systematic bias** giving rise to under/overestimation?
- **Compare upper bound uncertainty of radionuclide activity with the WAC** → if complies: no additional tests needed to confirm suitability and uncertainty has low relevance

15/02/2023 Training material eurad 32

RADIONUCLIDE ACTIVITY (INCL. VECTOR) – CLASSIFICATION AND ASSOCIATED ACTIONS

- Classification: to be **reduced and/or mitigated** (mitigated mainly for historical waste)
- How to reduce: Avoided | To be reduced | Mitigated
  - **Additional measurements** on the waste
  - Scaling factors → **regularly perform measurements and redefine/update** the scaling factor
  - Activation calculations and **verification by measurements**
- Important to have **close cooperation between WMO and waste producer**
- In case uncertainty is difficult to reduce:
  - Use **conservative approach** in inventory definition
- Other aspects: improvement of waste management pre-sorting, uncertainty oriented research, development of novel waste characterisation methods,…

15/02/2023 Training material eurad 33

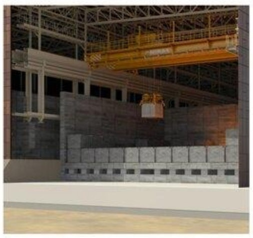
RADIONUCLIDE ACTIVITY (INCL. VECTOR) – REPRESENTATION IN THE SAFETY ASSESSMENT

- Representation in different ways:
  - Use of **reference values and upper bound values** for the activity in different scenarios, in combination with **conservative approaches** where needed
  - In case radionuclide activity uncertainty is dealt with on the level of testing the **compliance with the waste acceptance criteria**, there is no need for special representation in the safety assessment

15/02/2023 Training material eurad 34

MANAGEMENT OF UNCERTAINTIES RELATED TO RADIONUCLIDE ACTIVITY, AN EXAMPLE FROM THE BELGIAN SURFACE DISPOSAL FACILITY

- Surface disposal facility for Low and Intermediate Level Waste in Dessel – license expected < summer 2023.

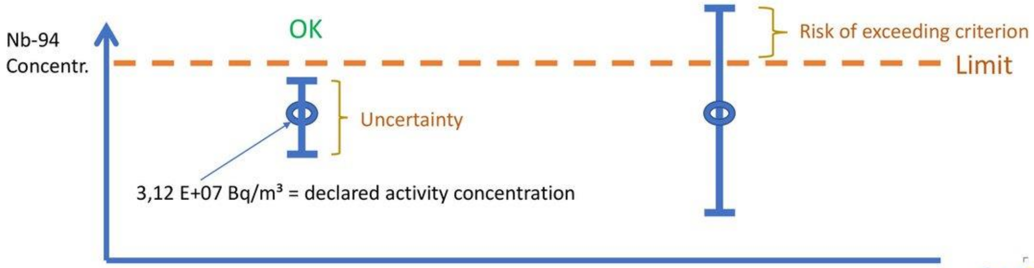

Images © NIRAS/ONDRAF

- Uncertainty on the radionuclide activity → might result in exceeding waste acceptance criteria (WAC), specifically concentration limits per nuclide

15/02/2023 Training material eurad 35

MANAGEMENT OF UNCERTAINTIES RELATED TO RADIONUCLIDE ACTIVITY, AN EXAMPLE FROM THE BELGIAN SURFACE DISPOSAL FACILITY

- Waste drum XX-245
  - Concentration limit for disposal: Nb-94: 7 E+08 Bq/m^3
  - Maximum concentration Nb-94 as declared in a drum: 3,12 E+07 Bq/m^3 → OK?



15/02/2023 Training material eurad 36

APPROACH

- Principle:
  - When [declared activity c° + uncertainty] does not exceed criterion → OK
  - When [declared activity c° + uncertainty] exceeds criterion → reduce uncertainty by additional tests to confirm radiological content (non destructive and/or destructive testing), because risk significant of exceeding limit. Certain % of the waste is tested.
- In practice:
  - For a given waste family → determine nuclides for which declared activity in waste is relatively close to the limit (e.g. < factor 100)
  - Determine uncertainty on activity concentration of these nuclides (see next slide)
  - Confront [declared activity c° + uncertainty] with limits and do according to the principle
  - Reiterate with nuclides excluded from uncertainty assessment that their exclusion is OK (e.g. exclusion > factor 100 is OK, given magnitude uncertainties obtained for other nuclides)

15/02/2023 Training material 37

DETERMINE UNCERTAINTY ON ACTIVITY CONCENTRATION

Uncertainty on the key nuclide

- In the example: Co-60 used as key nuclide for Nb-94 (both activation)
  - Nuclide is measured by using gamma spectroscopy
  - Uncertainties from measuring system, parameter settings, waste density, location of activity in the package,…
  - In our example: estimated to be an '**key nuclide uncertainty factor**' of 2 (which means that the activity can be 2x the declared activity c°
  - Uncertainty factor due to key nuclide 'i' measurement uncertainty: $Uf_{KeyNucl, i}$

15/02/2023 Training material 38

DETERMINE UNCERTAINTY ON ACTIVITY CONCENTRATION

Uncertainty on the vector

- Determined based on data from previous validation campaigns, verification measurements
  - Larger than uncertainty on measured key nuclides
  - In our example: **vector uncertainty factor** 20
  - Vector uncertainty factor on nuclide 'j' = $Uf_{Vector,j}$
- Total uncertainty factor for nuclide 'j', deteremined using measurements on nuclide 'i':
  - $Uf_{total,j} = Uf_{KeyNucl,i} \times Uf_{Vector,j}$
  - In our case: $Uf_{total,Nb\text{-}94} = Uf_{KeyNucl,Co\text{-}60} \times Uf_{Vector,Nb\text{-}94}$
  - In our case: $Uf_{total,Nb\text{-}94} = 2 \times 20 = 40$

DETERMINE UNCERTAINTY ON ACTIVITY CONCENTRATION

[Declared activity c° + uncertainty]

- $A_{j,+uncertainty} = A_{declared,j} \times Uf_{total,j} = A_{declared} \times f_{KeyNucl,i} \times Uf_{Vector,j}$
- In our case: $A_{declared,Nb\text{-}94} \times Uf_{total,Nb\text{-}94}$ = 3,12 E+07 Bq/m³ x 40= 1,24 E+09 Bq/m³ > limit (7 E+08 Bq/m³)
  - Ratio [declared activity c° + uncertainty]/Limit = 1,24 E+09 Bq/m³ / 7 E+08 Bq/m³ = ~1,78 >>1

DETERMINE UNCERTAINTY ON ACTIVITY CONCENTRATION

Radionuclide	Uncertainty factor on vector	Uncertainty factor on measurements	Total uncertainty factor
Nb-94	20	-	40
Co-60	1	2	
Sr-90	4	-	16
Sn-126	4	-	16
Cs-137	1	4	4
Pu-238	4	-	24
Pu-239	4	-	24
Pu-240	4	-	24
Pu-241	4	-	24
Am-241	1	6	6

Collo	Am-241	Cs-137	Nb-94	Pu-238	Pu-239	Pu-240	Pu-241	Sn-126	Sr-90
XX-244	2,17E-01	8,80E-04	1,82E-01	1,09E-01	6,90E-01	2,61E-01	6,14E-02	7,80E-04	2,66E-02
XX-245	2,76E-01	6,49E-04	1,78E+00	2,54E-01	8,78E-01	3,33E-01	7,80E-02	5,76E-04	1,96E-02
XX-246	1,32E-01	5,98E-04	2,68E-04	1,21E-01	4,20E-01	1,60E-01	3,74E-02	5,28E-04	1,81E-02
XX-247	2,57E-02	5,01E-04	4,86E+00	2,36E-02	8,20E-02	3,10E-02	7,27E-03	4,44E-04	1,50E-02
XX-248	1,55E-01	8,08E-05	5,04E-03	1,42E-01	4,88E-01	1,85E-01	4,37E-02	7,16E-05	2,44E-03
XX-249	2,68E-01	3,49E-04	1,65E+00	2,46E-01	8,53E-01	3,22E-01	7,65E-02	3,09E-04	1,04E-02
XX-250	5,58E-01	3,93E-04	8,93E-02	5,14E-01	1,79E+00	6,72E-01	1,59E-01	3,49E-04	1,18E-02
XX-251	2,66E-01	1,07E-03	6,75E+00	2,44E-01	8,47E-01	3,21E-01	7,50E-02	9,48E-04	3,22E-02
XX-252	7,12E-02	2,22E-04	8,68E-01	6,54E-02	2,26E-01	8,58E-02	2,03E-02	1,97E-04	6,68E-03
XX-253	3,43E-01	8,90E-04	1,12E+00	3,14E-01	1,09E+00	4,14E-01	9,75E-02	7,88E-04	2,67E-02
XX-254	1,01E+00	2,61E-04	1,88E-01	9,36E-01	3,22E+00	1,22E+00	2,87E-01	2,32E-04	7,92E-03
XX-255	8,63E-03	7,66E-05	1,18E-02	7,98E-03	2,77E-02	1,05E-02	2,47E-03	6,80E-05	2,30E-03
XX-256	2,50E-02	4,25E-04	7,93E+00	2,30E-02	7,97E-02	3,01E-02	7,13E-03	3,78E-04	1,28E-02
XX-257	3,11E-02	4,03E-05	1,14E-01	2,87E-02	9,92E-02	3,76E-02	8,85E-03	3,58E-05	1,22E-03
XX-258	1,38E-02	6,42E-06	1,60E-02	1,28E-02	4,40E-02	1,67E-02	3,95E-03	5,68E-06	1,94E-04
XX-259	5,94E-03	5,76E-04	1,56E-01	5,47E-03	1,88E-02	7,14E-03	1,69E-03	5,08E-04	1,73E-02
XX-260	6,52E-02	9,61E-04	2,50E-01	6,06E-02	2,08E-01	7,86E-02	1,85E-02	8,56E-04	2,91E-02
XX-261	8,33E-01	5,25E-04	6,21E-02	7,68E-01	2,68E+00	1,01E+00	2,38E-01	4,64E-04	1,58E-02
XX-262	1,53E-01	2,41E-04	5,18E-01	1,41E-01	4,87E-01	1,84E-01	4,34E-02	2,14E-04	7,24E-03
XX-263	3,32E-03	1,69E-05	3,46E-01	3,04E-03	1,05E-02	4,00E-03	9,38E-04	1,49E-05	5,08E-04
XX-264	1,17E-01	1,27E-03	9,96E-01	1,08E-01	3,74E-01	1,42E-01	3,34E-02	1,12E-03	3,80E-02

(This is a real example, but not with the real data)

Declared activity c° + uncertainty, devided by the limit
exceeding limit is >1: red

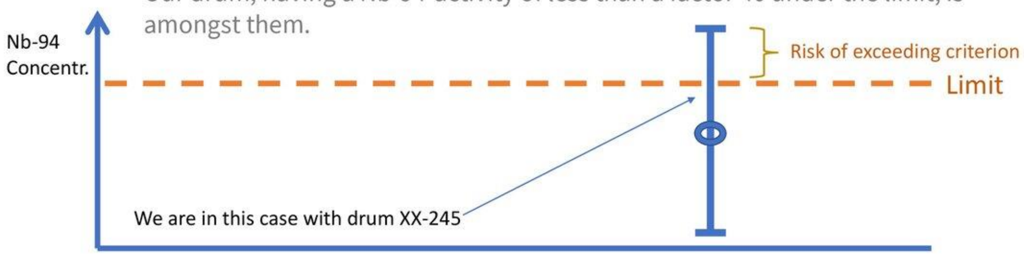
eurad

15/02/2023 Training material 41

DETERMINE UNCERTAINTY ON ACTIVITY CONCENTRATION

Several drums have risk of exceeding limit when taking into account uncertainty

- Our drum, having a Nb-94-activity of less than a factor 40 under the limit, is amongst them.



- Several of the drums will be selected for additional measurements (NDT/DT) in order to reduce uncertainty + confirm compliance

eurad

15/02/2023 Training material 42

CONCLUSIONS

- You have learned about different examples of uncertainties related to waste inventory, how to identify, characterize, assess the importance and manage them with the help of different management options. Examples on chemical composition, storage & disposal conditions, radionuclide activity were given.
- Almost each case of an uncertainty management is unique, because it depends on so many boundary conditions/parameters/…and so the way it is managed can easily differ from waste stream to waste stream, disposal concept to disposal concept, country to country. This course and the deliverables of UMAN related to this can hopefully be an inspiration for your cases, on how to deal with these uncertainties.

15/02/2023 Training material eurad 43

JUST A VERY FINAL THOUGHT FOR TODAY...

Just sharing a view I always kept in mind when working with uncertainty. Something learned from a book…..

JURASSIC PARK

15/02/2023 Training material eurad 44

JUST A VERY FINAL THOUGHT FOR TODAY…

Are all dinosaurs accounted for in the Jurassic park?
→ look for the 238 animals expected
→ yes they are all there – 238 found - OK

Total Animals 238

Species	Expected	Found	Ver
Tyrannosaurs	2	2	4.1
Maiasaurs	21	21	3.3
Stegosaurs	4	4	3.9
Triceratops	8	8	3.1
Procompsognathids	49	49	3.9
Othnielia	16	16	3.1
Velociraptors	8	8	3.0
Apatosaurs	17	17	3.1
Hadrosaurs	11	11	3.1
Dilophosaurs	7	7	4.3
Pterosaurs	6	6	4.3
Hypsilophodontids	33	33	2.9
Euoplocephalids	16	16	4.0
Styracosaurs	18	18	3.9
Microceratops	22	22	4.1
Total	238	238	

15/02/2023 Training material 45

JUST A VERY FINAL THOUGHT FOR TODAY…

Looking beyond what you expect to find

Total Animals 292

Species	Expected	Found	Ver
Tyrannosaurs	2	2	4.1
Maiasaurs	21	22	??
Stegosaurs	4	4	3.9
Triceratops	8	8	3.1
Procompsognathids	49	65	??
Othnielia	16	23	??
Velociraptors	8	37	??
Apatosaurs	17	17	3.1
Hadrosaurs	11	11	3.1
Dilophosaurs	7	7	4.3
Pterosaurs	6	6	4.3
Hypsilophodontids	33	34	??
Euoplocephalids	16	16	4.0
Styracosaurs	18	18	3.9
Microceratops	22	22	4.1
Total	238	292	

In uncertainty identification, characterization and management, it muight be useful to keep looking beyond what is expected to find, and question from time to time the boundary conditions…. e.g. are all relevant nuclides in the vector? Could certain waste stream have been cross contaminated by other waste?

15/02/2023 Training material 46

BIBLIOGRAPHY AND/OR REFERENCES.

- EURAD UMAN 4.2 deliverable on waste inventory, in Deliverable D10.11: Study on management options for different types of uncertainties and programme phases
- NPJ materials degradation 3, Article number: 38 (2019) , "Mathieu Debure, Yannick Linard, Christelle Martin & Francis Claret. In situ nuclear-glass corrosión under geological repository conditions. https://www.nature.com/articles/s41529-019-0100-7
- cAt-Surface disposal facility safety case – chapter 14 Long term safety assessment: https://www.niras.be/sites/default/files/HS14_Veiligheidsevaluatie%20-%20langetermijnveiligheid.pdf
- Decree No. 377/2016 on requirements for safe radioactive waste management and on decommissioning of nuclear installations or workplaces of category III or IV, available at : https://www.sujb.cz/fileadmin/sujb/docs/legislativa/vyhlasky/377_Radioactive_Waste.pdf

And many more are in the EURAD deliverable D10.11

15/02/2023 Training material 47

Appendix J. Slides of lecture C.1

C.1 Views of Civil Society on Uncertainty Management

Prepared by Julien Dewoghélaëre, NTW

VIEWS OF CIVIL SOCIETY ON UNCERTAINTY MANAGEMENT

EURAD Training on Uncertainty Management – Day 3

Julien Dewoghelaere (NTW)• WP 10 - UMAN

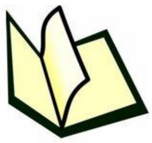
This project has received funding from the European Union's Horizon 2020 research and innovation programme 2014-2018 under grant agreement N°847593

16-02-2023 UMAN Training material 1

KEY WORDS

- Transparency and public participation
- Civil Society participation in research programmes
- Fruitful interactions between institutional/technical experts and civil society in uncertainty management linked to geological disposal
  - Pluralistic assessment and methodologies
  - Complex issues (geological disposal as a socio-technical tool)
  - Civil Society contribution to uncertainty management
  - Uncertainties related to human aspects

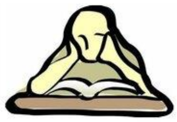
16-02-2023 UMAN Training material 2



CONTENTS

- Learning outcomes
- Introduction – Why having this lesson on civil society views related to uncertainty management ?
- Title 1 – Model of Civil Society (CS) involvement in EURAD and in UMAN project
- Title 2 – CS views on uncertainty management (global picture)
- Title 3 – CS views on uncertainties related to human aspects
- Title 4 – Identified methodologies to enable pluralistic management of uncertainties
- Summary and conclusions
- Bibliography and/or References
- Glossary

16-02-2023 UMAN Training material eurad 3



LEARNING OUTCOMES

After the completion of this training lesson, the participants should be able to:

- Better understand the conditions and means for enabling meaningful interactions between experts and civil society in the field of nuclear research and uncertainty management
- Mobilise basic knowledge on CS views related to uncertainty management with a focus on uncertainty related to human aspects (based on the UMAN project results)
- Identify several methodologies that could facilitate a pluralistic management of uncertainties all along the disposal programme

16-02-2023 UMAN Training material eurad 4

INTRODUCTION - WHY HAVING THIS LESSON ON CIVIL SOCIETY VIEWS RELATED TO UNCERTAINTY MANAGEMENT ?

- Involvement of stakeholders is essential at all stages of a Radioactive Waste Management (RWM) programme (and also it could be a legal requirement)
- Decisions have to be made in the presence of uncertainties. Dealing with uncertainties associated to disposal facilities is particularly challenging due to the long timescales (at least several generations)
- At the end of the process, some uncertainties will inevitably remain but it should be demonstrated that these uncertainties do not undermine safety arguments

In this context, it is necessary to implement a pluralistic management (diversity of actors, interdisciplinary and transdisciplinary) :

- o To enable a mutual understanding of the uncertainties at stake (or at least a better understanding of the views of the involved actors)
- o To enrich the research results of different views
- o To address all the types of uncertainties that are embedded (technical and non-technical)

The implementation of such pluralistic management requires developing and experimenting innovative tools and methods

16-02-2023 UMAN Training material 5

TITLE 1

MODEL OF CIVIL SOCIETY INVOLVEMENT IN EURAD AND IN UMAN PROJECT

16-02-2023 UMAN Training material 6

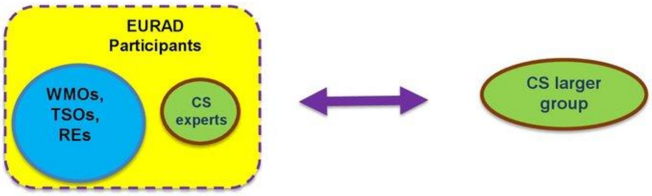
INTERACTIONS WITH CIVIL SOCIETY IN EURAD: WHY ?

- Civil Society (CS) participants have specific concern on RWM safety, they are not research partners
- CS participants are involved in EURAD in the perspective of the UNECE Aarhus Convention which reinforces the requirements of Public access to information and participation in decision-making.
- One objective of EURAD is to allow interactions between all categories of actors : WMOs, TSOs, REs and Civil Society ("3+1 Dialogue")
- Such interactions aim at improving mutual understanding of how and to what extent RD&D activities on RWM make sense and contribute improving decisions
- It also contributes to developing ideas, propositions and methodologies on
  - how to interact with Civil Society on scientific and technical results
  - how to deal with uncertainties

16-02-2023 UMAN training material eurad 7

ICS ACTIVITIES : HOW ? - DOUBLE WING MODEL

- **Model of pluralistic interactions developed and tested in previous projects (SITEX-II, JOPRAD)**
  - CS experts with technical and socio-technical background or/and experience on the involvement of CS in scientific and technical issues,
  - involved in EURAD activities through NTW (international association), translating scientific/technical results for exchanging with
  - A larger group of CS representatives (CSOs, representatives of local communities, individual experts)



CS Experts from Austria, Denmark, Finland, France, Hungary, Netherland, Slovakia, Slovenia, Sweden, United Kingdom

16-02-2023 UMAN training material eurad 8

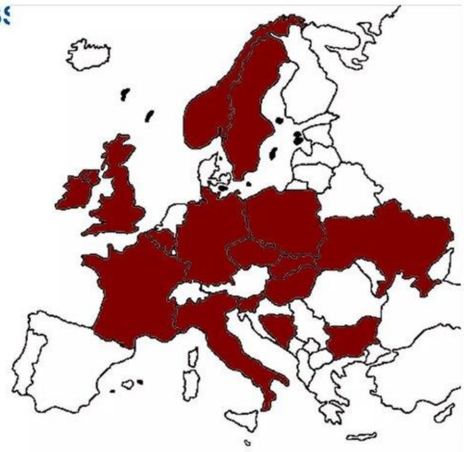
CS LARGER GROUP – COMPOSITION

- **D1.13 List of CS group members https://www.ejp-eurad.eu/publications/eurad-d113-list-cs-group-members**
- **Identification of potential members: 61 potential identified candidates coming from 25 countries**
- **Several categories of participants**
  - 2 categories of actors and organisations:
    - European and national associations
    - local stakeholders (individuals and representatives of local communities, partnerships, local associations)
  - 22 members invited (according to the available resources to cover the physical participation) – group finalized in March 2020

16-02-2023 UMAN training material 9

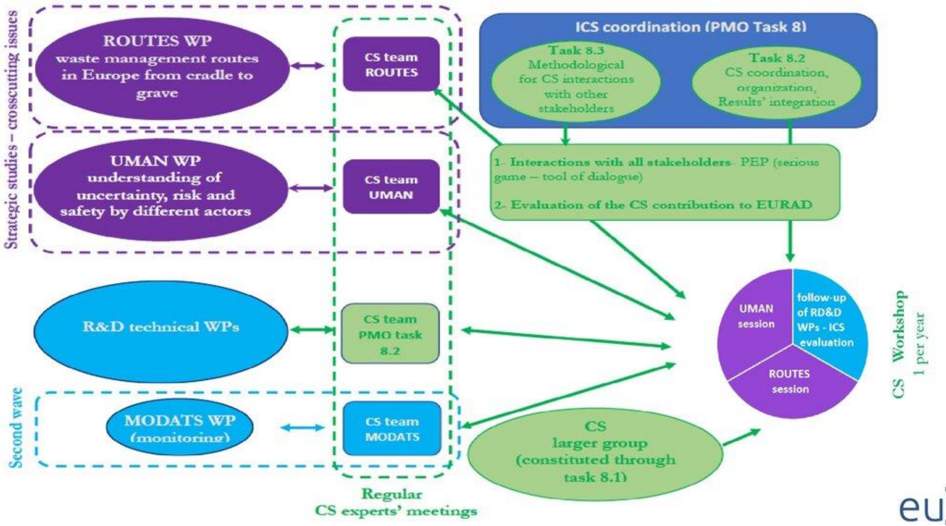
CS LARGER GROUP – REPRESENTATIVENESS

- **A well-balanced group:**
  - Equilibrium between Western and Eastern countries
  - Quite well-balanced gender representativity (9 Women and 13 Men)
  - Good repartition between the categories of involved stakeholders (12 individual or/and local stakeholders and 10 national or/and European associations)
  - **15 countries are represented in the CS larger group**: Belgium, France, Germany, Italy, Norway, Sweden, United Kingdom, Bosnia and Herzegovina, Bulgaria, Czech Republic, Hungary, Poland, Slovakia, Slovenia, Ukraine



16-02-2023 UMAN training material 10

STRUCTURE OF ICS ACTIVITIES IN EURAD



16-02-2023 UMAN training material 11

ICS ACTIVITIES IN UMAN

- During yearly seminars, **discussion of UMAN results with a pluralistic stakeholder group** including EURAD researchers, Civil Society actors, regulators and international organisations (FSC (Forum on Stakeholder Confidence) of NEA)
- **Integrative process** - each seminar constitutes one step of a process of integration of UMAN results:
  - Seminar 1: Meaning of uncertainty management for different actors (October 2020)
  - Seminar 2: Focus on Site and Geosphere related uncertainties (October 2021)
  - Seminar 3: Focus on Human Aspects related uncertainties (June 2022)
  - Seminar 4: Methods that can be used for discussing and organising pluralistic assessments of uncertainties throughout a disposal programme (December 2022)

16-02-2023 UMAN training material 12

TITLE 2

CS VIEWS ON UNCERTAINTY MANAGEMENT (GLOBAL PICTURE)

16-02-2023 UMAN Training material 13

RESULTS FROM UMAN SEMINAR 1 : GLOBAL PICTURE ON UNCERTAINTY MANAGEMENT

- **Shared concerns by involved actors emerged from the pluralistic discussion in UMAN:**
  - "Unknown unknowns" : how to address them? How to live with them? **How to be prepared to the unexpected**?
  - **Independence of expertise :** what does-it mean ? How it can be done in practice ?
  - Importance to consider uncertainty related to the process (governance issue), lot of **ignored knowns factors** (i.e. available knowledge one may not be aware of or fail to consider in one's activities) to explore
  - At the general level, **agreement on the importance of uncertainty management in Safety Case**, differences will appear in concrete implementation (according to cultural contexts, role of the actors in the process, risk appetite)

16-02-2023 UMAN training material 14

CS VIEWS ON UNCERTAINTIES RELATED TO GOVERNANCE

- **Continued independence of the authority is a precondition for effective Safety Case review.**
- Considerable uncertainties are attached to the continuity, availability and integrity of the governance framework (governing institutions and associated expertise) over long period of time.
- According to CS, this is already problematic in some EU member states.
- **Preserving independence of governing bodies cannot only be achieved on a national basis.**
- Safety standards depend on how democracy is handled**. The role of CS is very important in the upholding of the safety standards.** To increase confidence in the system, CS representatives should be involved in the decision-making of the governing institutions.
- There is also **uncertainty regarding the "independence" of the public** : compensation policies at local level can impede local inhabitants' awareness of safety priorities.

16-02-2023 UMAN training material 15

SOCIETAL EXPECTATIONS ON SAFETY STANDARDS VARY OVER TIME

- **Uncertainties exist all along the successive phases of the repository program (and all along the whole RWM programme)**. It is the reason why the decision to authorize (or not) implementation of GD cannot be a blank cheque.
- **The GD Safety Case has to evolve over time** due to science and interaction with society.
- A given option that is considered as safe today does not entail that future generations would have the same opinion. Would we accept today battlefield surgery conditions endured by soldiers on the 17th Century?
- **Evolution of the interpretation of the safety requirements should be anticipated** as a proof of the fairness of the decision-making process
- **Flexibility on the interpretation of safety standards is definitely a factor of confidence** on the long term.

16-02-2023 UMAN training material 16

CS VIEWS - INVESTIGATING NON-TECHNICAL UNCERTAINTIES

- **Placing RW into Deep Geology of a given place in the planet is, by no mean, solely a technical task.**
- **There is often some reluctance in the public with idea of reposing radioactive wastes in the geology, this is beyond the question of safety.**
  - To incorporate GD in the geology of the place where I live is connected with the concrete relation I have with my territory and with other humans and non-human components of my environment.
  - This is linked with my vision of the planet, of the future, of the human destiny and role.
- **Political and societal decision to authorize a GD is not a unidimensional consequence of the acceptance of the safety case by authorities. The safety case acceptance is only a pre-condition of the political decision.**
- **Achieving a decision to host or not a repository entails complex human and contextual aspects. Refusing to host a repository cannot be reduced to a NIMBY attitude. This should further be investigated by research.**

16-02-2023 UMAN training material eurad 17

CS VIEWS - UNCERTAINTIES ON ALTERNATIVES

- **Will alternative scenarios and alternatives to the deep geological disposal be fully elaborated, reviewed and assessed beforehand as well as all along its implementation?**
- Will feedback on the operation and review of earlier decisions be performed, even at the later phases?
- Will there be a Plan B available if needed? (needs to be developed in parallel to Plan A)
- **Will the risk of abandoning the project before completion be taken into proper account?** (due to new knowledge on geology or technology, political crisis, end of budget …)
- It is important for CS group members **that a failure to find a "good enough" plan will lead to a second, alternative Plan B. Then the uncertainty in the process itself that is perceived by the public may be reduced.**

16-02-2023 UMAN training material eurad 18

TOWARDS THE END OF TIME: SOME REFLECTIONS ON UNCERTAINTIES IN THE POST-CLOSURE PHASE

- **Will it be possible to recover the nuclear waste in the post-closure phase? For how long?**
- Will the possibility of full retrievability/recoverability be one of the determining criteria for choosing the proper type of disposal method?
- **What is needed is a characterisation of the needs for retrievability options and the corresponding criteria** in order to make it possible to plan for keeping these options open as long as possible.
- **Uncertainties on trans-generational aspects include information transfer from generation to generation**, the risk of memory and data loss, warning over time, the time perspective of surveillance (when can it be stopped?) and responsibilities, also after the responsible bodies have disappeared.

16-02-2023 UMAN training material 19

CS VIEWS ON UNCERTAINTIES IN TRANSPARENCY AND PUBLIC PARTICIPATION (T&PP) – EFFECTIVE INTERACTION WITH CIVIL SOCIETY

- **THE OBJECTIVE OF ICS IN REGARD TO UNCERTAINTIES IS EFFICIENCY**
- The conditions for effective interaction with CS within R&D in RWM are linked to the **conditions for effective transparency in the governance on decision-making in RWM**. Transparency in decision-making is essential for the enduring and constructive engagement of CS.
- This is important for improving the **safety of RWM projects, facilities and repositories**. Effective transparency leads to better decision-making and can thereby increase confidence of CS in the quality and fairness of RWM decision-making processes.
- Effective Interaction with CS in R&D for RWM can **build up competence** that will allow for better understanding of issues of importance during decision-making.

16-02-2023 UMAN training material 20

TITLE 3

CS VIEWS ON UNCERTAINTIES RELATED TO HUMAN ASPECTS

16-02-2023 UMAN Training material 21

THE LIST OF THE 10 UNCERTAINTIES RELATED TO HUMAN ASPECTS SELECTED BY UMAN PROJECT FOR FURTHER INVESTIGATION

- A: Process for the identification of a workable set of repository requirements
- B: Continuity of the waste management policy along political changes
- C: Robustness of the presently considered safety requirements with regard to the long term
- **D: Public acceptance of the repository at potentially suitable or projected locations**
- **E: Schedule to be considered for implementing the different phases of the disposal programme**
- F: Robustness of the safety case vis-à-vis sociotechnical factors
- **G: Reliability of monitoring results and safety analysis**
- **H: Adequacy of safety-related activities (in siting, design, construction, operation and closure) for the implementation of safety provisions**
- I: Robustness of safety performance vis-à-vis possible cyber-attacks or programming
- J: Availability of well-educated human resources and relevant experts in radioactive waste management along the repository lifetime until closure

16-02-2023 UMAN training material 22

RELEVANCE OF PUBLIC ACCEPTANCE IN REGARD TO CS INVOLVEMENT

- **CS ASSERTION**: *In an open, democratic society*, **public acceptance of any GD** *is* **a GOAL IN ITSELF**.
- **As part of an UNCERTAINTY MANAGEMENT STRATEGY**, public acceptance can **CONFIRM** the quality of **safety solutions**. Conversely, public non-acceptance can be a way to **CORRECT the wrong implementation of safety measures**.
- Thus, public acceptance and non-acceptance can **change over time**, especially if safety measures are perceived as better or proven wrong.
- **ALSO**: Even if it is seen only as a mean to succeed with final disposal of RW – which could be the case by some of the research actors in EURAD– one could argue that the achievement of public acceptance is **one of the main reasons for the EURAD 3+1 dialogue itself**.

16-02-2023 UMAN training material eurad 23

CS VIEWS ON SCHEDULE TO BE CONSIDERED FOR IMPLEMENTING THE DIFFERENT PHASES OF THE DISPOSAL PROGRAMME 1/2

- **To what extent should uncertainty on schedule be considered as an uncertainty** for safety ?
- **Postponing decisions can be a condition for improving safety** (precautionary principle), taking appropriate time to manage unexpected events or uncertainties
- Differences of views between several authorities involved in the decision might be at the origin of disclosure of problematic aspects of safety
- **However postponing decision requires appropriate plan B,** in order to prevent waste packages ageing and rock and structures behaviour …

16-02-2023 UMAN training material eurad 24

CS VIEWS ON SCHEDULE TO BE CONSIDERED FOR IMPLEMENTING THE DIFFERENT PHASES OF THE DISPOSAL PROGRAMME 2/2

- **Stepwise approach should provide due time in order to give proper attention** to setting the safety conditions for reaching a new step.
- **Stepwise approach should be embedded in a Long-term/Rolling Stewardship (RS) perspective** required by a multi-stakeholder and intergenerational governance, this could involve e.g. :
  - Scheduling a license renewal procedure every 10 years, in order to update the GD safety case review according to monitoring results and to incorporate updated stakeholder's views
  - There might be big and small steps, leading to foreseen or unforeseen direction.
- Flexibility (reversibility, retrievability, proper funding for alternative options should be part of RS provisions)
- Proper provisions to maintain safety while postponing is requested

16-02-2023 UMAN training material eurad 25

CS VIEWS ON NEW KNOWLEDGE

- The possibility of new knowledge is inherent to a safety analysis of a long-term process,
- New knowledge does not undermine the credibility of the safety review, on the contrary it does contribute to reinforce it
- The question is therefore the extent to which new knowledge can be integrated in the GD implementation in order to reinforce safety
- A structure has to be implemented to produce new knowledge and consider its relevance for the GD (esp. in the far future). Possibly the periodic safety reviews and the renewal of the licenses could be used as points in time to introduce and discuss new knowledge in a democratic , participatory way.
- Such a structure has to be linked to Rolling Stewardship.

16-02-2023 UMAN training material eurad 26

CS VIEWS ON ADEQUACY OF SAFETY-RELATED ACTIVITIES FOR THE IMPLEMENTATION OF SAFETY PROVISIONS

The implementation of an enlarged safety culture appears to be a precondition for ensuring continuity of safety related activities

The term 'Safety Culture' was first introduced in INSAG's *Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident,* published by the IAEA in 1986,

> *Safety culture is that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance.*

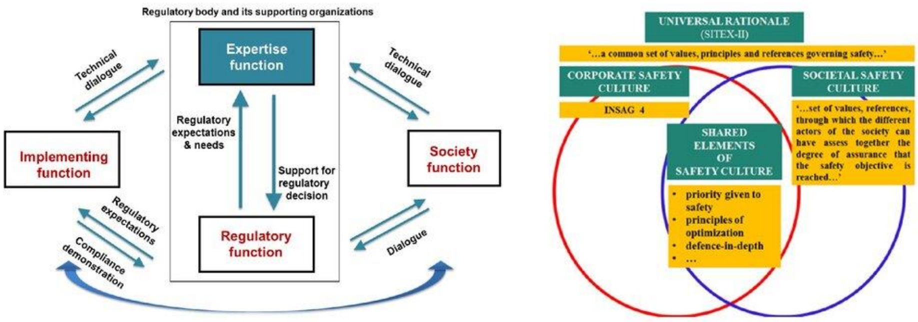
The Safety Culture is addressing the first circle of nuclear actors involved in nuclear safety: governments, regulators, operators, researchers & designers at institutional and individual levels

16-02-2023 UMAN training material 27

SITEX Network

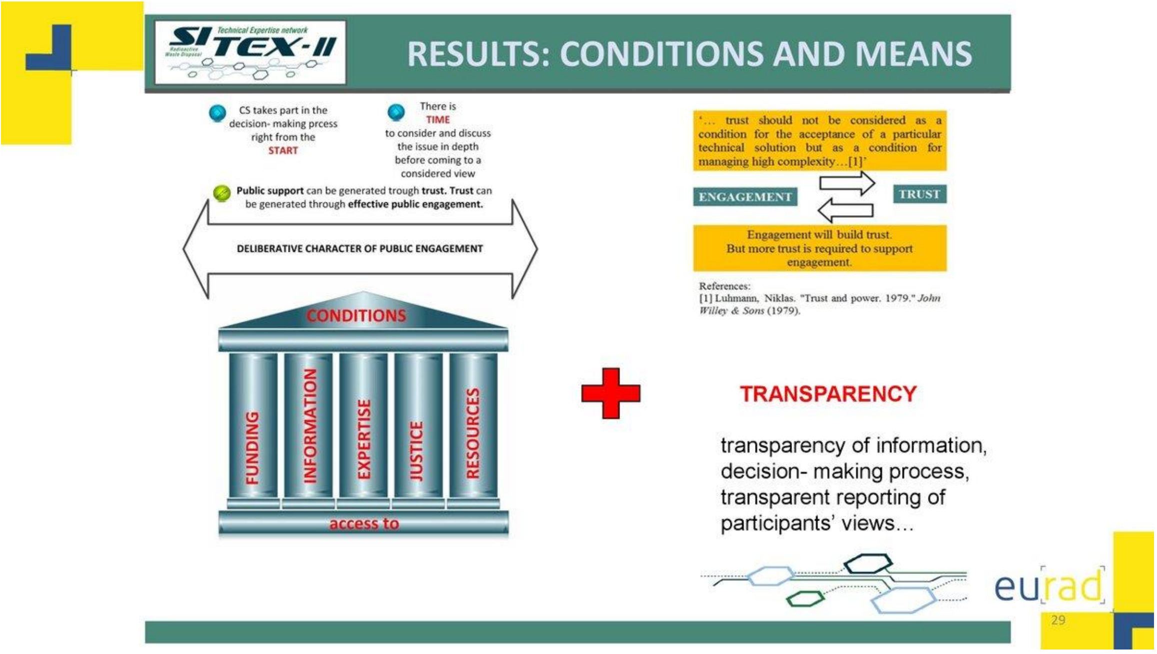
AN ENLARGED SAFETY CULTURE TO SUPPORT VERY LONG TERM INTERACTIONS WITH SOCIETY (SITEX II) – FANC (TASK – LEADER)

VERY LONG TERM INTERGENERATIONAL GOVERNANCE



HOW TO CREATE CONDITIONS FOR SUSTAINED MUTUAL TRUST?

28



TITLE 4

IDENTIFIED METHODOLOGIES TO ENABLE PLURALISTIC MANAGEMENT OF UNCERTAINTIES

16-02-2023 UMAN Training material

eurad 30

IDENTIFICATION OF METHODOLOGIES AND PROCESSES TO ENABLE PLURALISTIC MANAGEMENT OF UNCERTAINTIES

During the UMAN seminars, thoughts and ideas have been raised regarding pluralistic management of uncertainties.

Task 5 gathered these ideas and conceptualised them in methodologies and processes enabling **multi-actors and multi-disciplinary** management of uncertainties in the frame of geological disposal.

The methodologies are divided in two categories:

- the generic methodologies identified during discussions
- methodologies that have been tested in the frame of EURAD research

GENERIC METHODOLOGIES 1/3

Development of a **shared Safety culture** and its intergenerational transmission:

- Safety Culture is a very promising concept in order to sustain trustworthy interactions among the concerned categories of actors in the context of long-term RWM processes involving uncertainties but also need for flexibility according to progress & errors necessitating reorientation along the process
- Safety Culture is typically a sociotechnical concept
- Further research is needed to update the Safety culture concept to the specificities of RWM in order to:
    - Encompass the very long- term dimension of RWM processes
    - Include Civil Society at international, national and local level, along the development of the Safety Case within a Long-term/Rolling Stewardship perspective
    - Develop the specific requirement vis-à-vis Civil Society as a genuine contributor of the quality of RWM decisions, in the perspective of the Aarhus Convention

GENERIC METHODOLOGIES 2/3 – LONG-TERM/ROLLING STEWARDSHIP AS A MANAGEMENT METHOD

Almost all uncertainties linked to RWM will have an unpredictable impact on future generations. Therefore, ensuring recoverability and keeping the memory of the repository alive could be important.

Implementation of a Long-Term/**Rolling Stewardship culture could be a management strategy to investigate:**

- **knowledge and responsibility for the nuclear waste is handed over in society from generation to generation in a structured way**: every 25 (?) years the nuclear waste is visited, checked, if needed repacked, the instructions are updated for the next generation
- it implies notably intergenerational transmission of information, empowerment of communities, cultural heritage, e.g., regular celebration around waste like Dutch case.

Rolling stewardship ideas need to be further investigated

16-02-2023 UMAN training material 33

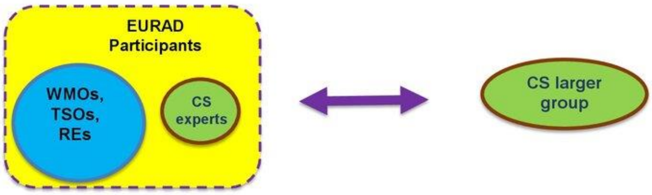
GENERIC METHODOLOGIES - 3/3

- Reinforcement of an **appropriate legal framework** enabling pluralistic interaction:
  - Aarhus Convention and its three pillars (access to information, effective public participation including report on ways public consultations are duly taken into consideration, access to justice if the two other pillars are denied)
  - Access to resources for enabling effective public participation as indicated in the BEPPER report
  - Prescriptive EU directives (e.g., Article 10 Transparency of RWM directive, promotion, and enhancement of public participation)
  - International recommendations and guidance (e.g., FSC, IGSC)
- Implementation of **a stepwise approach** including notably:
  - intergenerational safety case review
  - reversibility/Retrievability/ Recoverability principles
  - a continuous knowledge management

16-02-2023 UMAN training material 34

METHODOLOGIES TESTED IN THE FRAME OF EURAD 1/2

- **Double Wing Model** in the frame of research
  - for translating technical knowledge to enable a larger public to understand it and make up their own minds on the topic,
  - for problematizing socio-technical issues
  - Could the double wing model be extended to other situations? (e.g., follow-up of Geological Disposal implementation for instance) On what conditions?



16-02-2023 UMAN training material 35

METHODOLOGIES TESTED IN THE FRAME OF EURAD 2/2

Pathway Evaluation Process (PEP) approach: concrete cases to organize pluralistic discussions on uncertainties on the same footing.

- tool of dialogue (designed as a serious game) developed under the frame of the SITEX.network that enable multi-actors' discussions in the field of radioactive waste management
- Methodologies could be used in in different formats and in different contexts:
  - E.g. in UMAN - Discussion in small groups are based on concrete cases illustrating the issues to be discussed (uncertainties in our case). The link with concrete issues enables all actors to enter the discussion on the same footing.

16-02-2023 UMAN training material 36

GAME MECHANISM – PEP METHODOLOGY 1/2

- Elaboration of scenarios to test the robustness of a pathway :

  one testing condition card (TC) associated with two Evaluation Criteria cards

Political upheaval

A major political change affects the decision-making process.

E.g.: • The split of the country jeopardizes its RWM strategy.
• During internal troubles, existing storage site falls in the hands of separatists.
• A neighbouring country obtains that a facility is closed / moved.

Disruptive Events B5

\+

???

Risk of abandonment

To what extent is the pathway vulnerable to possible abandonment in uncontrolled conditions, before reaching a Safe Terminus?

Governance Quality Y9

???

Confiscation from future generations

What are the unavoidable consequences of the pathway for future generations? What are the issues to be addressed by the successive generations? What margin for effective decision does the pathway leaves them?

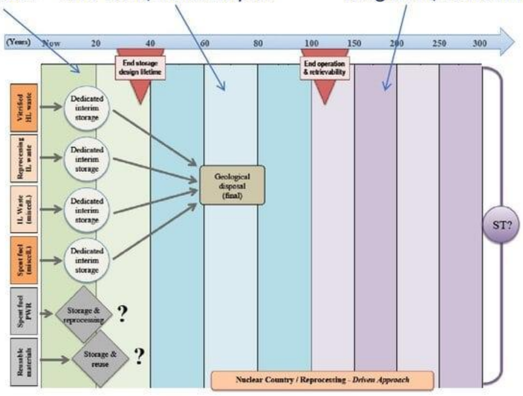
Values & Ethics Z3

16-02-2023 UMAN training material eurad 37

GAME MECHANISM - PEP METHODOLOGY 2/2

- The TC card is positioned at a specific period:

Now/few decades Mid-Term/hundred year Long term/ few centuries



eurad 38

KEY MESSAGES REGARDING PEP TOOL

- PEP is not a tool to choose between approaches. The main aim is to allow a pluralistic discussion on the way to secure safety of humans and the natural environment through different strategies that have all advantages and disadvantages.
- PEP allows discussing a broad range of issues and envisioning situations and solutions participants may not have thought of.
- PEP helps the players to grasp the complexity of RWM that is considered here as a socio-technical issue, not only a technical one.
- PEP discussions emphasize the importance of transversal elements (to have in mind in all the pathway), notably institutional structure and background, meaningful public participation, pluralistic expertise, availability of financial resources, monitoring and memory in long-term horizons.

16-02-2023 UMAN training material eurad 39

SUMMARY AND CONCLUSIONS 1/2

- Interactions between experts and civil society aim at improving mutual understanding on uncertainty, contribute to the development of a shared safety culture and therefore contribute to improve R&D results and safety (at the end of the process).
- CS actors involved in EURAD have a strong interest to maintain independence of expertise, to reinforce research on uncertainties related to "unknown unknowns", governance issues (including reversibility, transparency and post-closure) and non-technical uncertainties in general
- Public acceptance can be seen as an uncertainty management strategy: a complementary way to ensure the quality of the system (not necessarily as a human uncertainty)
- Postponing decisions can be a condition for improving safety (precautionary principle), taking appropriate time to manage unexpected events or uncertainties
- New knowledge does not undermine the credibility of the safety review, on the contrary it does contribute to reinforce it

16-02-2023 UMAN Training material eurad 40

SUMMARY AND CONCLUSIONS 2/2

Methodologies and processes can be implemented to enable **multi-actors and multi-disciplinary** management of uncertainties in the frame of geological disposal :

- The implementation of an enlarged safety culture appears to be a precondition for ensuring continuity of safety related activities and for supporting an intergenerational, multi-actors management of uncertainties related to GD
- Implementation of a Long-Term/Rolling Stewardship culture could be a management strategy for ensuring intergenerational transmission of information, empowerment of communities, cultural heritage
- Reinforcement of an appropriate legal framework is necessary to enabling pluralistic management of uncertainty
- Double Wing Model in the frame of research is a way for translating technical knowledge in order to enable a larger public to understand technical results and make up their own minds on the research topic
- Development of dialogue tool (under the format of serious game) could facilitate the development of pluralistic management of uncertainties

16-02-2023 UMAN Training material 41

BIBLIOGRAPHY AND/OR REFERENCES

- Text of the Aarhus Convention: https://unece.org/environment-policy/public-participation/aarhus-convention/text
- BEPPER Report: transparency in Radioactive Waste Management, December 2015: https://www.nuclear-transparency-watch.eu/a-la-une/new-publication-bepper-report.html
- EURAD Deliverable D 1.13: List of members of the Civil Society group, Mars 2020 : https://www.ejp-eurad.eu/publications
- Including civil society in R&D projects on Radioactive Waste Management: Interactions with Civil Society (ICS) in EURAD, BASE Symposium, November 2021: https://sand.copernicus.org/articles/1/247/2021/sand-1-247-2021.pdf
- EURAD Deliverable D1.14 : Mid-term evaluation of the ICS activities and experimental model of interaction between EURAD participants and Civil Society, April 2022
- EURAD Lunch and Learn Session on PEP methodology: https://www.ejp-eurad.eu/news/recording-ll-pluralistic-tool-dialogue-rwm-pathway-evaluation-process-pep

Future planned publications:

- Multi-actor dialogue on managing site and geosphere uncertainties in a radioactive waste management programme: lessons from the UMAN project (EURAD), WM2023 Conference, Phoenix Arizona (February-March 2023)
- EURAD UMAN Deliverable D 10.13: Understanding of uncertainty management by the various stakeholders, April 2023
- EURAD UMAN Deliverable D 10.14: Pluralistic analysis of site and geosphere uncertainty, April 2023
- EURAD UMAN Deliverable D 10.15: Pluralistic analysis of humans aspects related uncertainty, June 2023
- EURAD UMAN Deliverable D 10.16: Methods that can be used for discussing and organising pluralistic assessments of uncertainties throughout a disposal programme , June 2023

16-02-2023 UMAN Training material 42

GLOSSARY

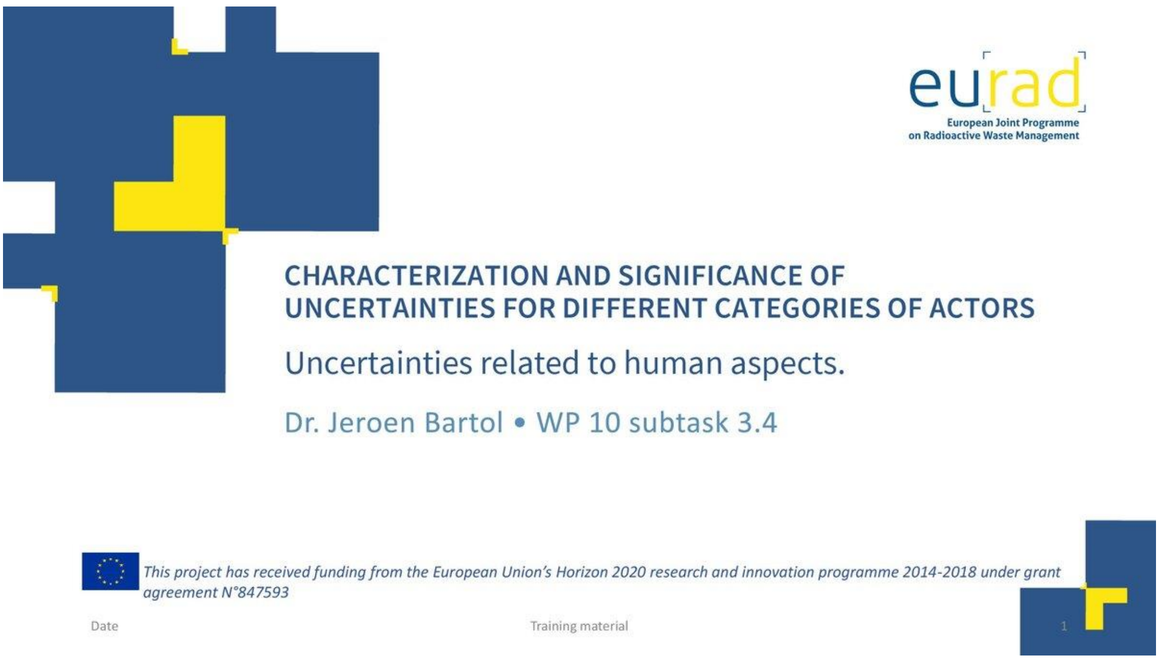
- CS = Civil Society
- ICS = Interaction with Civil Society
- NTW = Nuclear Transparency Watch
- RE = Research Entities
- R&D = Research and Developement
- RWM = radioactive waste management
- TSO = Technical Support Organisation
- UMAN = Uncertainty Management multi-Actor Network (project in EURAD programme dedicated to uncertainty management and interactions between the different types of actors for reaching a mutual understanding)
- UNECE = The United Nations Economic Commission for Europe
- WMO = Waste Management organisation

16-02-2023 UMAN Training material eurad 43

Appendix K. Slides of lecture C.2

C.2 Characterization and significance of uncertainties related to human aspects

Prepared by Jeroen Bartol, COVRA



CONTENTS

- Learning outcomes.
- Introduction.
- Before we start : phases.
- The process.
- Important uncertainties.
- Uncertainties about uncertainties.
- Summary and conclusions.
- Bibliography and/or References.

Date Training material 3

LEARNING OUTCOMES.

After the completion of this training lesson, the students/participants should have an idea about the uncertainties identified in WP 10 subtask 3 and the 10 most important (as identified in the workgroup) uncertainties, their impact and how to deal with them. They will also learn how they can apply the method used in WP 10 subtask 3.4 to identified uncertainties and what they shouldn't do.

The uncertainties.

The ten most important ones, their impact and how to deal with them.

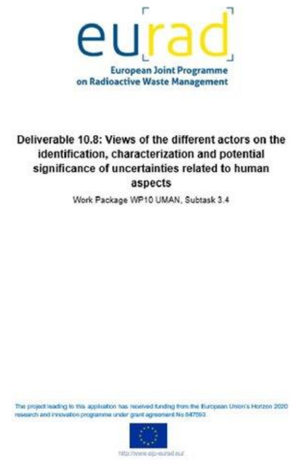
How to identify uncertainties.

Date Training material 4

INTRODUCTION

Over a period of 3 - 4 years, we Jean-Noël DUMONT (ANDRA), Nadja ZELEZNIK (EIMV), Jeroen BARTOL (COVRA), Erika HOLT (VTT), we have worked on this subtask. In this presentation, I will go deeper into this work package. More specifically, the process and the result.

The report has not been published yet but is very close to be finished (currently in review).


eurad
European Joint Programme on Radioactive Waste Management

Deliverable 10.8: Views of the different actors on the identification, characterization and potential significance of uncertainties related to human aspects

Work Package WP10 UMAN, Subtask 3.4

Cover of the report of Dumont et al., (2023)

16-02-2023 Training material eurad 5

INTRODUCTION | THE UNCERTAINTIES

The time period we are considering for the uncertainties. Note that we miss the need for action, disposal concept etc. They are before the site selection.

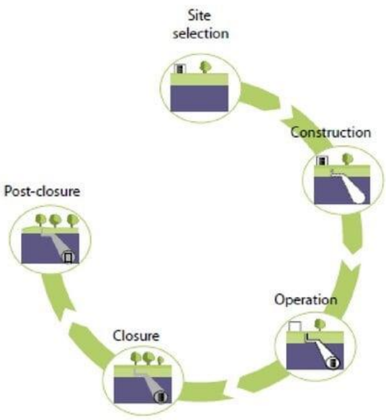


Figure from Verhoef et al., (2017)

16-02-2023 Training material eurad 6

INTRODUCTION | IMPLICATIONS AND HOW TO DEAL WITH IT

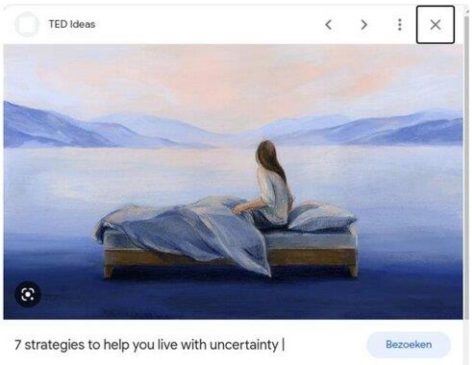


Image from google search when searching for uncertainty humans.

16-02-2023 Training material eurad 7

BEFORE WE START | PHASES

Before we start, a word of caution. In our report, we have used **different names** for the phases. A reason for the discrepancies is that they have been established with categories of human activities in mind **(design, siting, construction...)**, whereas the EURAD phases are defined as successive periods of time, even if their labelling refers to the main activity within each period.

Stage of the repository used for uncertainties identification	Stage Identification number	EURAD phase number	EURAD phase and theme
Need for action	0	Phase 11	Initiation: Policy, framework and programme establishment Theme 1: National Programme Management
Disposal concept development	1a	Phase 22	Site Selection: Site(s) identification and selection, Generic assessment of options Site Requirements and waste inventory Themes 2 (Pre-Disposal), 3 (EBS), 4 (Geoscience), 5 (Disposal facility design and optimisation), 7 (Safety case)
Site evaluation and detailed design	1b-2	Phase 22 Phase 33	Site Selection: Site(s) identification and selection, Site characterisation: Underground investigations and site confirmation, Site Requirements, Evaluation Theme 6 (siting and licensing) Site Characterization & Selection
Construction	3	Phase 44 Phase 55	Construction: Facility construction, Operations and Closure: Facility operation and closure (facility construction and construction work carried out during operation and closure) Theme 3 (EBS), 5 (Disposal facility design and optimisation) and 7 (Safety case)
Operation	4a	Phase 55	Operations and Closure (except final closure) Theme 1 (National Programme Management), 5 (Disposal facility design and optimisation) and 7 (Safety case)
Closure	4b	Phase 55	Operations and closure (subphase related to final closure) Theme 1 (National Programme Management), 5 (Disposal facility design and optimisation) and 7 (Safety case)
Post-closure – Indirect oversight	5a	Phase 5	Post-closure phase (first subphase)
Post-closure – No oversight	5b	Phase 5	Post-closure phase (second subphase)

Dumont et al., (2023)

16-02-2023 Training material eurad 8

THE PROCESS

The process | Step 1 Brainstorm

↓

The process | Step 2 Reduction

↓

The process | Step 3 Questionnaire

THE PROCESS | STEP 1 IDENTIFICATION

A **structured brainstorming** within the expert group (representatives from **2 waste management organizations (WMOs)**, **1 research entity (RE)** and **1 civil society, (CS)**, to identify as completely as possible the relevant uncertainties. The result was a long **list of uncertainties (58)** that are related to the humans. For the structured brainstorm sessions, we used the **different phases of a repository life cycle**. This was our inspiration.

When published, you can find the entire list of uncertainties online.

Identification							Selection	
3.9	*3*	*Management system: safety culture*	*Safety of operation*	*Governance*	*How will the safety of operation be assured from the management and other societal points of views?*	*Who will take part in operation? Will there be an independent body to oversight management?*	*Medium*	Similar to the safety culture within the company, at national level. Stresses the need for independent oversight.
4a.1	4a	Robustness of the safety case vis-à-vis sociotechnical factors	Sociotechnical uncertainties related to safety case and political uncertainties related to licensing	*Sociotechnical, Political, Societal,*	Are human and organizational factors together with technical factors properly taken into account in the safety case? How can political uncertainties affect licensing?	How is efficient communication ensured between the different experts? Who has expertise to have an overall picture of the safety? How do political uncertainties affect licensing? Is the possibility of unintentional errors properly addressed?	High	Sociotechnical i.e. interconnectedness of societal, organizational and technical aspects create emerging risks and surprises. They play relevant role in safety case and licensing, and therefore, it is necessary to understand, identify, mitigate and tackle with these sociotechnical issues.
4a.2	4a	Reliability of monitoring results and safety analysis	Sociotechnical challenges related to monitoring and long-term safety	*Socio-technical, technological*	Will new knowledge, insights or monitoring techniques reveal deficiencies that need to make corrective measures?		High	Consequences of weaknesses in monitoring techniques may have safety significance, even though it can be assumed that weaknesses in monitoring techniques will be noticed early enough.
4a.3	4a	Adequacy of activities in operation for the implementation of (operational and long-term) safety provisions	Human and organisational factors	*Socio-technical, organizational, Governance*	How can changes in organization and safety culture affect the safety of the operation phase?	How is it ensured that knowledge management is taken care of? How is it ensured that people have got adequate training?	High	Human and organizational aspects are inherently involved in the management of operation phase and in any decisions regarding operation, resources and technology. Furthermore, outsourcing of services and work complicates the management of human and organizational aspects. Sociotechnical systems view emphasizes the need for seeing technical and organizational aspects simultaneously (Harvey and Stanton 2014)[*].
4a.4	4a	Robustness of operational safety vis-à-vis possible societal disruptions	Societal disruptions	*Societal*	How could societal disruptions affect safety?		Low	Societal disruption can have severe impacts on operation.
4a.5	4a	Robustness of safety vis-à-vis possible cyber-attacks or	Sociotechnical interface, unintentional (e.g. programming	Technological	How could cyber security and security aspects affect safety?	How should organizations take into account the possibility of intentional actions and errors?	High	Remote control, programming and related cybersecurity risks and uncertainties are worth of further investigations.

THE PROCESS | STEP 1 IDENTIFICATION

Subsequently each of the uncertainty was assigned an specific category that was relevant in the identification of human related uncertainties. These categories are the following: **Societal, Political, Technological systems, Financial, Governance and risk governance, Socio-technical and Organizational.**

Identification							Selection	
3.9	*3*	*Management system: safety culture*	*Safety of operation*	*Governance*	*How will the safety of operation be assured from the management and other societal points of views?*	*Who will take part in operation? Will there be an independent body to oversight management?*	*Medium*	Similar to the safety culture within the company, at national level. Stresses the need for independent oversight.
4a.1	4a	Robustness of the safety case vis-à-vis sociotechnical factors	Sociotechnical uncertainties related to safety case and political uncertainties related to licensing	*Sociotechnical, Political, Societal,*	Are human and organizational factors together with technical factors properly taken into account in the safety case? How can political uncertainties affect licensing?	How is efficient communication ensured between the different experts? Who has expertise to have an overall picture of the safety? How do political uncertainties affect licensing? Is the possibility of unintentional errors properly addressed?	High	Sociotechnical i.e. interconnectedness of societal, organizational and technical aspects create emerging risks and surprises. They play relevant role in safety case and licensing, and therefore, it is necessary to understand, identify, mitigate and tackle with these sociotechnical issues.
4a.2	4a	Reliability of monitoring results and safety analysis	Sociotechnical challenges related to monitoring and long-term safety	*Socio-technical, technological*	Will new knowledge, insights or monitoring techniques reveal deficiencies that need to make corrective measures?		High	Consequences of weaknesses in monitoring techniques may have safety significance, even though it can be assumed that weaknesses in monitoring techniques will be noticed early enough.
4a.3	4a	Adequacy of activities in operation for the implementation of (operational and long-term) safety provisions	Human and organisational factors	*Socio-technical, organizational, Governance*	How can changes in organization and safety culture affect the safety of the operation phase?	How is it ensured that knowledge management is taken care of? How is it ensured that people have got adequate training?	High	Human and organizational aspects are inherently involved in the management of operation phase and in any decisions regarding operation, resources and technology. Furthermore, outsourcing of services and work complicates the management of human and organizational aspects. Sociotechnical systems view emphasizes the need for seeing technical and organizational aspects simultaneously (Harvey and Stanton 2014)[iv].
4a.4	4a	Robustness of operational safety vis-à-vis possible societal disruptions	Societal disruptions	*Societal*	How could societal disruptions affect safety?		Low	Societal disruption can have severe impacts on operation.
4a.5	4a	Robustness of safety vis-à-vis possible cyber-attacks or	Sociotechnical interface, unintentional (e.g. programming	Technological	How could cyber security and security aspects affect safety?	How should organizations take into account the possibility of intentional actions and errors?	High	Remote control, programming and related cybersecurity risks and uncertainties are worth of further investigations.

16-02-2023 Training material

eurad 11

THE PROCESS | STEP 1 EXAMPLES

Societal, Political, Technological systems, Financial, Governance and risk governance, Socio-technical and Organizational.

Societal relates to or **involves society**. Societal concerns /problems/values Examples of societal questions relevant for the nuclear waste management context would include social acceptance of nuclear waste management, **social media**, and **societal support for education of experts in the nuclear waste management**. Other examples for societal problems that could affect nuclear waste management are **wars**, **distrust** in institutions, and increase of right- and left-wing extremists.

Identification						Selection	
Phase	Object of uncertainty	Origin of uncertainty		Describing the uncertainty			
		Origin	Typology	General question	Examples of specific questions	Priority	Rationale for rating
1b-2	Urgency of the availability of a repository	Possibility of societal disruptions enhancing the risks associated with existing waste	**Societal**	Will the need for such repository be modified?	How should we take into account the possibility of a societal disruption making the availability of a solution more urgent?	low	This uncertainty has limited impacts on safety and decision making and is rated as low.

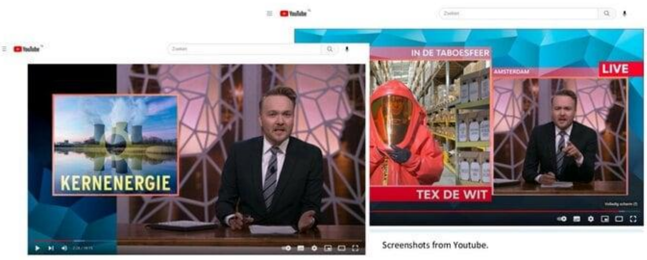
16-02-2023 Training material

eurad 12

THE PROCESS | STEP 1 EXAMPLES

Societal, Political, Technological systems, Financial, Governance and risk governance, Socio-technical and Organizational.

Societal relates to or **involves society**. Societal concerns /problems/values Examples of societal questions relevant for the nuclear waste management context would include social acceptance of nuclear waste management, **social media**, and **societal support for education of experts in the nuclear waste management**. Other examples for societal problems that could affect nuclear waste management are **wars, distrust** in institutions, and increase of right- and left-wing extremists.



Screenshots from Youtube.

16-02-2023 Training material 13

THE PROCESS | STEP 1 EXAMPLES

Societal, **Political**, Technological systems, Financial, Governance and risk governance, Socio-technical and Organizational.

Political means the way power is achieved and used in a country or society. Synonyms: governmental, government, state, parliamentary Examples of political issues: **Changes in parliament** and governmental power**, power politics affecting nuclear waste management**, **visions and policies regarding nuclear waste management**. Aspects of political issues can also cover issues of future geographical borders of countries.

Identification						Selection	
Phase	Object of uncertainty	Origin of uncertainty		Describing the uncertainty			
		Origin	Typology	General question	Examples of specific questions	Priority	Rationale for rating
0-2	Waste inventory	Possibility of societal disruptions enhancing the risks associated with existing waste	**Political**	Are there new, emerging needs associated to changes in energy policy?	Should we consider spent MOX as waste (France)?	Medium	Evolutions in energy policy will surely happen. They will modify, at least, the inventory of the various types of RW, but also sometimes will make new types of wastes appear. Nevertheless, the spectrum of already identified RW allows taking into account some future evolutions, when launching a disposal programme and in the design.

16-02-2023 Training material 14

THE PROCESS | STEP 1 EXAMPLES

Societal, **Political**, Technological systems, Financial, Governance and risk governance, Socio-technical and Organizational.

Political means the way power is achieved and used in a country or society. Synonyms: governmental, government, state, parliamentary Examples of political issues: **Changes in parliament** and governmental power**, power politics affecting nuclear waste management**, **visions and policies regarding nuclear waste management**. Aspects of political issues can also cover issues of future geographical borders of countries.

Photo from COVRA.

Is waste that is not radioactive still waste or a resource?

16-02-2023 Training material eurad 15

THE PROCESS | STEP 1 EXAMPLES

Societal, **Political**, Technological systems, Financial, Governance and risk governance, Socio-technical and Organizational.

Political means the way power is achieved and used in a country or society. Synonyms: governmental, government, state, parliamentary Examples of political issues: **Changes in parliament** and governmental power**, power politics affecting nuclear waste management, visions and policies regarding nuclear waste management.** Aspects of political issues can also cover issues of future geographical borders of countries.

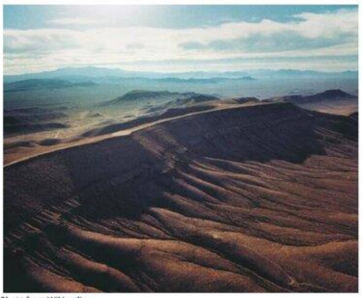


Photo from Wikipedia.

Yucca mountain is still no repository mostly because of political reasons.

16-02-2023 Training material eurad 16

THE PROCESS | STEP 1 EXAMPLES

Societal, Political, **Technological systems**, Financial, Governance and risk governance, Socio-technical and Organizational.

Technological systems include technical devices, the organizational routines and procedures, legislative artefacts, and scientific and other **knowledge elements such as skills, rules of thumbs** and norms for handling of the technology.

Identification						Selection	
Phase	Object of uncertainty	Origin of uncertainty		Describing the uncertainty			
		Origin	Typology	General question	Examples of specific questions	Priority	Rationale for rating
1a	Robustness of technological choices	Perspective of new technological solutions	**Technological**	Could our present choices be undermined in the future?	Should we shift to extended interim storage in order to allow transmutation technologies to be used?	Low	Both for the safety and decision-making process, the impact is low. Regarding safety, the repository is designed with the latest knowledge available with a safety margin. New insights and new technologies could change insights, but these insights can still be incorporated in this stage. Regarding the decision-making process, although different techniques might be developed in the future, if a country is already in this stage, they already made the decision to use a repository for their waste rather than wait for new techniques. And therefore, impact is low. As both are low, the research priority is also set to low; it comes close to what if scenarios.

16-02-2023 Training material 17

THE PROCESS | STEP 1 EXAMPLES

Societal, Political, Technological systems, **Financial**, Governance and risk governance, Socio-technical and Organizational.

Financial is a field that is concerned with the allocation (investments) of assets and liabilities over space and time, often under condition of risk and uncertainty. Examples of financial aspects: The **sufficiency of financial resources regarding** the nuclear waste management and final disposal, the way the financial **resources are collected and the way** sufficient resources are estimated, uncertainties related to management of financial resources, economic depressions.

Identification						Selection	
Phase	Object of uncertainty	Origin of uncertainty		Describing the uncertainty			
		Origin	Typology	General question	Examples of specific questions	Priority	Rationale for rating
1a	Availability of the funds when they will be necessary	Prediction over decades	**Financial**	Will the necessary funds be available?	How much money should the waste producers allow now for the costs of the planned repository and associated research?	Medium	In this stage, funding problems could lead to delays in the decision-making processes and could impact the safety (longer above ground as not enough research is done or no funds are available for the construction of the repository). But as this is still an early stage, additional funding could be found (extra funding from the state) or collected (waste tariffs) and therefore the impact is only medium for both. As both are medium and the consequence of not having enough funds could be high, research priority is set to medium

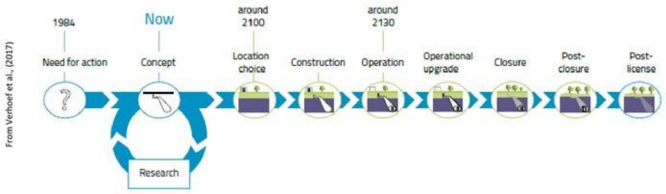
eurad

16-02-2023 Training material 18

THE PROCESS | STEP 1 EXAMPLES

Societal, Political, Technological systems, **Financial**, Governance and risk governance, Socio-technical and Organizational.

Financial is a field that is concerned with the allocation (investments) of assets and liabilities over space and time, often under condition of risk and uncertainty. Examples of financial aspects: The **sufficiency of financial resources regarding** the nuclear waste management and final disposal, the way the financial **resources are collected and the way** sufficient resources are estimated, uncertainties related to management of financial resources, economic depressions.



Waste producers pay for the repository but how to make sure that there are enough funds over 100 years?

16-02-2023 Training material 19

THE PROCESS | STEP 1 EXAMPLES

Societal, Political, Technological systems, Financial, **Governance and risk governance**, Socio-technical and Organizational.

Governance comprises both the institutional structure (formal and informal) and the policy process that guides and restrains collective activities of individuals, groups and societies. It aims to avoid, regulate, **reduce or control risk problems** (Renn 2014). Risk governance refers to a complex of coordinating, **steering, and regulatory processes conducted for collective decision-making involving uncertainty** (Renn 2014).

Identification						Selection	
Phase	Object of uncertainty	Origin of uncertainty		Describing the uncertainty			
		Origin	Typology	General question	Examples of specific questions	Priority	Rationale for rating
1b-2	Compliance wrt repository requirements	Plurality of decision-makers, with various sets of criteria	**Governance**	How will the points of view of the various actors on the compliance with respect to repository requirements be integrated along the licensing processes?	What kind of obstacles could the licensing processes, other than the nuclear safety, be confronted with?	medium	Some other decision makers can bring other views to decision making process, which can impact the safety and the process itself to some degree. The overall is the uncertainty assessed as medium.

16-02-2023 Training material 20

THE PROCESS | STEP 1 EXAMPLES

Societal, Political, Technological systems, Financial, Governance and risk governance, **Socio-technical** and Organizational.

Socio-technical systems refer to intrinsic complexity arising from the **multidimensional interactions between the human, technical and organizational systems**. This is driven by how humans utilize the technologies within the boundaries of the organizational issues, so it is really the interaction of many of the above categories

Identification							Selection
Phase	Object of uncertainty	Origin of uncertainty		Describing the uncertainty			
		Origin	Typology	General question	Examples of specific questions	Priority	Rationale for rating
1b-2	Availability of useful knowledge	Internal (for the company) uncertainties: managing long-lasting projects	**Socio-technical**	Will the necessary knowledge be transmitted?	How can the competences be maintained?	medium	If already at the beginning of this project, the management of this project is not good, research that should have been done, might not have been carried out or is not good / conclusive enough. But since this is still in the early stage, additional research can be carried out later in a later stage if the problems and gaps in knowledge are identified. The latter is not a certainty and therefore the impact is medium. This has only a low impact on decision making processes as managing long lasting projects is not part of the decision-making process. At most, it might delay this process and therefore the impact is low. Research priority is set to medium as this is an exceptional long-term process that would require good management.

16-02-2023 Training material 21

THE PROCESS | STEP 1 EXAMPLES

Societal, Political, Technological systems, Financial, Governance and risk governance, Socio-technical and **Organizational**.

Organizational refers to structures, policies, resources, roles and responsibilities, relationships between the members of an organization, shared values, norms, beliefs and practices in an organization. Examples of organizational aspects: **safety culture**, **whether adequate resources are allocated to important tasks**, whether organization ensures that there are adequate number of experts.

Identification							Selection
Phase	Object of uncertainty	Origin of uncertainty		Describing the uncertainty			
		Origin	Typology	General question	Examples of specific questions	Priority	Rationale for rating
4a	Adequacy of activities in operation for the implementation of (operational and long-term) safety provisions	Human and organisational factors	**Socio-technical, organizational , Governance**	How can changes in organization and safety culture affect the safety of the operation phase?	How is it ensured that knowledge management is taken care of? How is it ensured that people have got adequate training?	High	Human and organizational aspects are inherently involved in the management of operation phase and in any decisions regarding operation, resources and technology. Furthermore, outsourcing of services and work complicates the management of human and organizational aspects. Sociotechnical systems view emphasizes the need for seeing technical and organizational aspects simultaneously (Harvey and Stanton 2014) .

16-02-2023 Training material 22

THE PROCESS | STEP 2 REDUCTION

The result was a long list of uncertainties that are related to the humans. **How to reduce it?**

We used four criteria:

The potential impact on safety.

The potential impact on decision-making.

The existence of referenced work in this field and the interest for further studies and research.

Take the diversity of situations of the national programmes represented by the members of the expert group into account

16-02-2023 Training material

eurad

23

THE PROCESS | STEP 2 REDUCTION

Selection: Import! Always record why you have selected (or not) an uncertainty. We did this in the selection column of out graph. This is important as others can better understand your selection criteria.

Q1: A general question related to the uncertainty.

Q2: A more specific question related to the uncertainty. In general these can be regarded as examples.

Q1 *Q2* *Selection*

Identification							Selection	
3.9	*3*	*Management system: safety culture*	*Safety of operation*	*Governance*	*How will the safety of operation be assured from the management and other societal points of views?*	*Who will take part in operation? Will there be an independent body to oversight management?*	*Medium*	Similar to the safety culture within the company, at national level. Stresses the need for independent oversight.
4a.1	4a	Robustness of the safety case vis-à-vis sociotechnical factors	Sociotechnical uncertainties related to safety case and political uncertainties related to licensing	*Sociotechnical, Political, Societal,*	Are human and organizational factors together with technical factors properly taken into account in the safety case? How can political uncertainties affect licensing?	How is efficient communication ensured between the different experts? Who has expertise to have an overall picture of the safety? How do political uncertainties affect licensing? Is the possibility of unintentional errors properly addressed?	High	Sociotechnical i.e. interconnectedness of societal, organizational and technical aspects create emerging risks and surprises. They play relevant role in safety case and licensing, and therefore, it is necessary to understand, identify, mitigate and tackle with these sociotechnical issues.
4a.2	4a	Reliability of monitoring results and safety analysis	Sociotechnical challenges related to monitoring and long-term safety	*Socio-technical, technological*	Will new knowledge, insights or monitoring techniques reveal deficiencies that need to make corrective measures?		High	Consequences of weaknesses in monitoring techniques may have safety significance, even though it can be assumed that weaknesses in monitoring techniques will be noticed early enough.
4a.3	4a	Adequacy of activities in operation for the implementation of (operational and long-term) safety provisions	Human and organisational factors	*Socio-technical, organizational, Governance*	How can changes in organization and safety culture affect the safety of the operation phase?	How is it ensured that knowledge management is taken care of? How is it ensured that people have got adequate training?	High	Human and organizational aspects are inherently involved in the management of operation phase and in any decisions regarding operation, resources and technology. Furthermore, outsourcing of services and work complicates the management of human and organizational aspects. Sociotechnical systems view emphasizes the need for seeing technical and organizational aspects simultaneously (Harvey and Stanton 2014).
4a.4	4a	Robustness of operational safety vis-à-vis possible societal disruptions	Societal disruptions	*Societal*	How could societal disruptions affect safety?		Low	Societal disruption can have severe impacts on operation.
4a.5	4a	Robustness of safety vis-à-vis possible cyber-attacks or	Sociotechnical interface, unintentional (e.g. programming	Technological	How could cyber security and security aspects affect safety?	How should organizations take into account the possibility of intentional actions and errors?	High	Remote control, programming and related cybersecurity risks and uncertainties are worth of further investigations.

Dumont et al., (2023)

16-02-2023 Training material

eurad

24

THE PROCESS | STEP 3 QUESTIONNAIRE

Acronym		WMO	TSO	RE	CS	Near surface	Subsurface	DGD	Belgium	Czech Rep	Finland	France	Germany	Netherlands	Slovakia	Slovenia	Spain	Sweden	Switzerland	Online answers	Word files
V	VTT		1					1			1									1	
A	Andra	1				1		1				1								2	
Be	BelV/FANC		1			1		1	1												2
Bg	BGE	1						2					1								2
Co	COVRA/NRG	1						1						1							1
Cv	CVR			1		1	1	1		1										3	
Ei	EIMV		1			1	1	1								1				3	
En	ENRESA	1				1											1				1
G	GRS			1				2					1								2
I	IRSN		1				1	1				1									2
N	NAGRA	1						1											1		1
O	ONDRAF	1				1		1	1												1
Sk	SKB	1					1											1			1
Sura	SURAO	1						1		1										1	
Sur	SURO		1			1	1	1		1										3	
Sut	SUT			1		1		1							1						1
	Total	8	5	3	0	8	5	16	2	3	1	2	2	1	1	1	1	1	1	13	14

Lesson learnt: Don't use two ways of getting the data. It will be difficult to combine them. Another issue, specifically at that moment in time, is the large number of questionnaires that were send. People were "questionnaire tired".

Date16-02-2023 Training material 25

THE PROCESS | THE 10 UNCERTAINTIES

- **A**: Process for the identification of a workable set of repository requirements
- **B**: Continuity of the waste management policy along political changes
- **C**: Robustness of the presently considered safety requirements with regard to the long term
- **D**: Public acceptance of the repository at potentially suitable or projected location
- **E**: Schedule to be considered for implementing the different phases of the disposal programme

16-02-2023 Training material 26

THE PROCESS | THE 10 UNCERTAINTIES

- **F**: Robustness of the safety case vis-à-vis sociotechnical factors
- **G**: New knowledge
- **H**: Adequacy of safety-related activities (in siting, design, construction, operation and closure) for the implementation of (operational and long-term) safety provisions
- **I**: Robustness of safety vis-à-vis possible cyber-attacks or programming errors
- **J**: Availability of well-educated human resources, and relevant experts in radioactive waste management along the repository lifetime until closure

16-02-2023 Training material eurad 27

A | PROCESS FOR THE IDENTIFICATION OF A WORKABLE SET OF REPOSITORY REQUIREMENTS

From the sometimes diverging requests of the various actors, what should be the consensus on requirements specification for the design?

How will the set of requirements (regarding long-term safety performance, WAC, environmental impact, etc.) be fixed, taking account the sometimes-conflicting expectations of the various stakeholders?

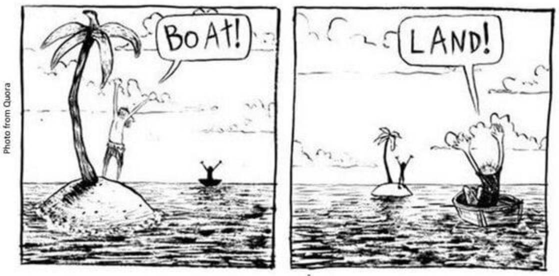
How could the legitimate requests be included in the RWM policy?

What is the willingness to include requests connected to public acceptance of repository?

How is the consistency of governance policies maintained?

16-02-2023 Training material eurad 28

A | PROCESS FOR THE IDENTIFICATION OF A WORKABLE SET OF REPOSITORY REQUIREMENTS



From the sometimes diverging requests of the various actors, what should be the consensus on requirements specification for the design?

16-02-2023 Training material eurad 29

A | PROCESS FOR THE IDENTIFICATION OF A WORKABLE SET OF REPOSITORY REQUIREMENTS

Potential consequences of uncertainty

Delaying the decisions for a repository may have consequences on **the whole schedule of radioactive waste management,** when for example waste already exists and is stored in surface facilities without sustainable solution. The absence of definitive solution may also **tend to delay the dismantling of the reactors**.

16-02-2023 Training material eurad 30

A | PROCESS FOR THE IDENTIFICATION OF A WORKABLE SET OF REPOSITORY REQUIREMENTS

Challenges and potential options for risk management

When developing the approaches to the RWM policy, framework and programme establishment, therefore already at beginning in **phase 0**, it has to be taken into consideration also the **international legal framework** which relates to the different and diverging requests of the various actors which will participate in the RWM activities, and RW disposal establishment.

The requests of other actors may on one **hand conflict** with nuclear **regulatory requirements**, thus cannot be considered, or on the other hand could benefit the process without jeopardizing the safety issues.

16-02-2023 Training material eurad 31

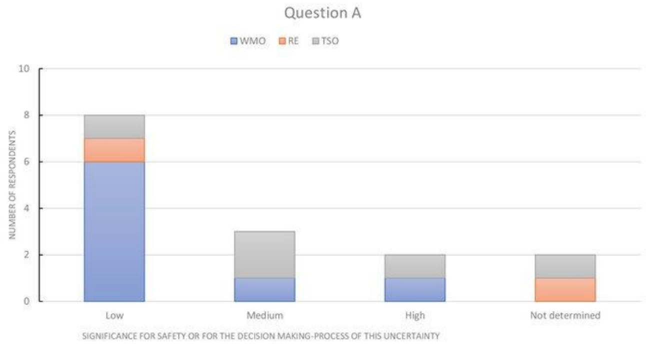
A | PROCESS FOR THE IDENTIFICATION OF A WORKABLE SET OF REPOSITORY REQUIREMENTS

A good example of a interaction between the different actors is the Tabloo in Belgium.

16-02-2023 Training material eurad 32

A | PROCESS FOR THE IDENTIFICATION OF A WORKABLE SET OF REPOSITORY REQUIREMENTS

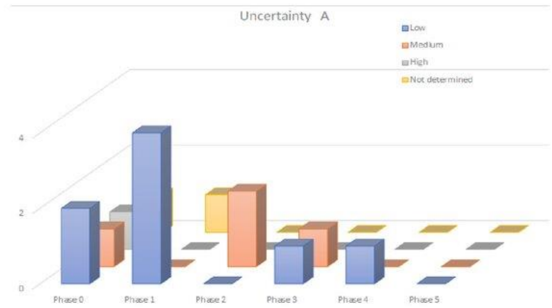
How did other actors think? Most of them do not consider this uncertainty as having a high significance. Most likely this is because most of them are in a country in which the program is not fully developed.



*Results from actors on the questionnaire on uncertainty of identification of a workable set of repository regulations for **deep geological disposal facility**. Note that most actors indicated that the impact on the safety or the decision-making process of this uncertainty is low.*

16-02-2023 Training material 33

A | PROCESS FOR THE IDENTIFICATION OF A WORKABLE SET OF REPOSITORY REQUIREMENTS



*Results from actors on the questionnaire on uncertainty of identification of a workable set of repository regulations for **deep geological disposal facility**. From the figure, no clear correlation can be deduced between the phase and the impact of this uncertainty on the safety or the decision-making process.*

16-02-2023 Training material 34

B | CONTINUITY OF THE WASTE MANAGEMENT POLICY ALONG POLITICAL CHANGES

Question

Is there assurance of RW policy continuity where political changes can impact the process?

How should the RW disposal process be defined?

Which basic elements should be agreed to assure continuation?

What EU level requirements should be set?

16-02-2023 Training material eurad 35

B | CONTINUITY OF THE WASTE MANAGEMENT POLICY ALONG POLITICAL CHANGES

Potential consequences of uncertainty

This uncertainty, for example, could lead to an **increase in decision time** and potentially in an increase of cost as **longer storage at the surface is needed**. This could also have **consequences for the safety.**

If wastes are still produced when no decision has been made, the **waste may pile up at different nuclear sites** under a **wide variety of conditions** which might have a deteriorating effect on the waste. This in turn could **increase the cost of disposal and might even affect the safety of disposal.**

Could result in the production of waste that **cannot easily be processed or stored.**

Could be a lack of **funds for a repository.**

16-02-2023 Training material eurad 36

B | CONTINUITY OF THE WASTE MANAGEMENT POLICY ALONG POLITICAL CHANGES

Challenges and potential options for risk management

Strong disposal statements at the EU level are helpful. Hence, at the EU level, it would be good to have a more precise description of what are the minimum levels of acceptability, transposing such requirements to the national legal framework, and monitoring the implementation at the EU level (similar system as now adopted by the Waste Directive).

But foremost, **it is important that the RW policy has a (very) broad governmental support** making it more robust to changes in government while keeping the option open to change or reverse the RW policy.

Furthermore, **a participatory approach (i.e., local partnership)** could help to get good local support that could in turn **help to keep the programme on-going.**

16-02-2023 Training material eurad 37

B | CONTINUITY OF THE WASTE MANAGEMENT POLICY ALONG POLITICAL CHANGES

But:

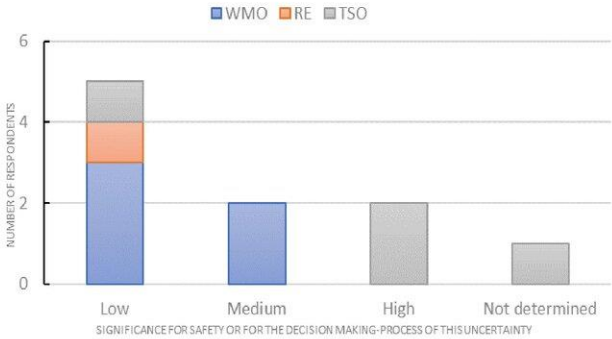
What if the people select a government that is against nuclear energy and as the policy of stopping collecting waste etc? It is the will of the people but will result in problems in the long term.

Photo from Wikipedia: election posters in Italy.

16-02-2023 Training material eurad 38

B | CONTINUITY OF THE WASTE MANAGEMENT POLICY ALONG POLITICAL CHANGES

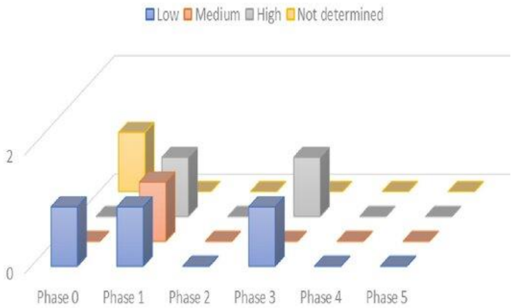
How did other actors think? Most of them do not consider this uncertainty as having a high significance. This is partly due to the fact that most waste management programs are well established. Once established, it is not easy to stop them.



Results from actors on the questionnaire on continuity of the waste management policy along political changes for ***deep geological disposal facility****. Note that most actors indicated that the impact on the safety or the decision making process of this uncertainty is low.*

16-02-2023 Training material 39

B | CONTINUITY OF THE WASTE MANAGEMENT POLICY ALONG POLITICAL CHANGES



Results from actors on the questionnaire on continuity of the waste management policy along political changes for deep geological disposal facility. From the figure, no clear correlation can be deduced between the phase and the impact of this uncertainty on the safety or the decision making process.

16-02-2023 Training material 40

C | UNCERTAINTY ASSOCIATED WITH THE ROBUSTNESS OF THE PRESENTLY CONSIDERED SAFETY REQUIREMENTS WITH REGARD TO THE LONG TERM

Questions

What does the protection of man and the environment mean in the long term?

Which level of effort, supported by present and next generations, should we achieve to protect remote future generations?

What will Man be like in the long term?

Does it make sense to assess safety at 50 000 years based on scenarios that consider human civilization as in the present state?

For long-lived, low-level wastes, which is the suitable trade-off between protection in the long-term (pointing towards deep disposal) and protection against a low level of danger (pointing towards surface disposal)?

16-02-2023 Training material eurad 41

C | UNCERTAINTY ASSOCIATED WITH THE ROBUSTNESS OF THE PRESENTLY CONSIDERED SAFETY REQUIREMENTS WITH REGARD TO THE LONG TERM

What does the long-term protection of Man and the Environment mean?

What level of effort, supported by present and next generations, should we achieve to protect remote future generations?

Potential consequences of uncertainty

A potential consequence of this uncertainty is that it **could increase the time (and costs) to reach** a decision on the concept and associated changes in safety requirements that most agree on.

16-02-2023 Training material eurad 42

C | UNCERTAINTY ASSOCIATED WITH THE ROBUSTNESS OF THE PRESENTLY CONSIDERED SAFETY REQUIREMENTS WITH REGARD TO THE LONG TERM

Challenges and potential options for risk management

The main challenge is related to the evolution of society, **resulting in changing priorities already** on the **short term (several years to a few decades), and making long-term predictions impossible.**

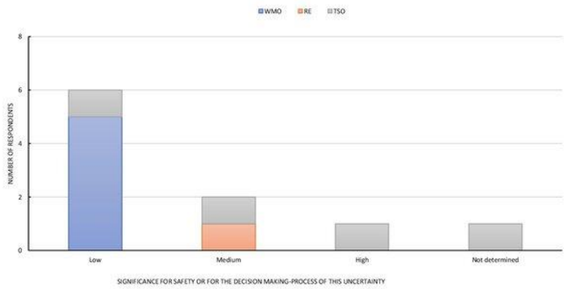
One potential option for managing the risk of this uncertainty is, for example, defining the adequate **long-term safety goal by involving the whole society**.

Furthermore, the **holistic radioactive** waste management programme, of both surface pre-disposal facilities and eventual repository disposal, **should be consistent with the development plans of the affected region and municipalities.**

Additional care should be taken to **avoid overlooking some processes** with potentially significant impact, especially when the requirements are formulated at a general level, while safety must be demonstrated at a detailed level.

16-02-2023 Training material eurad 43

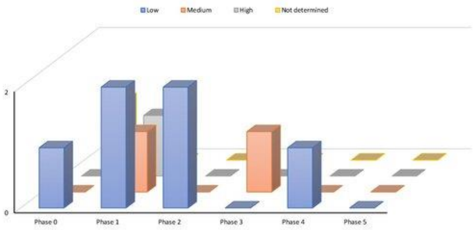
C | UNCERTAINTY ASSOCIATED WITH THE ROBUSTNESS OF THE PRESENTLY CONSIDERED SAFETY REQUIREMENTS WITH REGARD TO THE LONG TERM



Results from actors on the robustness of the presently considered safety requirements with regard to the long term for a deep geological disposal facility. Note that most actors indicated that the significance for safety or the decision-making process is low.

16-02-2023 Training material eurad 44

C | UNCERTAINTY ASSOCIATED WITH THE ROBUSTNESS OF THE PRESENTLY CONSIDERED SAFETY REQUIREMENTS WITH REGARD TO THE LONG TERM



*Results from actors on the robustness of the presently considered safety requirements with regard to the long term for **deep geological disposal facility**. From the figure, no clear correlation can be deduced between the phase and the significance for safety or the decision-making process.*

16-02-2023 Training material eurad 45

D | UNCERTAINTY IN THE PUBLIC ACCEPTANCE OF THE REPOSITORY AT POTENTIALLY SUITABLE OR PROJECTED LOCATIONS

Questions

What is the attitude towards repository in the community?

Has there been any facility for which the public showed the NIMBY effect?

What possibilities for engagement are given to the public?

Are all relevant stakeholders identified and mapped?

Is there a relevant process established to communicate and engage with stakeholders?

How is the communication and stakeholder engagement process integrated into the decision-making process for site selection?

16-02-2023 Training material eurad 46

D | UNCERTAINTY IN THE PUBLIC ACCEPTANCE OF THE REPOSITORY AT POTENTIALLY SUITABLE OR PROJECTED LOCATIONS

Potential consequences of uncertainty

Site selection can be **delayed for a relatively long period** or, in the most extreme case, it can even be **stopped**. Delaying or stopping the siting can have a **significant financial consequence as the siting process may have to start from scratch again.**

Furthermore, **not building a repository**, due to lack of public acceptance, requires maintaining active measures to ensure the safety and **security of storage facilities that must remain open**. Keeping storage facilities open for extended periods will in the **long term (1) cost even more money, (2) place the burden on future generations and (3) increase the risk associated with the skills loss political instabilities and aging of the storage facilities.** Furthermore, keeping these facilities open increases the exposure times for workers and the number of exposed workers.

Date Training material eurad 47

D | UNCERTAINTY IN THE PUBLIC ACCEPTANCE OF THE REPOSITORY AT POTENTIALLY SUITABLE OR PROJECTED LOCATIONS

Challenges and potential options for risk management

It is **advisable not to start building a repository** if public acceptance is **not high enough**.

Besides local aspects, the **public acceptance of a disposal facility may also be affected by larger economic uncertainties, pandemics, etc**. Thus, any risk assessment should consider relevant threats and possibilities that go **beyond the particular location** but may affect local people's acceptability.

Potential options for risk management of this uncertainty are wide. They will be based on open **communication**, hence access to information, public participation in decision making and access to justice in environmental matters. **It is advisable to have participative decision-making processes implemented at each phase.**

16-02-2023 Training material eurad 48

D | UNCERTAINTY IN THE PUBLIC ACCEPTANCE OF THE REPOSITORY AT POTENTIALLY SUITABLE OR PROJECTED LOCATIONS

Challenges and potential options for risk management

Specifically, the local community must get strong guarantees that the **negative impact on its environment will be low at short term and in the long term**, and that the **avoid/reduce/compensate strategy** has been properly implemented. It must receive recognition and economic benefits from the efforts they make for the good of the country.

In addition, trust building is important during a **long-lasting continuous dialog** that is independent from future decision points. The **trust building process** requires clear rules, powers and responsibilities for each actor. A potential challenge is that it takes long time to gain trust, but it can be lost within an instant.

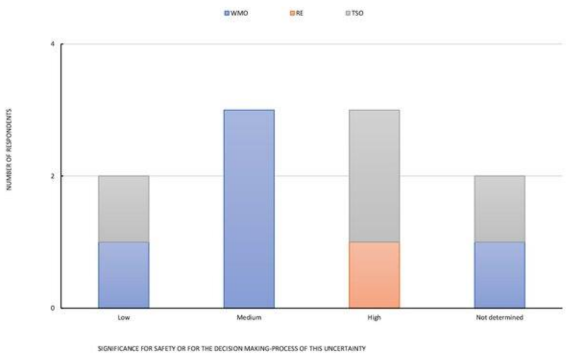
Implementing a stepwise process, as **well as popularizing the science** (especially to the new generations, so that they become more familiar with the nuclear industry)

Photo from COVRA.

16-02-2023 Training material eurad 49

D | UNCERTAINTY IN THE PUBLIC ACCEPTANCE OF THE REPOSITORY AT POTENTIALLY SUITABLE OR PROJECTED LOCATIONS

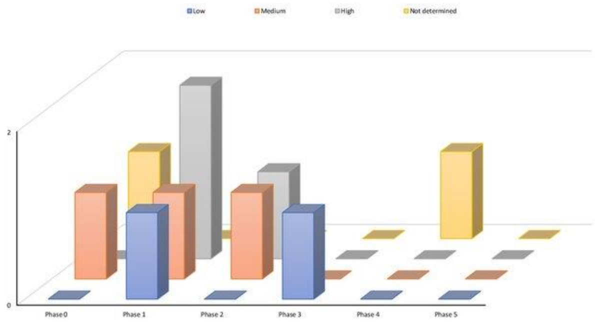
How did other actors think? Most of them think it has some impact, but still relative limited.



*Results from actors on the questionnaire on the significance of the public acceptance for a **deep geological disposal facility**. From the figure, it is clear that there no consensus on the significance of this uncertainty for safety or the decision-making process.*

16-02-2023 Training material eurad 50

D | UNCERTAINTY IN THE PUBLIC ACCEPTANCE OF THE REPOSITORY AT POTENTIALLY SUITABLE OR PROJECTED LOCATIONS

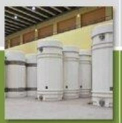


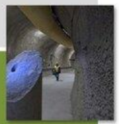
Results from actors on the questionnaire on the significance of public acceptance for ***deep geological disposal facility****. From the figure, no clear correlation can be deduced between the phase and the significance of this uncertainty for safety or the decision-making process. However, most actors indicate that the significance is higher than low.*

16-02-2023 Training material eurad 51

UNCERTAINTIES

	Information is available	Information is not available
Level of information is used	(known knowns)	known unknowns
Level of information is not used	Unknown knowns	unknown unknowns





Date16-02-2023 Training material eurad 52

SUMMARY AND CONCLUSIONS.

- We have identified 58 human related uncertainties. Although the list might appear to be complete, there is no guarantee it actually is.
- These 58 uncertainties have been characterized and 10 uncertainties were selected.
- These 10 uncertainties have been developed further. This includes the characterization of their impact and potential management options.
- General speaking, actors did not see the 10 uncertainties as being of high significance.

Date

53

BIBLIOGRAPHY AND/OR REFERENCES.

- Dumont J.-N., Bartol J., Holt E., Zeleznik N. (2023): Deliverable D10.08 "Views of the different actors on the identification, characterization and potential significance of uncertainties related to human aspects", HORIZON 2020 project EURAD. EC Grant agreement no: 847593.
- Verhoef, E.V., Neeft, E.A.C., Chapman, N., McCombie, C., 2017. Opera safety case.

Date

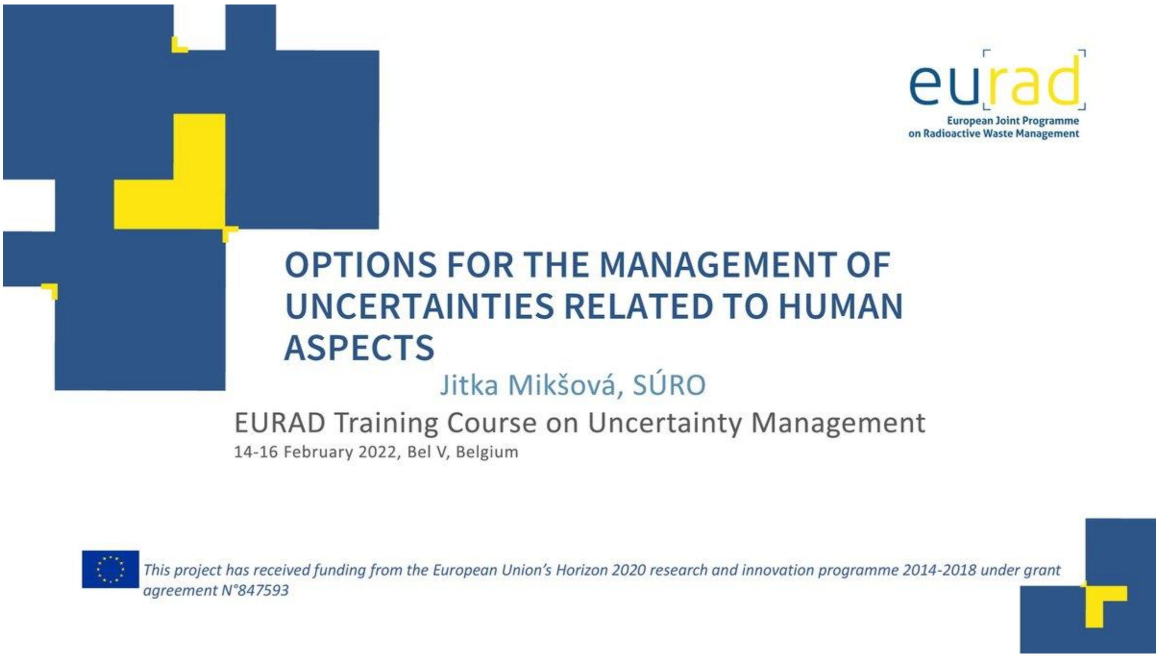
Training material

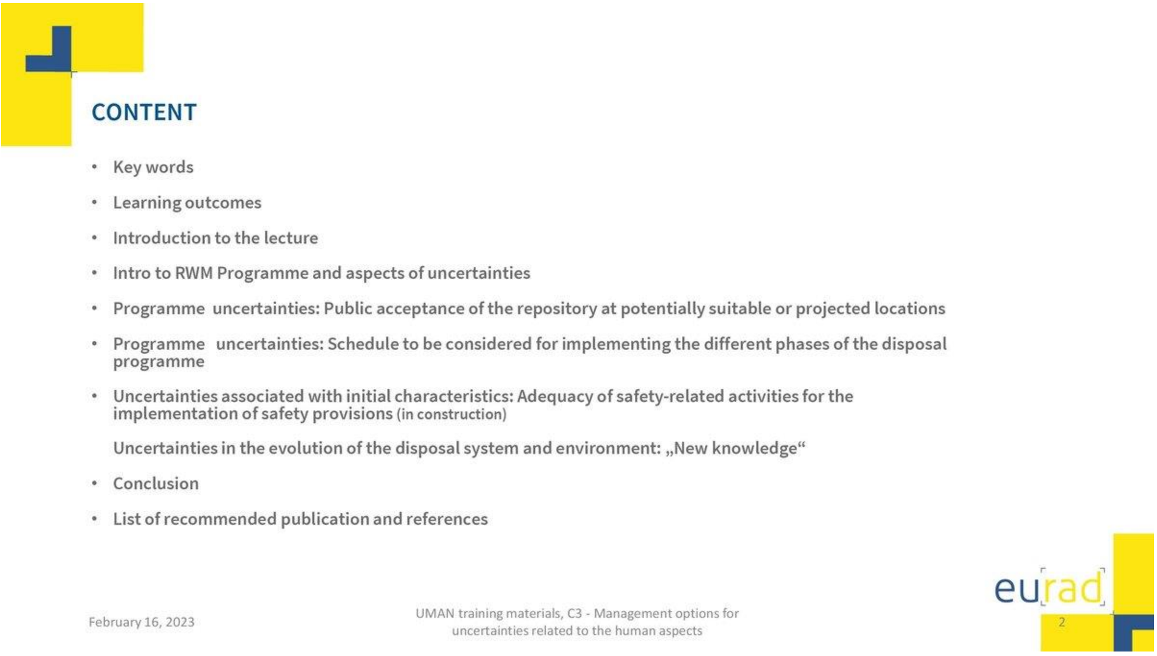
54

Appendix L. Slides of lecture C.3

C.3 Options for the management of uncertainties related to human aspects

Prepared by Jitka Miksova, SURO





KEY WORDS

- RWM Programme implementation
- Human aspects
- Programme uncertainties
- Public acceptance
- Programme schedule
- Repository construction
- New knowledge
- Management actions

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 3

LEARNING OUTCOMES

After the completion of this training lecture, the participants should be able to describe:

- Understand and classify the different types of uncertainties that may need to be managed in a RW disposal programme
- Explain the links between uncertainty management related to chosen human aspects and safety case, the safety case and the decision-making process within programme implementation
- To be aware about global UMAN scheme of uncertainty management strategies
- Explain the main strategies and approaches available to manage uncertainties caused by human aspects
- To have an insight into views of different actors engaged in RWM and involved in EURAD on uncertainty management
- Understand potentially significant uncertainties related to human aspects and discuss their significance
- To have overview about possible main sources of information and recommended publications

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 4

INTRODUCTION TO THE LECTURE

UMAN WP is focused on developing a common understanding among European Waste Management Organisations (WMOs), Technical Support Organisations (TSOs), Research Entities (REs) and Civil Society (CS) of strategies and approaches for managing uncertainties through knowledge sharing and identification of remaining and emerging issues.

The main UMAN goal is to develop a comprehensive overview about **different approaches and uncertainty management options to assess** and where relevant to reduce risks and optimise safety

Origin of input data/information:

- UMAN Questionnaires disseminated to UMAN participants (WMO, TSO, RE, CS)
- UMAN WSs and Seminars
- UMAN deliverables

The uncertainties' topics identified as of high priority and relevance to safety aspects (safety case) of RW disposal from the addressed respondents:

1. Site and geosphere-related uncertainties (in particular in the course of host rock and site selection processes),
2. **Uncertainties related to human aspects,**
3. Uncertainties related to spent fuel (including those associated with their characterisation, intermediate storage (wet or dry) and possible long-term storage),
4. Uncertainties related to the waste inventory (including uncertainties associated with their pre-disposal management having impact and implications for the safety of the disposal facility).

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad 5

CLASSIFICATION SCHEMES USED IN UMAN

- The schemes for classification of uncertainties resulting from UMAN work served as a tool to identify management options depending on the type of uncertainty and temporal aspects.
- The views of different actors on the uncertainties in a safety analysis and in a safety case for geological disposal of radioactive waste and uncertainty evolution have been assessed.

The main goal:

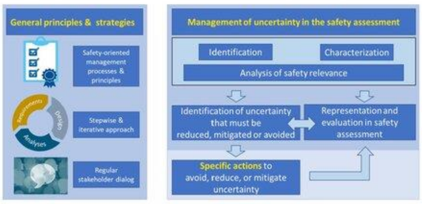
to identify various types of uncertainties potentially relevant to the safety case that the various actors, in particular WMOs, TSOs, REs and civil society, considered as of the highest priority

- The following types of uncertainty were identified :
  - **programme uncertainties,**
  - **uncertainties associated with initial characteristics,**
  - **uncertainties in the evolution of the disposal system and its environment**,
  - uncertainties associated with data, tools and methods used in the safety case, including quality of QA/QC measures,
  - uncertainties associated with the completeness of FEP's considered in the safety case

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad 6

GENERIC STRATEGIES AND MANAGEMENT OPTIONS

- **General principles and strategies used for all selected topics:**
  - Safety-oriented management processes and principles
  - Stepwise and iterative approach
  - Regular stakeholder dialog
- **Management of uncertainties:**
  - **identification**
  - **assessment of the safety relevance** (this can be done either through a preliminary analysis of the safety relevance or through a comprehensive evaluation of the results of the safety assessment)
  - **characterisation**
  - identification of uncertainties that must be reduced, mitigated or avoided
  - classification into “to be reduced”, “to be mitigated”, “to be avoided”
  - **representation of safety-relevant uncertainty in safety assessment**
- **Specific actions to (i) reduce, (ii) mitigate or (iii) avoid uncertainty**



February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad | 7

TOPICS SELECTION FOR FURTHER INVESTIGATION

Selection process (more details see in the lecture C2):

Task 3 proposed 10 uncertainties considered as of a high priority for further investigation. 4 of them (in red) were subsequently investigated by Subtask 4.2 in more details and served as input to UMAN Subtask 4.3 Workshop 2 (Management options and preferences of different actors regarding uncertainties related to human aspects):

- A: Process for the identification of a workable set of repository requirements,
- B: Continuity of the waste management policy along political changes,
- C: Robustness of the presently considered safety requirements with regard to the long term,
- D: Public acceptance of the repository at potentially suitable or projected locations,
- E: Schedule to be considered for implementing the different phases of the disposal programme,
- F: Robustness of the safety case vis-à-vis sociotechnical factors,
- G: Reliability of monitoring results and safety analysis
- H: Adequacy of safety-related activities (in siting, design, construction, operation and closure) for the implementation of safety provisions,
- I: Robustness of safety performance vis-à-vis possible cyber-attacks or programming errors,
- J: Availability of well-educated human resources and relevant experts in radioactive waste management along the repository lifetime until closure.

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad | 8

SELECTED TOPICS FURTHER INVESTIGATED IN TASK 4

The uncertainty management options for selected topics presented in this lecture were identified through a compilation, review and synthesis of existing documentation and examples of pitfalls resulting from Task 4 WS 2, taking into account Task 3 results and Task 5/Seminar 3.

Topics selected:

1. Public acceptance of the repository at potentially suitable or projected locations
2. Schedule to be considered for implementing the different phases of the disposal programme

→ associed with programme uncertainties

3. Adequacy of safety-related activities (in siting, design, construction, operation and closure) for the implementation of safety provisions

→ associated with uncertainties initial characteristics

4. Reliability of monitoring results and safety analysis, transferred to „NEW" knowledge

→ associed with uncertainties in the evolution of the disposal system and its environment

Involved actors: WMO, TSO, REs, CS

Core group members: SURO, BGE, Andra, Nagra

Main goal: to focus specifically on developing a comprehensive overview of different approaches and uncertainty management options to assess, and where relevant, to reduce potential risks and share possible management

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 9

INTRO TO RWM PROGRAMME AND ASPECTS OF UNCERTAINTIES

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 10

RADIOACTIVE WASTE MANAGEMENT PROGRAMME/1

Radioactive Waste Management:

- All administrative and operational activities involved in the handling, pre-treatment, treatment, conditioning, transport, storage and disposal of radioactive waste, (IAEA glossary)
- Activity which refers to the safe treatment, storage and disposal of liquid, solid and gas discharge from nuclear industry operations with the goal of protecting people and the environment (NEA, FSC definition)

Radioactive Waste Management Facility:

Facility specifically designed to handle, treat, condition, store or permanently dispose of radioactive waste (IAEA glossary).

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects

eurad 11

RADIOACTIVE WASTE MANAGEMENT PROGRAMME/2

Important aspect of every RWM programme:

Disposal facilities for radioactive waste shall be **developed, operated and closed in a series of steps**. Each of these steps shall be supported, as necessary, **by iterative evaluations of the site, of the options for design, construction, operation and management, and of the performance and safety of the disposal system** (Requirement 11: Step-by-step development and evaluation of disposal facilities, IAEA No. SSR-5, 2011).

The long development time for a DGR affords time for the **collection and investigation of further information to enhance the knowledge of repository performance through a carefully planned programme** of testing during the underground construction, emplacement of waste, and any subsequent observational period **until the permanent closure of the repository**. **At each step, the information is evaluated to ensure the determination that a decision to continue to the next step is appropriately supported** (NEA, 2005).

The uncertainties associated with the evolution of the disposal system must be appropriately considered and managed throughout a repository development programme. At each stage of a stepwise development programme, **decisions should be based on appropriate levels of confidence about the achievability of long-term safety, with the current level of technical confidence established through uncertainty analysis** (NEA, 2005).

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects

eurad 12

RADIOACTIVE WASTE MANAGEMENT PROGRAMME/3

- The NEA Radioactive Waste Management Committee (RWMC) established the **Forum on Stakeholder Confidence (FSC)** **to foster learning about stakeholder dialogue and ways to develop shared confidence, informed consent and acceptance of radioactive waste management solutions**. (NEA 2015):
- The FSC experience suggests that, in addition to technical requirements, **societal concerns about risk and safety need to be addressed** in order for public trust and confidence to develop.
- The FSC recommended that facilities should allow for **community oversight and stewardship** as a part of enhancing confidence in the DGR process.
- Many countries acceded to the Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters (**Aarhus Convention**) in order to enhance and respect a **stakeholder involvement** and participation in the RWM programme.

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad 13

RADIOACTIVE WASTE MANAGEMENT PROGRAMME/4

Stakeholder by definition:

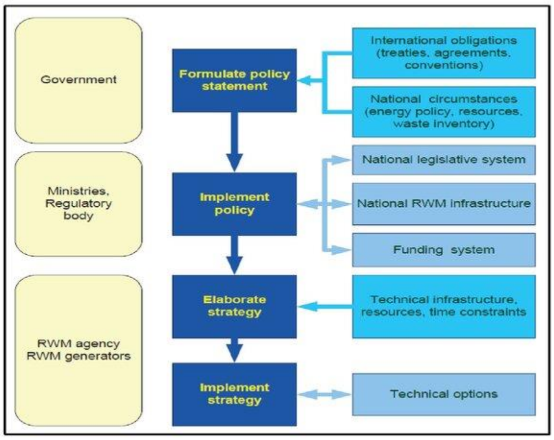
Stakeholder is any actor – institution, group or individual – with an interest or a role to play in the radioactive waste management process (NEA,FSC)

- Stakeholder involvement **may take the form** of sharing information, consulting, dialoguing or deliberating on decisions at different phases. It has to always be seen as a meaningful part of formulating and implementing good policy.
- It is important **to secure stakeholder involvement** through the life cycle of all nuclear facilities, including spent fuel storage facilities and radioactive waste disposal.
- International experience has shown that, especially in the case of disposal facilities, the **project's progress often relies upon public support**.
- **Decision making on long term SF and RWM is complex**, as it not only concerns the current generation, but also **future** ones, since disposal facilities are designed to operate for many decades and to contain the hazard for thousands of years.
- The **stakeholders' expectations have to be taken into consideration**

The Forum on Stakeholder Confidence Report on Dialogue in the Long-Term Management of Radioactive Waste, 2021, https://www.oecd-nea.org/jcms/pl_56330/the-forum-on-stakeholder-confidence-report-on-dialogue-in-the-long-term-management-of-radioactive-waste

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad 14

RADIOACTIVE WASTE MANAGEMENT PROGRAMME/5



National policy typically addresses the following:

(a) Responsibilities within the country for spent fuel and radioactive waste management;

(b) Arrangements for financing the management (including disposal and decommissioning);

(c) Preferred management options for spent fuel, policies for waste disposal, import and export of spent fuel and radioactive waste;

(d) Decommissioning of nuclear facilities;

(e) **Public information and public involvement in related decisions.**

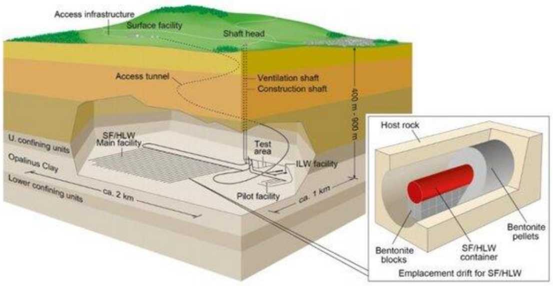
Principal steps in the development and implementation of a national radioactive waste management (RWM) policy and strategies, IAEA

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad 15

GEOLOGICAL DISPOSAL FACILITY CONCEPT SELECTION

Selection of disposal concept depends on:

1. National policy
2. **Implementation strategy (considering e.g. timescale, novel technologies development)**
3. Legal and regulatory framework
4. National inventory (volume, characteristic, location, etc)
5. Scope of nuclear activities (past, running, envisaged)
6. Funding, cost estimate
7. **Existing infrastructure (technical, human)**
8. Geological background, host rock suitability
9. **Conflict of interest (land use and nature protection, transport networks, etc.)**
10. **Stakeholders influence and expectation**
11. **Public acceptation**
12. **Political commitment, preferences**



Source: *"Swiss Geological Studies to Support Implementation of Repository Projects: Status 2015 and Outlook", Nagra, 2015*

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad 16

SUCCESSFUL FACTORS FOR SNF/RWM PROGRAMME IMPLEMENTATION

- Long term political commitment to resolve SNF and RW issues
- National strategy and discipline policy
- Well defined liabilities and roles, governance
- Early established funding system
- Early involvement of regulatory body in project and strategy planning
- Agreement of local community in hosting repository and in stepwise licencing process
- Implementor programme establishment (structured, stepwise, open and defendable using graded approach and rolling document strategy)
- Good safety culture and importance of dialog between regulatory body and implementer based on comparable levels of technical competence
- Transparency and engagement of public (supported by domestic and international scientists and technical experts)
- Knowledge management, knowledge transfer, education and training, human resources sustainability

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 17

UNCERTAINTY ASSOCIATED WITH THE NATIONAL RWM PROGRAMME AND OTHER PREVAILING CIRCUMSTANCES

Uncertainty associated with the national RWM programme and other prevailing circumstances:

include, in particular, societal and political uncertainties relating to the waste to be disposed of, stakeholder conditions, the regulatory framework, the disposal concepts and schedule, available financial resources, and available skills and experience.

Two types of uncertainties have been selected by UMAN for further investigation for the category "programme uncertainties":

1. Public acceptance of the repository at potentially suitable or projected locations
2. Schedule to be considered for implementing the different phases of the disposal programme

Both types of these uncertainties are closely interlinked and overlap

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 18

PROGRAMME UNCERTAINTIES

TOPIC 1: PUBLIC ACCEPTANCE OF THE REPOSITORY AT POTENTIALLY SUITABLE OR PROJECTED LOCATIONS

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | 19

PUBLIC ACCEPTANCE UNCERTAINTIES - GENERAL REMARKS

- This uncertainty comes into play mostly during site selection
- There is no correlation between the impact of this uncertainty and the phase of the programme
- Regarding the evolution of this uncertainty, there is a consensus that it will decrease over time, especially when a participative decision process is implemented at each phase to ensure that the decisions made at each phase are supported by the public
- Since this has no direct impact on safety, this uncertainty was assessed as having a medium level of significance for safety
- It may not be strictly limited to the local community hosting the repository, as other communities in the repository vicinity may feel also concerned, especially because of the transportation of the waste to the repository, and lower benefits expected (in terms of jobs, infrastructure, etc.).
- In the early programme phases, this uncertainty may lead to a total failure of a siting process
- it is difficult to decrease this uncertainty through RD&D.
- the stakeholders may require new elements to be included in the decision-making process (more discussions, more meetings, new ideas, etc.), which will impact the decision-making process and potentially the schedule
- associated uncertainties concern the measurement of the public acceptance, in particular how to determine that a sufficient level of acceptance is reached and how to measure the acceptance level.

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | 20

IDENTIFICATION AND ASSESSING THE SAFETY RELEVANCE /1

Identification:

- In the framework of a **decision-making process**
- Should be identified during the **early stages** of disposal programme implementation: programme initiation, siting and characterization.
- Through **open communication** between different stakeholders
- Through an active **public participation**
- Through an independent **safety reviews**
- High importance within **siting**

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 21

IDENTIFICATION AND ASSESSING THE SAFETY RELEVANCE /2

Safety relevance:

- **No direct impact on safety**
- If site selection is also driven by **public acceptance criteria**, the safety concepts and finally disposal facility safety may depend **indirectly** on public acceptance.
- **It can cause important delays in the implementation** of the disposal programme which may eventually lead to safety issues in storage facilities or during transportation
- the safety relevance is very much dependent on resulting delays in programme implementation, having impact on lifetime and capacity of storage facilities, and on possible **ageing phenomena affecting the waste and these facilities.**
- Different stakeholders may introduce **new safety-related issues** that need to be considered or reassessed in the safety analysis.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 22

CHARACTERIZATION

- The **stakeholder acceptance becomes an increasingly important issue** in a number of national programmes (e.g. the existence of a requirement that the siting of the facility does not take place without the consent of the public concerned).
- Should be done during the early stages of disposal programme implementation: programme initiation, site selection and characterization.
- Possible approaches to characterize these uncertainties include:
  - Multi-channel communication with stakeholders: public meetings, newspapers, door to door, webinars, web site, etc.
  - Identification of stakeholder categories as well as of their interest, influence and relationships through stakeholder analysis.
  - Quantitative representation using statistical methods on data, consideration of accuracy of measurements, e.g. socio-economic studies.
- These uncertainties are closely related to the consideration of the expectations of different stakeholders notably on various operational issues such as operational monitoring, the retrievability of the waste, costs, conditioning of radioactive waste, location of surface installations etc.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 23

CLASSIFICATION AND ASSOCIATED ACTIONS /1

This uncertainties cannot be avoided but could be adequately reduced or mitigated

In particular, achieving a level of sufficient public acceptance is needed.

The following measures can be taken to reduce this uncertainty:

- Development and establishment of a **fair, sustainable, transparent procedure for the repository site selection**
- **Mutual dialogue between stakeholders**, including the public, and the timely involvement of the public in the decision-making process. It should be a continuous dialog with the public instead of one-way communication (i.e. issuing of information), particularly with a network of citizen experts.
- Communication and **stakeholders engagement strategy/concepts** are a tool for managing the acceptance uncertainty but may be unsuccessful.
- Development of **support programmes in preselected sites**.
- Performance of **RD&D activities** with a focus on transdisciplinary research and social science.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 24

CLASSIFICATION AND ASSOCIATED ACTIONS /2

The following actions can be taken **to reduce** this uncertainty (cont.):

- Ensuring **mutual understanding** of the repository safety during the operational phase and in the long-term (timespan of one million years) and on possible site/repository evolutions.
- Public acceptance may also be affected to some extent by the way in which **conflicts of interest** (including the interests of the public concerned) are resolved, and the degree of compatibility of the disposal project with the site development plan.
- **Building and/or improving credibility** of the responsible organizations/institutions involved in the management of radioactive waste and decision-making process (e.g. clearly defined functions and responsibilities, independency, transparency, learning organizations, self-questioning process, science, open to criticism).
- **The role of the various reviewers**, namely the regulator and its TSO, is prominent to foster confidence on safety.
- **Independent safety reviews by the regulator and its TSO** and/or by other independent experts mandated by civil society organisations.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 25

REPRESENTATION IN SAFETY ASSESSMENTS

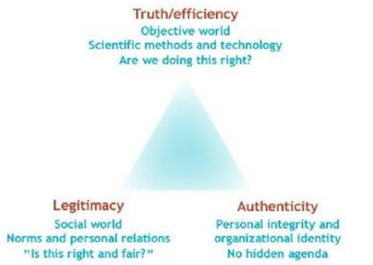
Even there is no direct impact on disposal facility safety it may be appropriate to assess the possible implications for safety of this uncertainty in the safety case. In particular, **possible consequences of the delays resulting from a lack of public acceptance could be assessed in the safety assessment.**

If certain requirements related to the repository are set due to **acceptability constraints** (e.g. reversibility), the **consequences of the resulting provisions on safety shall be presented in the safety assessments**, e.g. the measures for retrievability **need to be shown not to impact post-closure safety** as requested in one of the national regulation.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 26

PUBLIC ACCEPTANCE - ADDITIONAL REMARKS

- **NIMBY effect**, extending licensing process, veto right, prospects of new technologies.
- From facility construction phase, it should be demonstrated that any **remaining uncertainty** will **not jeopardize the safety of the facility.**
- The uncertainty is indirectly addressed e.g. in **the Council Directive 2011/70 /Euratom** - basic requirements for ensuring the transparency of the process with the active involvement of the municipalities and the public concerned. These requirements are usually implemented also into **national legislation.**
- The **advances in science and technology** over future decades may allow development of novel concepts that not only meet stakeholder wishes but also provide benefits in terms of both pre-and post-closure safety



Main pillars of interaction with civil society, RISCOM project

- **To avoid negative "surprises" in the process from both sides**, future disposal facility implementer and public

Uncertainties should be described in a way that **stakeholders can understand** what we do not know and why we think this is not relevant or why it is relevant for safety and, if so, **how and when we will deal with it.**

*NIMBY, an acronym for "**Not In My Backyard**," describes the phenomenon in which residents of a neighborhood designate a new development (e.g. shelter, affordable housing, group home) or change in occupancy of an existing development as inappropriate or unwanted for their local area, (wiki)*

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 27

PROGRAMME UNCERTAINTIES

TOPIC 2: SCHEDULE TO BE CONSIDERED FOR IMPLEMENTING THE DIFFERENT PHASES OF THE DISPOSAL PROGRAMME

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 28

PROGRAMME UNCERTAINTIES – SCHEDULE – GENERAL REMARKS

This uncertainty is related to **possible delays in the implementation of the programme schedule**

This uncertainty can occur **in all phases of disposal facility lifecycle until its closure**.

The schedule may be affected by uncertainties regarding insufficient support and acceptance by the public (or by other stakeholders), provision of sufficient financial and raw material resources, human resources, and the availability of appropriate technologies , by accidents during repository construction and operation and also due to political changes, etc.

Some of these aspects being subjects **to quick changes**, thus these uncertainties are **very difficult to characterize.**

It affects the **timing of the agreement on the completeness** of the safety case and resources for evaluation.

Technical, administrative and social problems may significantly change any implementation plan.

Implementation process should be checked regularly, including at each milestone, for updating the planning.

It is expected, according to the preliminary governance of the project, that the major decision points will be subject to public consultation.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 29

IDENTIFICATION AND ASSESSING THE SAFETY RELEVANCE

Identification:

- **should start in the phase of policy framework and programme establishment** and be pursued during subsequent phases (Site evaluation and site selection, Site characterization, Facility construction)
- should be identified **through risk analysis** (e.g. risk matrix, risk register, hazard identification, scenario analysis) and project management.
- can be performed through a **stepwise approach and open communication between the different stakeholders**

Safety relevance:

- the impact of this uncertainty on safety can **be indirect and/or direct** - depending on the phase of the programme. No direct consequences are expected before construction of the facility. Indirect consequences are possible during all phases and remain until repository closure.
- Uncertainties on the date of availability of the disposal facility may lead to necessary decisions for **extending the duration of interim storage**. Delays can also lead to a diminished robustness vis-à-vis potential societal disruptions, to **enhanced ageing of waste packages** before final disposal and affect the **ability to retrieve the waste** safely if necessary.
- In the case of DGR, delay of installation of stabilizing measures may cause **stability problems and may affect long-term safety as well**. It is possible to assess the potential consequences of this uncertainty through e.g. mining experience, numerical calculations considering stability of mining excavations and barrier integrity, etc..
- Delays can cause loss of expertise and knowledge, which can also have an indirect effect on the safety.
- Further, delays in the programme implementation can cause **increasing costs**, which in turn **may affect the quality of the execution** of future activities due to lack of resources and **can thus adversely affect the repository safety**

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 30

CHARACTERIZATION

- This uncertainty is very difficult to characterize and quantify, it is directly related to a number of other "programme uncertainties"
- Should be characterized during the early stages of disposal development – program development and subsequent revision during the next phases: site selection, characterization…
- Should be characterized via stepwise approach, with intense communication with the stakeholders at each step; draft planning of the successive major decisions updated and shared regularly.
- The actual schedule is the result of a mixture of technical constraints and societal aspects (e.g. of strategies of the various actors, with sometimes opposite interests), leading to unreducible uncertainties.
- It could be derived through the determination of the degree of public acceptance in the frame of socio-economic studies (e.g. NIMBY, it depends on communication with public and level of active stakeholder engagement, on flexibility of the disposal facility development programme)
- The main question for this uncertainty is the appropriate timing, for involved decision makers especially, with regard to the agreement on the completeness of the safety case and resources for evaluation.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 31

CLASSIFICATION AND ASSOCIATED ACTIONS /1

- This uncertainty needs to be reduced and mitigated but cannot be avoided.
- This uncertainty will presumably be reduced with the implementation of the disposal programme throughout the phases (stepwise approach).
- The following actions can be undertaken to reduce this uncertainty:
  - through the implementation of good project and risk management practices.
  - Through a more robust planning by establishing a draft planning of the successive major decisions regarding the repository in the (pre-)licensing phase and beyond, and presenting it for comments to the various stakeholders, so that a consolidated shared view on the planning may emerge.
  - Holistic approach for the waste management programme with soft links between components.
  - Professional, forward-looking human resources planning.

We must expect significant delays in the schedule as the normal evolution of the project, thus it requires managers and scientists to accept it as an irreducible uncertainty and to plan suitable mitigation measures. Past experiences have shown sufficient evidence of schedule changes.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 32

CLASSIFICATION AND ASSOCIATED ACTIONS /2

- **The following measures allowing to mitigate this uncertainty:**
  - Implementation of a **participative and transparent decision-making process at each programme phase** in order to ensure that the decisions made at each phase are supported by the various stakeholders
  - Planning the necessary resources (not only financial) to complete corrective action in connection with delay.
  - Flexibility measures:
    - The provision of a flexible disposal programme implementation.
    - Repository design that will be flexible and adaptable, i.e. robust vis-à-vis modifications of the waste emplacement schedule robustness of the design with respect to ageing processes
    - Defining a waste management programme (interim storage + repository) that will be flexible, i.e. where the licensing decisions for the repository cannot be suspected of being dictated by the fact that the storage capacity is saturated.
  - In the construction phase and the operation and closure phase of the programme, the potential consequences of this uncertainty on the stability of the disposal facility can be handled by observation methods (monitoring, e.g. deformations of mining cavities), can be quantitatively described
  - Different engineering methods and assessed by numerical calculation should be applied.

February 16, 2023 — UMAN training materials, C3 - Management options for uncertainties related to the human aspects — eurad 33

REPRESENTATION IN SAFETY ASSESSMENTS

- **This can be done by defining scenarios investigating the potential impact on safety of delayed backfilling or closure.**
- **The consequences of this uncertainty for the stability of the facility may also be explicitly addressed, in the licencing procedure by the regulatory authority in charge of underground safety aspects.**

February 16, 2023 — UMAN training materials, C3 - Management options for uncertainties related to the human aspects — eurad 34

End of the part 1

Thank you for your attention!

February 16, 2023

UMAN training materials, C3 - Management options for uncertainties related to the human aspects

eurad

35

UNCERTAINTIES ASSOCIATED WITH INITIAL CHARACTERISTICS

ADEQUACY OF SAFETY-RELATED ACTIVITIES FOR THE IMPLEMENTATION OF SAFETY PROVISIONS (IN CONSTRUCTION)

February 16, 2023

UMAN training materials, C3 - Management options for uncertainties related to the human aspects

eurad

36

UNCERTAINTIES ASSOCIATED WITH INITIAL CHARACTERISTICS – GENERAL REMARKS

This uncertainty is related to the adequacy of safety related activities for the implementation of safety provisions (with a focus on the disposal facility construction phase)

Uncertainty identification should be done in early programme phases

This uncertainty **has an impact on occupational health and safety as well as radiological safety** mainly within **in construction and operation phases**

Inadequate construction activities and processes **could jeopardize operational safety**

Inadequate construction activities and processes **could jeopardize long-term safety function of** individual components of disposal facility and thus affect **post closure phase**.

February 16, 2023 — UMAN training materials, C3 - Management options for uncertainties related to the human aspects — eurad 37

UNCERTAINTIES ASSOCIATED WITH INITIAL CHARACTERISTICS

From CS view: **It is uncertainty generated by human activities during the implementation of disposal facility**

Question - What is a gap between theory and safety case VS concrete implementation?

From WMO view:

How can it be ensured that the safety provisions taken into account in the safety assessment are adequately implemented?

How robust is the safety assessment vis-à-vis any potential inadequate implementation of the safety provisions?

Key uncertainties:

Long-term safety: Inadequate safety-related activities in the construction phase **potentially affect long-term safety functions of individual components** and as a consequence **may affect the performance of the whole system** in the long-term.

Operational safety: **Inadequate safety-related activities in the construction phase may cause local instabilities** (roof falls, collapse of drift face) with consequences to **conventional and radiological safety in the operational phase**.

IAEA GEOSAF II project - Managing integration of pre-closure and post-closure safety in the Safety Case for geological disposal:

„Development of a process to assure that construction and operation of a geological disposal facility will deliver the expected post-closure safety functions."

February 16, 2023 — UMAN training materials, C3 - Management options for uncertainties related to the human aspects — eurad 38

ADEQUACY OF SAFETY-RELATED ACTIVITIES FOR THE IMPLEMENTATION OF SAFETY PROVISIONS IN CONSTRUCTION - INTRODUCION

This uncertainty :

- is linked to safety provisions in a disposal facility construction phase, e.g. construction errors
- has an impact on the properties of the components of the disposal system in the real state.
- **includes the socio-technical aspects associated** with the activities required for the implementation of the safety provisions
- It is affected by changes in organisation and safety culture, lack of knowledge management, inadequate training of the staff

Existing construction codes and operating rules take into account operational and long-term safety, BUT:

- **Rules are subject to interpretation.** Implicit requirements, evident at the time the rules are set, may be ignored later due to lack of appropriate knowledge management.
- **Rules may be violated by ignorance, laziness, greed or malice of employees.** The quality insurance system in place may allow violations to go undetected.
- **Interactions between humans and technology** (e.g. human-machine interface) could also contribute to the uncertainties occurrence.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 39

IDENTIFICATION AND ASSESSING THE SAFETY RELEVANCE/1

This kind of uncertainties and their safety significance could appear over construction and operation, including closure phases of the disposal facility and should be reduced and/or mitigated through the implementation of suitable construction activities.

- Uncertainties on the proper implementation of safety-related activities during repository construction **need to be identified at early programme phases** before facility construction phase.

Identification through:

- lessons learned and **available experience from similar construction activities** (in other disposal facilities or in other fields such as mining and tunnelling), can be very useful in identifying possible construction errors and assessing their impact
- **monitoring system** during repository construction, operation and closure, (i.e. in case the behaviour of the repository system differs from expectation)
- **inspections** of accessible parts of the facility.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 40

IDENTIFICATION AND ASSESSING THE SAFETY RELEVANCE/2

- impact on occupational health and safety + radiological safety in the construction and operational phases (i.e. operational safety).
- inadequate construction activities and processes could jeopardize long-term safety functions of individual components of the disposal system.
- oversight of several design steps by licensing authorities, having expertise in different relevant fields (safety assessment, mining, civil engineering, etc.):
  - Deep scrutinising of safety case by the regulator and its TSO,
  - External audits or inspections by the regulator and its TSO.
- framework of Periodic Safety Review (PSR), which evaluates separately "human factors"

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 41

CHARACTERIZATION

- This uncertainty is related to the management provisions for the activities related to safety during repository construction.
- It is affected by:
  - changes in organization and safety culture
  - lack of knowledge management, and inadequate training
  - lack of experts involved in construction activities

Can be characterised through:

- the quantitative description of the uncertainties may be limited, however, their quantification, respectively quantification of their impact, might be needed when their representation in the safety assessment is necessary.
- a certain percentage of undetected defects may be quantified based on return on experience from construction activities of other disposal facilities or from other similar activities

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 42

CLASSIFICATION AND ASSOCIATED ACTIONS /1

These uncertainties need to be reduced and where possible avoided or mitigated.

The following actions can be undertaken to reduce this uncertainty:

- the disposal of radioactive waste should be treated from the socio-technical perspective (and not as a solely technical issue),
- interactions between human, technology and the organization is recommended/needed
- appropriate design of a disposal facility according to current national and international standards needs to be considered in order to reduce future construction errors or uncertainties

Basic means to reduce/mitigate this uncertainty:

- implementation of a quality assurance system within the organization (quality assurance documents, training, dedicated teams of quality experts, independent levels of quality management and control within the organization, etc.)

The quality assurance system ensures that the parameters stay within the domains taken into account in the safety assessments

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 43

CLASSIFICATION AND ASSOCIATED ACTIONS /2

Uncertainty reduction, avoidance or mitigation can be also achieved through:

- inspections during or following the repository construction of the proper implementation of procedures as well as of as-built properties
- external audits already by the regulator and/or its TSO, and by quality certification auditors during the design phase on the repository project as well as on construction activities
- set of behavioural expectations and fostering a strong safety culture (**Safety Culture Development Programme**) among the employees involved in construction activities (including subcontractors) and repository operation
- implementation of a feedback programme is essential to reduce the uncertainties and the risks associated.
- consideration of processes from other repositories already in operation (at least for L/ILW) in order to benefit from available experience and expertise.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 44

CLASSIFICATION AND ASSOCIATED ACTIONS /3

Uncertainty reduction, avoidance or mitigation can be also achieved through (cont.):

- **ensuring compliance** of the disposal **facility design and construction methods with the current state of science and technology, international experience**, experience from the operation of nuclear installations with regard to ageing of its systems, structures and components throughout life cycle of the disposal facility.
- regular updates and implementation of a national RD&D programme in accordance with the disposal programme schedule, including demonstration tests
- documentation and knowledge management
- networking and collaboration with external groups
- education of specialists in fields related to RW disposal
- **good governance at all!**

February 16, 2023

UMAN training materials, C3 - Management options for uncertainties related to the human aspects

eurad

45

REPRESENTATION IN SAFETY ASSESSMENTS/1

- Human factor is a separately evaluated element **within Periodic Safety Review (PSR)** thus it is necessary to establish the safety case iteratively, in several steps (feasibility, safety options, preliminary safety report, etc.) over a long period of timeover a long period of time allowing for extensive reviews by the regulator and its TSO.
- **The safety case shall specify how uncertainties are identified, how they are characterized and what is the approach for their management**
- The safety assessment must **address the technical feasibility** of the proposed repository design options to demonstrate that as-built properties are as assumed in the safety case. This implies use of proven methods/techniques, in which the following is stated: "**The licensee shall construct the disposal facility in accordance with the design as described in the safety case and by application of appropriately proven techniques**".
- These **new techniques need future confirmation through experimental tests**: demonstrated through qualification programme defining systematic approach to the qualification of new technology, ensuring that the technology functions reliably within specified limits.
- The approach is applicable for components, equipment and assemblies, which can be defined as new technology

February 16, 2023

UMAN training materials, C3 - Management options for uncertainties related to the human aspects

eurad

46

REPRESENTATION IN SAFETY ASSESSMENTS/2

Question/challenge arisen:

- how to reconcile the goal of applying advanced technologies and/or the latest scientific results ?

- how to comply with the application of the best proven methodologies and technologies (BAT principle) ?

Therefore a choice has to be made between the uncertainties associated with this latest scientific and techological progress and the robustness principle and/or to find a balance between such progress uncertainties and SAHARA principle (Safety As High As Reasonably Achievable).

- With respect to this, Technology Readiness Level (TRL) has to be taken into account (e.g. two technologies with different levels of maturity cannot be compared) and also its potential affect on a possible optimization process has to be considered.
- Optimization should be kept reasonable and efficient

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 47

REPRESENTATION IN SAFETY ASSESSMENTS/3

- Implementation of the repository "Defence in Depth" principle (DiD)
- DiD is one of the fundamental safety principles identified by IAEA, it includes protective measures against disturbing events and processes, presence of aboveground constructions, controls and corrective measures to prevent defects and damages to the disposal (developing quality control measures during construction based on clearly defined conformity criteria/quality requirements and periodic testing and inspections), maintaining the performance of system components when subjected to construction errors (e.g. through provision of safety margins in the design, diversity and redundancy, multi-barrier system, etc.).
- **Periodic safety reviews along the disposal programme, knowledge management system, quality management system, collaborations with universities are considered as helpful tools.**
- Changes of personnel along the long-term disposal programme make documentation and knowledge management highly important. Therefore, it is necessary to have an adequate knowledge management already in place at a very early programme stage. This will help to improve safety for the repository.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 48

REPRESENTATION IN SAFETY ASSESSMENTS/4

Possible constructions errors can be represented explicitly in the safety assessment:

- through using of specific parameter values or
- through consideration of developed scenarios.

This might be done in the framework of (i) the expected repository system evolution or (ii) reference scenarios or (iii) dedicated altered evolution scenarios, depending on the probability of occurrence of the deviations.

The quality assurance system aims at guaranteeing that the parameters stay within the domains taken into account in the safety assessments

Data on the probability of these errors occurring are relatively rare and usually available on a limited scale. This can also be done through conservative assumptions/parameter values or specific scenarios and by including a "poor quality construction" FEP-category in the FEP database.

Safety case needs to demonstrate not only "a good system" but also "good processes", namely a "good safety analysis", i.e. it needs to prove that these uncertainties have been dealt with adequately (e.g. QA system, clear roles, etc.).

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 49

UNCERTAINTIES IN THE EVOLUTION OF THE DISPOSAL SYSTEM AND ENVIRONMENT

„NEW KNOWLEDGE"

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 50

UNCERTAINTIES IN THE EVOLUTION OF THE DISPOSAL SYSTEM AND ENVIRONMENT - „NEW KNOWLEDGE“

This uncertainty related to a "new knowledge" is associated with the evolution of the disposal system and environment (e.g. ignoring the possible magnitudes of disturbing events, unexpected new knowledge)

"New knowledge" means here that the knowledge has emerged by research and monitoring, but also is new for certain actors and has been ignored by others.

- **Relevant to all phases of disposal facility lifecycle**
- Includes any new knowledge becoming available in the course of a RWM
- Occurance of unexpected new knowledge or findings emerged by research, characterization or monitoring (i.e. unknown unknowns),
- the knowledge is available but is new for certain actors which were not aware of this knowledge (i.e. unknown knowns)
- the knowledge is available but is ignored by certain actors (i.e. ignored knowns). Ignoring the possible magnitudes of disturbing events (e.g. in Fukushima, the tsunami was not part of the key FEP) .
- International / broad exchange helps to identify and rank/assess "new" knowledge.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 51

UNCERTAINTIES IN THE EVOLUTION OF THE DISPOSAL SYSTEM AND ENVIRONMENT

Knowledge is available	***Lack of knowledge***
Known Knowns *What is known & used*	**Known Unknowns** *What we know we don't know*
Unknown/Ignored Knowns *What is known but we are not aware of or do not consider*	**Unknown Unknowns** *What we don't know we don't know*

Uncertainties associated with FEP completeness *in relation to the "information awareness" classification.*

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 52

IDENTIFICATION AND ASSESSING THE SAFETY RELEVANCE/1

- **Unknown unknowns, by definition, cannot be identified**
- Ignored knowns can be identified, e.g. through audits and independent reviews
- Unknown knowns can be identified through:
  - steady monitoring of the research landscape and research developments (new knowledge/technologies, scientific findings, etc.),
  - international/national exchange with experts from the field of radioactive waste management,
  - interdisciplinary exchange of knowledge and experiences,
  - consideration of pitfalls and lessons learnt.
- **The identification of unknown knowns leads automatically to their elimination.**

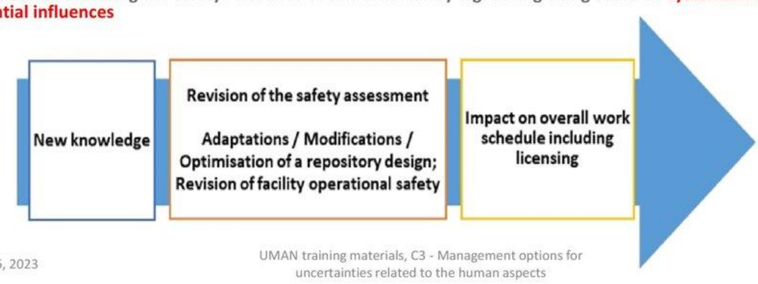
- Known unknowns can be identified through:
  - exploration activities,
  - operation of a monitoring system.
- **The long-term evolution of the disposal system – new knowledge could lead to a revision of the safety assessment and the repository design**

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 53

IDENTIFICATION AND ASSESSING THE SAFETY RELEVANCE/2

Safety significance over time **expected to increase at the beginning of the site selection process:**

- from low/medium in Phase of Policy, framework and programme establishment
- to high in Phases Site evaluation and site selection; Site characterisation; Facility construction; Facility operation and closure,
- and high even in Post-closure phase in connection with post-closure issues such as post-closure monitoring and possibly radioactive waste recoverability
- One mean of assessing the safety relevance of this uncertainty e.g. during siting could be **systematic analyses of its potential influences**



February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects 54

IDENTIFICATION AND ASSESSING THE SAFETY RELEVANCE/3

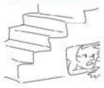
- In case of a DGR, the most **"unknown known"** knowledge is the close connection between repository safety and mining safety (at least in the operational phase). The death **risk associated with mining activities is much higher than the radiological risk**. This leads to different risk perception and acceptance as well as different safety cultures among different groups of staff.
- The safety significance of „**unknown and ignored knowns**" is **considered as high as the return on experience shows that past accidents/incidents** were often associated with these uncertainties. An example of that would be the Fukushima NPP accident due to the earthquake and subsequent tsunami and ignorance of possible magnitudes of these disturbing events.
- The safety significance of „**unknown and ignored knowns**" will remain **potentially important** during the different programme phases (i.e. the consequences could only appear much later).
- The uncertainty management strategy should ensure that, **at the end of the decision-making process, no remaining uncertainty can potentially jeopardize repository safety**.
- **Question arisen:** how **new results**, emerging in the course of the implementation of a disposal programme (e.g. from monitoring), **can be taken into account in the safety case and the safety assessment.**

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad | 55

"NEW KNOWLEDGE" UNCERTAINTY - CHARACTERIZATION

Characterization of these uncertainties can be realized through:

- **Stepwise approach:**



Safety case established in several successive steps, prior to the licence for construction, each of them being reviewed in detail by the regulator and its TSO

The regulator will authorize only operations that will have be duly demonstrated as safe

- Methods have to be defendable with respect to **good practice and quality requirements**
- Assessing the relevance of the new knowledge in the site selection procedure - **systematic analyses of potential influences**
- **Safety margins:** values of the parameters taken into account are set in order to cover uncertainties related to known unknowns.
- Intense **communication with the stakeholders** and interdisciplinary cooperation at each step

The categorization into known unknowns, unknown/ignored knowns, and unknown unknowns constitutes a way to characterize these uncertainties in the best manners.

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad | 56

CLASSIFICATION AND ASSOCIATED ACTIONS/1

This uncertainty is difficult or impossible to be reduced as any uncertainty about the occurrence of unexpected new findings or knowledge is representing **a persistent uncertainty**.

BUT: safety-relevant unknown unknowns need to be avoided or reduced as much as possible, this can be done by carrying out the following actions:

- **Well planned RD&D programme** in the area of RAW/NSF management
- **Site selection:** determination of criteria to properly characterize the site and the host rock, refined modelling: 3D modelling can also raise some new issues/new knowledge
- **Data acquisition and site characterization, monitoring** (it goes beyond the individual objectives of operational safety and compliance with the set values and is also aimed at gaining knowledge).
- **Appropriate design & construction** of a disposal facility (e.g. use of proven methods and materials) with respect to **good practice and quality requirements.**
- **Establishment of limits & conditions/waste acceptance criteria**
- **Interactions with stakeholders.**
- **Exchange with international experts**

CLASSIFICATION AND ASSOCIATED ACTIONS/2

AND: Safety-relevant unknowns and ignored knowns (e.g. deliberately ignoring the possible magnitudes of disturbing events) need to be minimized, this can be done by carrying out the following actions:

- ✓ **Implementation of a sound management system** ensuring notably an adequate performance of the uncertainty management process (e.g. supported by uncertainties roadmap).
- ✓ **Knowledge management** (including training and qualification of the staff involved in safety-relevant activities); development and application of standardized approaches for managing information, data and knowledge*
- ✓ **Systematic FEP management** - derivation of national and international FEP lists and database and their regular review/updating.
- ✓ **Peer review of scientific developments**
- ✓ **Monitoring** - beyond the individual objectives of operational safety and compliance with the set values and is also aimed at gaining knowledge.

** E.g. NEAs RWMC : Working Party on Information, Data and Knowledge Management - WP-IDKM. (January 2020 - December 2022). Subjects for the working party include safety issues, knowledge management, archiving and preservation of data and information. It strives to propose standardized approaches for managing information and data of radioactive waste and repositories.*

CLASSIFICATION AND ASSOCIATED ACTIONS/3

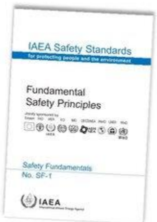
AND: Safety-relevant unknowns and ignored knowns (e.g. deliberately ignoring the possible magnitudes of disturbing events) need to be minimized, this can be done by carrying out the following actions:

- ✓ **Self-questioning and learning associated** with the reversible character of the site selection procedure (for stepwise regulatory and/or policy strategies to be credible): decisions must be reversible or at least modifiable in view of new information, to the extent that this is feasible. Therefore, reversibility refers to the possibility of reconsideration of one or a series of steps at various stages of a programme. This involves a review of earlier decisions with the appropriate stakeholders and requires that the necessary means to reverse a step be available. The reversibility within a planned process should probably be discussed ahead of time.
- ✓ **Implementation of an experience feedback programme** → to take benefit of the experience gained in other facilities
- ✓ **Safety culture** – e.g. implementation of a Safety Culture Development Program → improvement of the responsibility (and in particular of the safety leadership), professional competence and credibility of the responsible decision-makers, experts and employees.
- ✓ **Interactions with stakeholders** → raising awareness of new knowledge

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 59

CLASSIFICATION AND ASSOCIATED ACTIONS/4

- **Several measures can also be implemented to mitigate remaining and emerging (safety-relevant) uncertainties:**
  - ✓ **Implementation of a flexible programme**:
    - to manage e.g. unexpected features or events
    - to keep options open (incl. e.g. retrievability option)
    - optimisation of the repository design - design flexibility and flexibility in design steps
  - ✓ **Interactions with stakeholders** to manage e.g. "programme uncertainties"
  - ✓ **Implementation of the defence in depth principle** (i.e. one of the fundamental safety
  - ✓ principles identified by IAEA):
    - Protective measures against disturbing events & processes
    - Controls & corrective measures to prevent defects and damages to the disposal
    - Safety margins: values of the parameters taken into account in the design are set in order to cover uncertainties related to known unknowns and possibly to unknown unknowns or ignored knowns.
    - Multi-barrier system with independent and complementary safety functions and components



February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 60

CLASSIFICATION AND ASSOCIATED ACTIONS/5

STEP wise approach

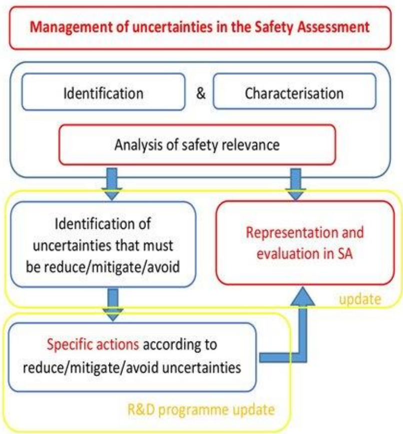
- **Stepwise decision-making process and iterative approach to managing uncertainties as the programme processes through each phase of disposal facility development**
  - ✓ Results from a safety assessment can be used to understand the parameters to which performance measures are most sensitive → provide clues to subsequent data collection activities → reduce the associated uncertainty in a meaningful way
- **Stepwise approach in safety assessment:**
  - ✓ Safety case established in several successive steps, prior to the licence for construction, each of them being reviewed in detail by the regulator and its TSO → opportunity to identify unknown or ignored knowns
  - ✓ The regulator will authorize only operations that will be duly demonstrated as safe
- **Process ensuring regular updates and implementation of R&D programme** in the area of RAW/ NSF management in compliance with the schedule for disposal facility development.

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects

eurad 61

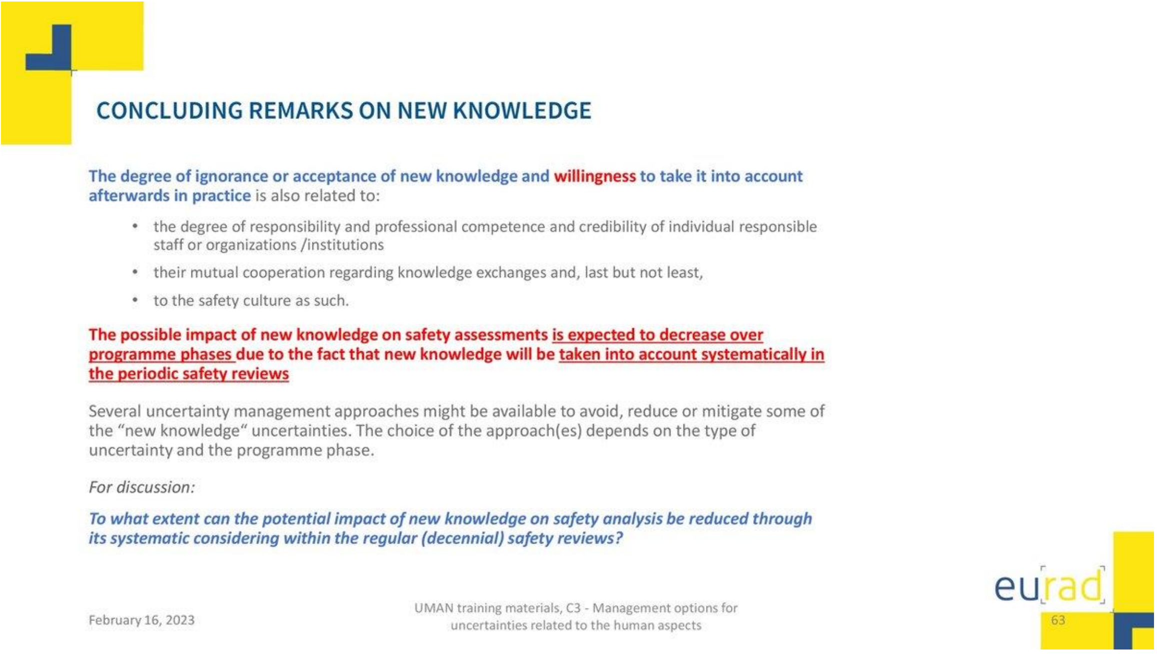
REPRESENTATION IN SAFETY ASSESSMENTS

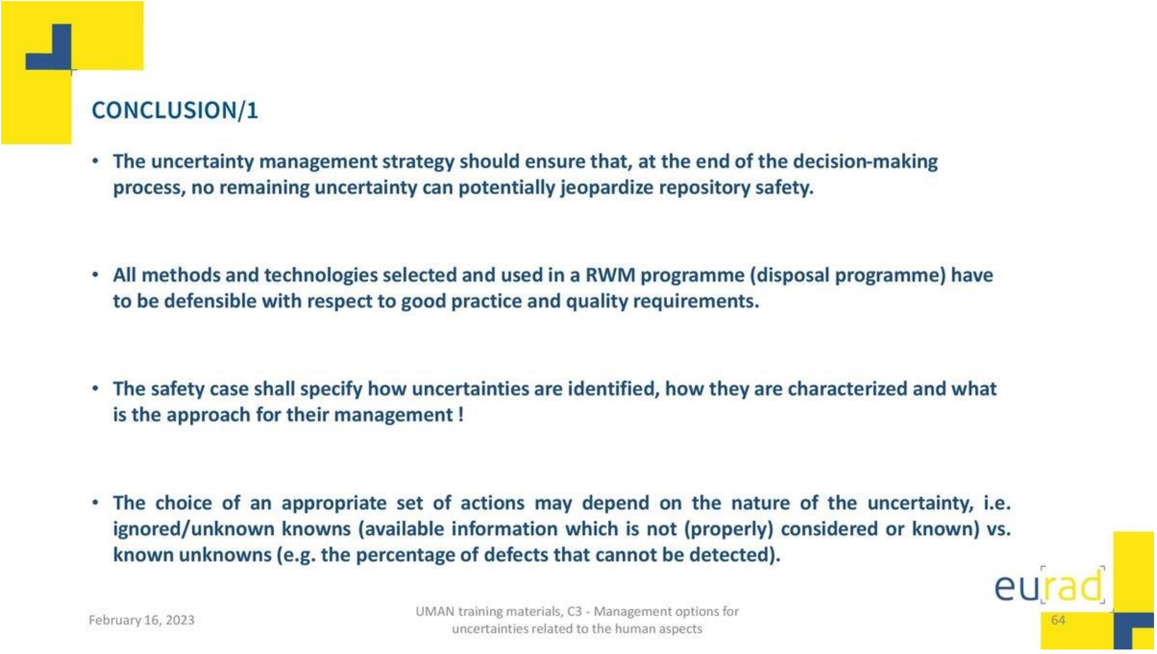
- **The safety case** as a basic methodology to assure the consistency of all safety-related issues **can be challenged when new evidences, knowledge or techniques are developed.**
- New knowledge is incorporated in the successive versions of the safety assessments
- **The safety assessment can be used to demonstrate the robustness** of the disposal system w.r.t. uncertainties like the occurrence of (unexpected) disturbing events using dedicated scenarios.
- What-if scenarios / analyses can be used when the cause of the degradation or failure is not known.
- Such analyses contribute to the assessment of the level of defence in depth provided by the disposal system.
- **New knowledge should be included/referred in the safety assessment also through the systematic FEP's management**



February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects

eurad 62

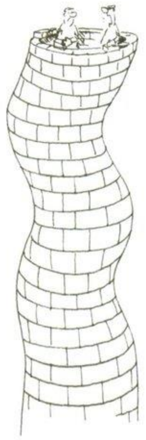

CONCLUDING REMARKS ON NEW KNOWLEDGE
The degree of ignorance or acceptance of new knowledge and willingness to take it into account afterwards in practice is also related to:
• the degree of responsibility and professional competence and credibility of individual responsible staff or organizations /institutions
• their mutual cooperation regarding knowledge exchanges and, last but not least,
• to the safety culture as such.
The possible impact of new knowledge on safety assessments is expected to decrease over programme phases due to the fact that new knowledge will be taken into account systematically in the periodic safety reviews
Several uncertainty management approaches might be available to avoid, reduce or mitigate some of the "new knowledge" uncertainties. The choice of the approach(es) depends on the type of uncertainty and the programme phase.
For discussion:
To what extent can the potential impact of new knowledge on safety analysis be reduced through its systematic considering within the regular (decennial) safety reviews?
February 16, 2023
UMAN training materials, C3 - Management options for uncertainties related to the human aspects
eurad
63


CONCLUSION/1
• The uncertainty management strategy should ensure that, at the end of the decision-making process, no remaining uncertainty can potentially jeopardize repository safety.
• All methods and technologies selected and used in a RWM programme (disposal programme) have to be defensible with respect to good practice and quality requirements.
• The safety case shall specify how uncertainties are identified, how they are characterized and what is the approach for their management !
• The choice of an appropriate set of actions may depend on the nature of the uncertainty, i.e. ignored/unknown knowns (available information which is not (properly) considered or known) vs. known unknowns (e.g. the percentage of defects that cannot be detected).
February 16, 2023
UMAN training materials, C3 - Management options for uncertainties related to the human aspects
eurad
64

CONCLUSION/2

- How to measure the "immediate benefits" of a given solution when facing intergenerational equity?
- Safety case needs to demonstrate not only "a good system" but also "good processes", namely a "good safety analysis", i.e. it needs to prove that these uncertainties have been dealt with adequately (e.g. QA system, clear roles, etc.).
- Building and/or improving credibility of the responsible organizations and institutions involved in the management of radioactive waste is essential for building public trust in the whole programme implementation, including decision-making process.

Trust is difficult to gain but easy to be lost!



Look, either you believe it or leave it...

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad 65

LIST OF RECOMMENDED PUBLICATION

REFERENCES

February 16, 2023 | UMAN training materials, C3 - Management options for uncertainties related to the human aspects | eurad 66

REFERENCES AND LIST OF RECOMMENDED PUBLICATIONS/1

- Status and Trends in Spent Fuel and Radioactive Waste Management, IAEA NES No. NW-T-1.14 (Rev. 1), Vienna 2022
- Nuclear Power Reactors in the World, IAEA Reference Data Series No. 2, IAEA, Vienna (2017)
- Communication and Stakeholder Involvement in Radioactive Waste Disposal , IAEA NES No. NW-T-1.16, Vienna 2022
- Stakeholder Engagement in Nuclear Programmes, IAEA NES No. NG-G-5.1, Vienna 2022
- Costing Methods and Funding Schemes for Radioactive Waste Disposal Programmes, IAEA NES No. NW-T-1.25, Vienna 2022
- Guide to Knowledge Management Strategies and Approaches in Nuclear Energy Organizations and Facilities , IAEA NES No. NG-G-6.1, Vienna, 2022
- Decommissioning after a Nuclear Accident: Approaches, Techniques, Practices and Implementation Considerations, IAEA NES No. NW-T-2.10, Vienna 2019
- Options for Management of Spent Nuclear Fuel and Radioactive Waste for Countries Developing New Nuclear Power Programmes, IEAE NES No. NW-T-1.24 (Rev. 1), Vienna 2018
- Knowledge Management and Its Implementation in Nuclear Organizations, IAEA NES No. NG-T-6.10, Vienna 2016
- Management of Disused Sealed Radioactive Sources, IAEA NES No. NW-T-1.3, Vienna 2014
- Nuclear Fuel Cycle Objectives, IAEA No. NF-O, Vienna 2013
- Options for Management of Spent Fuel and Radioactive Waste for Countries Developing New Nuclear Power Programmes, IAEA NES No. NW-T-1.24, Vienna 2013

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 67

REFERENCES AND LIST OF RECOMMENDED PUBLICATIONS/2

- Policies and Strategies for the Decommissioning of Nuclear and Radiological Facilities, IAEA NES No. NW-G-2.1, Vienna 2011
- The Management System for the Development of Disposal Facilities for Radioactive Waste, IAEA NES No. NW-T-1.2, Vienna 2011
- Radioactive Waste Management Objectives, IAEA NES No. NW-O,Vienna 2011
- Disposal Approaches for Long Lived Low and Intermediate Level Radioactive Waste, IAEA NES No. NW-T-1.20, Vienna 2010
- Policies and Strategies for Radioactive Waste Management, IEAE NES No. NW-G-1.1, Vienna 2009
- Geological Disposal of Radioactive Waste: Technological Implications for Retrievability, IAEA NES No. NW-T-1.19, Vienna 2009
- Determination and Use of Scaling Factors for Waste Characterization in Nuclear Power Plants, IEAE NES No. NW-T-1.18, Vienna 2009
- An Overview of Stakeholder Involvement in Decommissioning, IAEA NES No. NW-T-2.5, Vienna 2009
- Costing of Spent Fuel Storage, IEAE NES No. NF-T-3.5, Viemma 2009
- Responsibilities and Capabilities of a Nuclear Energy Programme Implementing Organization, No. NG-T-3.6, Vienna 2009???
- Managing Human Resources in the Field of Nuclear Energy, IEAE NES No. NG-G-2.1, Vienna 2009
- Nuclear Energy Basic Principles, IEAE NES No. NE-BP, Vienna 2008
- Classification of Radioactive Waste, No. GSG-1, IAEA, Vienna 2009

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 68

REFERENCES AND LIST OF RECOMMENDED PUBLICATIONS/3

- Management and Disposal of High-Level Radioactive Waste: Global Progress and Solutions, OECD 2020, NEA No. 7532
- Storage of Radioactive Waste and Spent Fuel, OECD 2020, NEA No. 7406
- The Evolving Role and Image of the Regulator in Radioactive Waste Management: Trends over Two Decades, OECD 2012, NEA No. 7083
- Engineered Barrier Systems (EBS) in the Safety Case: Design Confirmation and Demonstration, Workshop Proceedings Tokyo, Japan 12-15 September 2006, OECD 2007 NEA No. 6257

Integration Group for the Safety Case (IGSC)

- Features, Events and Processes (FEPs) for Geologic Disposal of Radioactive Waste, NEA, ISBN 92-64-18514-3 – No. 51449 2000
- Stakeholder Confidence in Radioactive Waste Managements, An Annotated Glossary of Key Terms, OECD 2013, NEA No. 6988
- The Forum on Stakeholder Confidence Report on Dialogue in the Long-Term Management of Radioactive Waste, OECD 2021 (https://www.oecd-nea.org/jcms/pl_56330/the-forum-on-stakeholder-confidence-report-on-dialogue-in-the-long-term-management-of-radioactive-waste)
- Optimisation of Geological Disposal of Radioactive Waste, National and International Guidance and Questions for Further Discussion, ISBN : 978-92-64-99107-1

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 69

REFERENCES AND LIST OF RECOMMENDED PUBLICATIONS/4

- Multifactor Optimisation of Predisposal Management of Radioactive Waste: Proceedings of the NEA Joint Workshop, NEA/RWM/R(2020)3
- Preservation of Records, Knowledge and Memory (RK&M) Across Generations, Final Report of the RK&M Initiative, OECD 2019, NEA No. 7421
- Preservation of Records, Knowledge and Memory(RK&M) Across Generations, Compiling a Set of Essential Records for a Radioactive Waste Repository, OECD 2019, NEA No. 7423
- Metadata for Radioactive Waste Management, OECD 2018, NEA No. 7378
- IAEA Safety Glossary Terminology Used in Nuclear Safety and Radiation Protection, 2018 Edition? Vienna (This publication has been superseded by the 2022 (Interim) Edition of the IAEA Nuclear Safety and Security Glossary)
- IAEA SSG poster – provides full information about existing guides derivered for the IAEA Fundamental Safety Principles (https://gnssn.iaea.org/nsni/eat/shareddocuments/forms/allitems.aspx?rootfolder=/nsni/eat/shareddocuments/safety+standards+poster&folderctid=0x012000b2fc1f055aa1a744b78f1941cc3aa7f4&view=%7Be9e90f12-9e7d-4c7a-80ad-6e6d7c97c05f%7D)
- https://www.iaea.org/topics/disposal/international-project-on-demonstrating-the-safety-of-geological-disposal
- Richardson, P., Galson, D., 2009. "How to communicate safety? Some reflections from European project studies," Proceedings of the "Values in decisions on risks" conference VALDOR09, Stockholm (8-11 June 2009)The Bridge. 2012. "Symposium on government-university-industry partnerships in regional innovation and entrepreneurship," Vol.42(2), pp.72-73. National Academy of Engineering
- Vojtechová, H., 2009. "Evaluation, testing and application of participatory approaches in the Czech Republic. Application of the RISCOM model in the Czech Republic," Deliverable of the ARGONA Project (Contract Number: FP6-036413), Number 14, Nuclear Research Institute Rez plc., Czech Republic
- Ustohalova, V., Minhans, A., Kallenbach-Herbert, B., 2012. "Short report about the results of the questionnaire on the participatory process for a radioactive waste repository for high level waste (HLW) in the Czech Republic," Deliverable of the IPPA Project (Contract Number: 269849), Number 5.1.3, Öko-Institut, Germany

February 16, 2023 UMAN training materials, C3 - Management options for uncertainties related to the human aspects eurad 70

Thank you for your attention!

February 16, 2023

UMAN training materials, C3 - Management options for uncertainties related to the human aspects

eurad

71

Appendix M. Short career summary of lecturers

This appendix provides a short career summary for each of the lecturers who prepared and gave the lectures of the course.

Valéry Detilleux, Bel V

Valéry DETILLEUX holds a Ph.D. in physical chemistry from the Université catholique de Louvain (Belgium). He joined Bel V in 2011 and works currently at Bel V as a branch manager and a project manager. He is notably involved in the review of safety assessments for radioactive waste treatment, conditioning and disposal facilities. He is responsible for the development and implementation of a R&D programme for supporting the regulatory review of the safety case for a geological disposal facility. He is actively involved in the EURAD Joint Programme, notably as Chairman of the Bureau of the General Assembly. Moreover, he is the SITEX.Network President since January 2022 and participated in several international working groups and projects such as IAEA-GEOSAF II, IAEA-PRISM, EC-FP7-SITEX and EC-H2020-SITEX-II.

Tim Hicks, GSL

Since 1994:	Consultant (now Technical Director) at Galson Sciences Ltd, UK (safety of radioactive waste management and disposal)
1988-1994:	Researcher at CSM Associates, Cornwall, UK (hot dry rock geothermal energy)
1986-1988:	Post-doc University of East Anglia, UK (semi-conductor crystal growth)
1988:	PhD at University of Bristol, UK (computational fluid dynamics)
1982:	BSc at University of Aston in Birmingham, UK (mathematics)

Work topics:

- Environmental safety case methodology
- Disposal concepts
- Safety assessment
- Criticality safety of fissile wastes

Vincenz Brendler, HZDR

Since 2017:	Professorship Radiochemistry at University of Applied Sciences Dresden
Since 2004:	Department head at HZDR (RN migration, surface processes, thermodynamics of actinides
Since 1993:	Researcher at Helmholtz-Zentrum Dresden-Rossendorf (HZDR)
1992-1993:	PostDoc at NTH Trondheim (Norway)
1993:	PhD at Bergakademie Freiberg (Physical chemistry of brines)
1989:	Diploma (Chemistry, Bergakademie Freiberg)

Work topics:

- Thermodynamics of aqueous solutions
- Geochemistry
- Molecular understanding of radionuclide migration
- Sensitivity and uncertainty analysis

Klaus-Jürgen Röhlig, TUC

Since 2007:	University professor for Disposal Systems at TU Clausthal
2010-2015:	Chair of the Integration Group for the Safety Case (IGSC) at OECD/NEA
1991-2007:	Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH Köln (scientific officer, project manager, deputy head of department)
1989-1991:	Institut für Energetik Leipzig (scientific officer)
1989:	PhD at Bergakademie Freiberg (mathematical analysis)
1985-1989:	Bergakademie Freiberg (research fellow)
1985:	Diploma (mathematics, Bergakademie Freiberg)

Work topics:

- Safety assessment / safety case methodology
- Analytical assessment of the long-term performance of geotechnical barriers
- Probabilistic methods and sensitivity analysis
- Sociotechnical research: Interface of technical and non-technical aspects in nuclear waste management

Dirk Alexander Becker, GRS

From 1989 to 1993 scientific employee of the Institute for Mathematical Physics of the Technical University of Braunschweig. From 1993 to 1995 employee of the Safety Analyses Group at GSF-Forschungszentrum für Umwelt und Gesundheit GmbH. Since 1995 scientific employee of the Repository Safety Department of the Disposal Division at Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH. Head of group “Statistic Methods”.

Attila Baksay, TSENERCON

Since 2017:	Consultant in TS Enercon Ltd.
2011-2017:	Physicist at Public Limited Company for Radioactive Waste Management
2008-2011:	Physicist at Golder Associates Hungary Ltd.
2003-2007:	Physicist at TS Enercon Ltd.
2003:	Engineer-physicist diploma at Budapest University of Technology and Economics

Work topics:

- Radioactive waste management techniques
- Safety assessment of radioactive waste management facilities
    - Derivation of radioactive waste inventories (derivation of stochastic inventory)
    - Dose assessments for operational phase of waste management facilities
    - Dose / risk assessment of post closure phase for disposal facilities (stochastic modelling, sensitivity analysis)
    - HAZOP assessments
- Calculations for nuclear safety (burnup, criticalty)
- Software development for safety calculations

Peter Schillebeeckx, JRC

Since 2001:	Scientific officer at European Commission, Joint Research Centre, Geel, Belgium
1989-2001:	Scientific officer at European Commission, Joint Research Centre, Ispra, Belgium
1988-1989:	Scientific officer at Institut Laue-Langevin, Grenoble, France
1987-1988:	Visiting scientist at the European Commission, CBNM, Geel, Belgium
1984-1987:	PhD student, RU Gent and SCK CEN Moll, Belgium

Work topics:

- Neutron detection techniques
- Neutron cross section measurements
- Neutron resonance analysis
- Production of evaluated nuclear data including covariance data
- Non-destructive assay of nuclear material (neutron and gamma-ray detection and calorimetry)

Chris de Bock, ONDRAF/NIRAS

Chris is involved in the management of the acceptance criteria for radioactive waste at ONDRAF/NIRAS, the Belgian Agency for management of radioactive waste and enriched fissile material. He is currently the coordinator of the expertise group charged with the development of the waste acceptance criteria. He is also a task leader in the strategic work package ROUTES of EURAD, a EU joint R&D programme on radioactive waste management. He is leader of Task 4, devoted to waste acceptance criteria. Chris De Bock was previously the project officer at ONDRAF/NIRAS in charge of the cost evaluation of both the geological and surface disposal projects. The cost evaluations provide a key input to the determination of the waste tariffs and budget provisions. Also previously at ONDRAF/NIRAS, he was chairman of the working group on the re-design of the Belgian geological repository and the preparation of its Safety Case. He is co-author of the Safety Analysis Report of the surface repository. Chris participated as Module leader in the 5-year R&D project ESDRED (of the EURATOM 6th Framework Programme), targeted on developing new geological repository technologies. Prior to joining ONDRAF/NIRAS, from 1989 to 2002 Chris De Bock was with Westinghouse Electric Company, where he was active in the design and safety evaluation of nuclear power plants. He managed several smaller and medium-scale study projects for the improvement of safety and/or efficiency in the fields of pressure vessel mechanics, thermo-hydraulics, reactor physics, control instrumentation and also for the development of plant-specific emergency response procedures. Chris De Bock holds a degree in civil engineering (electro-mechanics) from the university of Leuven (Belgium).

Jeroen Mertens, Bel V

Since 2019:	Nuclear engineer at Bel V
2007-2018:	Inspector-Expert Radioactive waste at FANC
2005-2007:	Nuclear safety analyst AVN
2001-2005:	Researcher at ONDRAF/NIRAS
2000-2001:	Researcher at KULeuven

Work topics:

- Waste acceptance criteria
- ‘Disposability’ of radioactive waste
- Surface disposal, specifically w.r.t:
    - Licensing,
    - Safety assessment,
    - Design,
    - Uncertainty management.
- Geological disposal

Julien Dewoghélaëre, NTW

Mr. Julien Dewoghélaëre has a graduate degree in Politics Sciences (Sciences Po Bordeaux, 2003). He has been working in MUTADIS from 2011 to July 2022 on research projects and network activities on the governance of hazardous activities, particularly on nuclear related matters. He was involved in the SITEX project (2012-2013) and SITEX-II project (2015-2017) and in the development of tools enabling pluralistic dialogue between various categories of actors on complex topics (including Radioactive Waste Management) entitled Pathway Evaluation Process (PEP). He is currently working for NTW and is member of the team in charge of coordinating the Interaction with Civil Society (ICS) activities in EURAD. In UMAN, he is Task leader of TASK 5.

Jeroen Bartol, COVRA

Jeroen Bartol started about five years ago at COVRA, the Dutch waste management organisation, as a research coordinator on disposal in rock salt. He is responsible for the safety case, safety assessment and the cost estimate. He did his bachelor, master and PhD at Utrecht University in geophysics with a focus on numerical modelling.

Jitka Miksova, SURO

Ms. Jitka Mikšová has received her master degree in applied geophysics at Charles Univesity in Prague in 1984. After graduation, she was engaged in the field investigation aimed at water and mineral resources as a prospector, then as a head of the Data Processing Department in a private company. She has been participating in the national RWM programme since 90s when she joined the Czech Geological Survey. Until 2004, as a member of the expert group, she was involved in DGR siting, data and information management, GIS implementation, radon programme establishment, until 2004. Then, more than 10 years she was working for SURAO (Czech WMO) in the Geological Repository Development Department, as a technical development project manager responsible, in particular, for far field research, natural analogues, siting issues, she was involved in project management and strategic documents development. Between 2014 and 2019 she was working in Nuclear Research Centre Rez, in Nuclear Fuel Cycle Department, as a research scientist-expert leading TSO group focusing on RWM. She joined SURO in 2017 (part time), since 2019 she is a head of the Division providing services to the SUJB (Czech regulatory authority) in the field of RWM, she is a member of the SITEX.Network MB, currently participating in EURAD, PREDIS and HARPERS projects and in national research projects on RWM.

Appendix N. Test

This test was prepared by the lecturers and performed by the participants at the end of the course. It aimed at verifying if the audience had broadly understood the lectures and at receiving feedback about the lectures. This is was not a "qualification test". The correct answers are indicated by a cross in the last column below (this information was provided to the course participants after the test).

A1: Introduction to the safety case, uncertainty management strategy and main types of uncertainties *Valéry Detilleux*		
Q A1-2.1: Uncertainties…		
a	…should not be discussed in the safety case, they have to be discussed in a separate document (not evaluated by the regulatory body).	
b	…are central in the safety assessment and the safety case. The safety case has to present how uncertainties are managed.	X
c	…management in the safety case is a good basis to have a dialogue between the interested partners and develop trust between them.	X
Q A1-2.1: The UMAN work package of EURAD…		
a	…contributes to build a mutual understanding about uncertainty management between the main actors involved in a radioactive waste management programme.	X
b	…identified that it is absolutely impossible to develop a mutual understanding about uncertainty management.	
c	…showed that uncertainties about waste inventory do not have to be managed, they are absolutely not safety significant.	
Q A1-2.3: All the uncertainties that are identified in a radioactive waste management programme can be reduced.		
a	Yes	
b	No, only epistemic uncertainties can (in principle) be reduced.	X
c	No, only uncertainties related to technical aspects can be reduced (and not those associated to human aspects).	

A3: Uncertainty management strategy and approaches *Tim Hicks*		
Q A3.1: A safety case produced at each decision-making stage in a disposal programme, should…		
A	…show that there are no remaining uncertainties that could be significant to safety	

B	…include a plan for how and when any remaining uncertainties that could be significant to safety will be addressed	X
C	…argue that any remaining uncertainties that could be significant to safety will be addressed by the next decision-making stage	
Q A3.2: All uncertainties…		
a	…should be reduced, mitigated or avoided with the objective of ensuring that the detrimental impacts of disposal are as low as is reasonably achievable	X
b	…should be reduced, mitigated or avoided	
c	…should be reduced, mitigated or avoided until they are of no significance to safety	
Q A3.3: Events and processes of irreducible uncertainty regarding their occurrence….		
a	…do not need to be considered in a safety assessment	
b	…can be characterised in terms of their probability of occurrence for inclusion in probabilistic safety assessments	
c	…can be assessed through deterministic or 'what-if' scenarios to understand their potential impacts on safety	X

A4: Uncertainty identification and quantification *Vinzenz Brendler*		
Q A4.1: What is the difference between aleatoric and epistemic uncertainties?		
a	Whether it is (theoretically) possible to reduce theuncertainty or not	X
b	Whether it concerns model or parameter uncertainty	
c	Whether it can be used for sensitivity analyses or not	
Q A4.2: What is the difference between risks and uncertainty?		
a	Risk is a psychological category, uncertainty a scientific one	
b	Risk is uncertainty combined with consequences	X
c	Risk is scenario-based, uncertainty is model-based	
Q A4.3: How can you manage uncertanties that turned out to be not neglectable?		
a	Do more investigations to check whether they can be reduced	X
b	Change system components to get rid of the respective parameter (and thus its uncertainty)	X

c	Search for good reasons why they are still acceptable for the public	

A5: Approaches to uncertainty and sensitivity analysis – Overview *Klaus-Jürgen Röhlig*		
Q A5.1: Sensitivity analysis: Local methods can be based on …		
a	… calculating the output variance.	
b	… estimating output derivatives.	X
c	… estimating correlation ratios.	
Q A5.2: Sensitivity analysis: Screening methods …		
a	… are supposed to detect non-monotonic input-output relationships.	
b	… often require specific space-filling sampling schemes and high sample sizes.	
c	… are supposed to identify uninfluential input parameters with relative few model evaluations.	X
Q A5.3: Sensitivity analysis: Variance-based methods …		
a	… are unable to detect non-monotonic input-output relationships.	
b	… might be able to detect input correlations.	
c	… might be able to detect input interactions.	X

A6: Approaches to uncertainty and sensitivity analysis – Practical application *Dirk-Alexander Becker*		
Q A6.1: What does sensitivity analysis not serve for?		
a	Improving model understanding	
b	Validating the model	x
c	Identifying influential model parameters	
Q A6.2: For polynomial metamodels, how should one choose the maximum polynomial orders?		
a	Not lower than 3	
b	The higher the better	
c	Carefully, depending on the model	x

Q A6.3: What does it mean if the rank-based sensitivity analysis yields, for a specific parameter, a lower (absolute) sensitivity than the direct evaluation?		
a	The parameter acts mainly on high model output values	x
b	The parameter acts mainly on low model output values	
c	The parameter is very uncertain	

B1: Characterization and significance of uncertainties related to the waste inventory *Attila Baksay*		
Q B1.1: What are the sources of the uncertainties related to radioactive waste inventory?		
a	Waste stream identification, Waste production rate, Radiological- Physico - Chemical Characterization, Waste processing (Pre-treatment, Treatment, Conditioning), Long-term physico-chemical interactions in Storage and Disposal	X
b	Only the radiological characterization provides significant uncertainties in the radioactive waste inventory.	
c	Scaling factor methodology used in radioactive waste characterization. Chemical properties of the waste. Long term behavior of the waste packages related to the final disposal.	
Q B1.2: In which areas does the uncertainty about the waste inventory play a role?		
a	The operational and post closure safety of the radioactive disposal sites is the related issue that can be effected by these uncertainties.	
b	Basically every aspects of radioactive waste management; operational and post-closure safety of the facilities, design of these facilities, selection of waste management routes. The uncertainties also have impact on the optimization of the predisposal and disposal of the radioactive waste.	X
c	The operational safety of the radioactive waste management facilities is the main issue, where the accidents related to waste treatment can be prevented.	
Q B1.3: What efforts are to be done in order to minimize the uncertainties related to the uncertainties of radioactive waste inventory?		
a	Development of radiological characterization. Improvement of Quality Assurance and Quality Control of the radiological characterization.	
b	The efforts of organisations involved in radioactive waste management to minimise these uncertainties cannot be foreseen. The scope for speculation is too great.	
c	Development in methodologies and technologies of radiological and non-radiological characterization. Efforts for multiple characterization of waste packages through the predisposal steps. Improvements in statistical methodology related to better process measured data. Improvement of Quality Assurance and Quality Control of the	X

	characterization and in the process of waste processing. Data collection in order to understand storage systems and disposal systems.	

B2: Uncertainties in the radiological characaterization of spent fuel
Peter Schillebeeckx

Q B2.1: What is the best procedure to estimate the decay heat rate (or decay power) of a spent fuel assembly together with the long timescale evolution of the decay power (> 100 year)?		
a	Determine the inventory of ^{90}Sr, ^{106}Ru, ^{137}Cs, ^{144}Ce, ^{238}Pu and ^{241}Pu from a representative sample by radiochemical analysis and use this inventory to calculate the decay power as a function of cooling time.	
b	Determine the decay power of the assembly by measurements with a calibrated and validated calorimeter and extrapolate the result for longer timescales.	
c	Use a validated depletion code to estimate the nuclide inventory at the end of irradiation in the reactor and use this inventory to calculate the decay power as a function of cooling time	X
Q B2.2: What is the minimum relative uncertainty of the calculated neutron emission rate due to spontaneous fission of a PWR spent nuclear fuel assembly with a cooling time of 10 years? The calculations are performed with the following input data: IE (initial enrichment) = 4.480 (45) wt% and BU (burnup) = 45.0 (9) MWd/kg.		
a	2%	
b	4%	
c	8%	X
Q B2.3: A measurement of a spent nuclear fuel sample with a calorimeter results in a decay power of 230 (9) W. An estimation of this decay power (for the same cooling time) using a reference method results in (300 $\pm$ 6) W. What is the estimated systematic error of the result of the calorimeter? Note that the uncertainties are given following the recommendations in the GUM.		
a	- 70.0 (95) W	X
b	- 70 (11) W	
c	70.0 (95) W	

B3: Uncertainties associated with waste management routes
Chris De Bock

Q B3.1: What can be considered to be the essence (“backbone”) of radioactive waste management ?		
a	The characterization of the radioactive waste	

b	The definition, for each waste type, of a route of activities from the generation of the waste to its disposal	X
c	The availability of a radioactive waste disposal facility	
Q B3.2: Name two important disadvantages of early conditioning (without an established disposal route)		
a	1. Uncertain qualification of the conditioning process 2. Need to keep the conditioned waste packages in storage for a long period of time	
b	1. Not being able to benefit from future more efficient conditioning techniques 2. Increased risk of degradation of the conditioned waste packages during storage	
c	1. Uncertain acceptability of the conditioned waste packages for the disposal facility 2. Early (up-front) investments	X
Q B3.3: What is an important prerequisite to developing shared solutions ?		
a	All participating countries must be countries with a small radioactive waste inventory.	
b	A common safety culture and a level playing field must exist between participating countries.	X
c	All participating countries must have a certain level of creditworthiness.	

B.5.: Options for the management of uncertainties related to the waste inventory *Jeroen Mertens*		
Q B5.1: Which of the following is a way in which the uncertainties related to chemical composition of the waste could be represented in the Safety Assessment		
a	By performing laboratory experiments that reduce the uncertainties	
b	By using conservative assumptions/parameter settings that envelope the uncertainties	X
c	By listing them as uncertainties that will be dealt with in a next iteration of the Safety Assessment	
Q B5.2: What is a way in which uncertainties related to physical-chemical conditions in the disposal installation could be reduced		
a	By performing monitoring of the above ground storage conditions (t°, humidity)	
b	By representing the uncertainties in altered evolution scenarios	
c	By performing mock-up experiments that simulate the physico-chemical environment of the disposal	X

Q B5.3: What uncertainties related to waste inventory were seen by the Waste management organisations/Technical support organisations/Research Entities as not very important		
a	Uncertainties related to radionuclide activity	
b	Uncertainties related to chemical composition	
c	Uncertainties related to voids in the waste	X

C1: Views of civil society on uncertainty management *Julien Dewoghelaere*		
Q C1.1: Why is it interesting to implement interactions between experts and civil society in the perspective of uncertainty management?		
a	It is a legal requirement	
b	Such interactions will help to develop a mutual understanding of the uncertainties at stake and to disseminate a shared safety culture	X
c	There is no interest	
Q C1.2: Regarding civil society views on human uncertainties, which of the following statement is true (based on the UMAN results)?		
a	Public acceptance should be understood as a way to guarantee the quality of the uncertainty management rather than an uncertainty in itself	X
b	It is possible to postpone decisions endlessly without any alternatives in mind	
c	The apparition of new knowledge undermines the credibility of the safety review	
Q C1.3: UMAN project identified methodologies to implement pluralistic management of uncertainties. Regarding these methodologies, which of the following statement is true?		
a	The involvement of civil society in the management of uncertainty does not require an appropriate legal framework	
b	The Pathway Evaluation Process (PEP game) is the method for the involved actors to choose the best technical solution	
c	Long-term/rolling stewardship, understood as a well-structured governance system could help ensuring intergenerational transmission of information, empowerment of communities and cultural heritage	X

C2: Characterization and significance of uncertainties for different categories of actors *Jeroen Bartol*		
Q C2.1: During the identification of the uncertainties, each uncertainty was assigned an category. Which was not a category?		
a	Societal	

b	Political	
c	Safety	x
Q C2.2: Which of the uncertainties here below were considered in the list of the 10 uncertainties that were elaborated on within more details and were used in the questionnaire?		
a	Continuity of the waste management policy along political changes	x
b	Human intrusion	
c	Public acceptance of the repository at potentially suitable or projected location	x
Q C2.3: What should you always do when you make a decision to include or exclude an uncertainty from the list of uncertainties that need further research?		
a	Nothing.	
b	Record why you made that decision and arguments why it was excluded or included and include this in the final report.	x
c	Make a note of why an uncertainty is included or exclude but do not put this in the final report.	

C3. Options for the management of uncertainties related to human aspects *Jitka Miksova*		
Q C3.1: Is it a public acceptance one of the important factors for a successful siting process? Has a public acceptance a direct impact on a disposal facility safety?		
a	The public acceptance is important and has a direct impact on the facility safety	
b	The public acceptance is important and but has not a direct impact on the facility safety	x
c	The public acceptance is not important and has a direct impact on the facility safety	
Q C3.2: Can uncertainty in the financial and raw resources affect the schedule of the RW programme implementation? Can be this uncertainty in the schedule avoided?		
a	An uncertainty in the financial and raw resources can affect the schedule and can be avoided.	
b	An uncertainty in the financial and raw resources can affect the schedule and can be avoided.	
c	An uncertainty in the financial and raw resources can affect the schedule and cannot be avoided.	x
Q C3.3: Should the safety case specify how uncertainties caused by human factors are identified, how they are characterized and what is the approach for their management? Should be these uncertainties evaluated within Periodic Safety Review?		

a	The management of uncertainties caused by human factors is not a part of safety case thus there is no need to periodically evaluate them within Periodic Safety Review.	x
b	The management of uncertainties caused by human factors should be an integral part of safety case but there is no need to evaluate them within Periodic Safety Review.	
c	The management of uncertainties caused by human factors should be an integral part of safety case and should be periodically reviewed.	