MUSA

Proceedings of the MUSA Final Open Workshop

CIEMAT Madrid
May 10-11, 2023

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https://musa-h2020.eu/
MUSA H2020 EUROPEAN PROJECT

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Abbreviations

AB	Advisory Board
AM	Accident Management
BEPU	Best Estimate Plus Uncertainty
CNSC	Canadian Nuclear Safety Commission
ExB	Executive Board
EURATOM	European Atomic Energy Community
EU	European Union
EUG	End Users Group
FOM	Figure Of Merit
IAEA	International Atomic Energy Agency
JAEA	Japan Atomic Energy Agency
MSc	Master of Science
MUSA	Management and Uncertainties of Severe Accidents
NEA	Nuclear Energy Agency
OECD	Organization for Economic Co-operation and Development
ONR	Office for Nuclear Regulation
PMO	Project Management Office
SA	Severe Accident
SAM	Severe Accident Management
SFP	Spent Fuel Pool
SNL	Sandia National Laboratories
ST	Source Term
UaSA	Uncertainty and Sensitivity Analysis
UP	Uncertainties of input deck Parameters
UQ	Uncertainties Quantification
WP	Working Package
1F4	Fukushima Daiichi Unit 4

1 Introduction

The overall objective of the **Management and Uncertainties of Severe Accident (MUSA)** project was to assess the capability of Severe Accident (SA) codes when modelling reactor and SFP (Spent Fuel Pool) accident scenarios of Gen II and III Nuclear Power Plants. The MUSA Consortium comprises 29 partners, spread across 3 continents, and involves some of the most experienced organizations in the scientific domain of SA.

MUSA was characterized by an innovative research agenda in order to move forward the predictive capability of SA analysis codes by combining them with the best available/improved Uncertainties Quantification (UQ) tools and embedding Accident Management (AM) as an intrinsic aspect of SA analyses. A special attention has been given to educational and training aspects, disseminating the acquired knowledge also towards the young generation of researchers.

The **Final open workshop** at the end of the project, whose Proceedings are collected in the present document, open to international participants outside of the MUSA consortium, was held in hybrid mode at CIEMAT Madrid from 10 to 11 May 2023, with about one hundred of registered participants. The main goals of this final workshop were the public dissemination of the MUSA project results and gathering conclusions and outcomes towards the nuclear European community and even beyond, such as IAEA and OECD/NEA.

1.1 Learning Modules Presentation

The major outcomes of MUSA have been directly disseminated to MSc students/young researchers and to a generic audience also through e-learning modules that are made available from the project public website https://musa-h2020.eu/ with a free access. These learning modules, compiling both the major outcomes from MUSA project and additional insights concerning codes predictability and the Fukushima accident, have been launched with a partner initiative, during this Final Open workshop. Three videos with a duration of about 45 min each have been realized, addressing the following MUSA topics:

- Analysis of severe accidents: From the early days to the near future (by CIEMAT).
- Methodologies for uncertainty assessment in SAs, with particular emphasis on the ST estimates (by UNIPI).
- Assessment of ST Uncertainties in Fukushima-like scenarios (by CIEMAT).

2 Synthesis

The Agenda of the Workshop is reported in the Annex I while the open presentations are collected in the Annex II.

Opening Session - The MUSA open workshop was launched with a session bringing external-to-MUSA information on SA uncertainties. It consisted in two invited lectures:

- "*Severe Accident Uncertainites Analysis*", D. Luxat (SNL, United States of America)[1].
- "*Uncertainties of Source Term in the Accident at the Fukushima Daiichi Nuclear Power Station*", Y. Maruyama (JAEA, Japan).

After the discussion of both keynote lectures, a round table with both authors and S. Gyepi-Garbrah (CNSC, Canada) and A. Tehrani (ONR, United Kingdom) on "*The use of UQ in the regulatory process*" was held. Among the very many ideas discussed a few can be cited: the need to proceed in a continuous enhancing of nuclear safety and an efficient way and how UaSA might

[1] This presentation is not included in the Annex II.

help; the potential new paths that "emergent models" might bring into the area; the need to bring advanced methods, particularly UaSA, as close as feasible to AM and look for the best way to fill the decision process; the tight and strong relation of uncertainties with the specific accident scenarios; the key role of understanding the analytical methods to be used on nuclear safety analysis, no matter which ones, from surrogates to multi-scales modelling; or the indispensable "substantiation" that should support any safety statement.

Session 1 consists of a single introductory presentation of the project (CIEMAT). MUSA was presented from its inception to how it was articulated to face with the known challenges. Emphasis was placed on the "expected outcomes" at the onset of the project and the achievement of most of them in the end. It was highlighted that systematization of a methodology was a way too ambitious objective and the fact that a further shot should be given in the form of another research project (called INNOMUSA) based on the outcomes of MUSA.

Session 2 was a recap of the essential elements of the project.

- Uncertainties database (GRS), about the rationale of the database produced, from FOMs to parameters.
- Methodologies Part I - the starting point (KIT), on the journey of gathering SA codes and statistical tools and coupling them, the initial diversities among the project partners' approaches and the open aspects of the different approaches.

Session 3 on UQ Applications

- First insights into the UQ application employing the PHEBUS-FTP1 test (ENEA), including the major issues risen and the diversity in the responses.
- Applications to in-reactor SA sequences (JRC), with an identification of the partners' different approaches and an illustration of the achieved results.
- Applications to Spent Fuel Pools (IRSN), with and identification of the different approaches (1F4 scenario, building presence), highlighting diversity among partners and different approaches to SFP modeling.

Session 4 Summary and Final Discussion

- Major insights from MUSA (CIEMAT)
- Reflections on final uncertainties database (GRS), highlighting what brought from the MUSA technical WPs and key issues still to be worked out.
- MUSA from the standpoint of AB & EUG
- The path forward with the presentation of the new project INNOMUSA (CIEMAT)

3 Main Highlights

The MUSA Open Workshop was a successful event in multiple regards, from the attendance and interest shown to the MUSA outcomes and discussions held during the event. A few major highlights are worth summarizing next:

- The MUSA project has been an "imperfect success", with outstanding results achieved in key elements of the application of Uncertainty and Sensitivity Analysis (UaSA) in the SA domain. Examples are: the extensive database collected on uncertainties of input deck parameters (UP); the large collection of SA code/UQ tool coupling fitted for the purpose and used in the project; and the identification of the major challenges that bringing UaSA in SA entail, from the extension of the UP database to the management of failed crashes

and the consistent and useful way of using data analysis techniques. Particular mention deserve the large databases built-up on in-reactor and Spent Fuel Pool (SFP) applications.

- The need for a systematic and consolidated methodology for the application of UaSA in SA was brought up in presentations and discussions as a mandatory step to make the best out of MUSA. A new project, INNOMUSA, is presently under construction to fill this need. More than 25 organizations within Europe have already expressed their interest.
- The “substantiated” expert judgement was said to be more essential than ever in the UaSA application in SA, from the selection of the UP set to the interpretation of all and every realization conducted, failed cases, bifurcations and outliers included. Emphasis was placed in “substantiating” each technical claims, from those made in the application of UaSA to the ones done in MUSA outcomes.
- The implication of estimated uncertainties on management and decision making during any postulated accident was pinpointed as an area that could substantially benefit from the work done within MUSA.

Finally, both the European Commission Officer and the members of Advisory Board and End User Group of MUSA agreed on the valuable outcomes presented and the exemplary progress of the project, even under the harsh conditions imposed by the COVID-19 pandemic situation.

Acknowledgments

The MUSA Project Coordinator, the ExB components and the Workshop organizers would like to acknowledge the EC Project Officer, the round table speakers and all the lecturers for their contributions to the success of this final event of the MUSA project.

Annex I: Workshop Agenda

MUSA Final Open Workshop

CIEMAT Madrid, 10 & 11 May 2023

Agenda

May 10, 2023

9:30 INITIAL SESSION 0: INVITED KEYNOTES (190')

- **Welcome** – E. González, CIEMAT (15')
- **On the UQ use in SOARCA** – D. Luxat, SNL (30'+ 15' Q&A)
- **On the major uncertainties of Fukushima SAs** – Y. Maruyama, JAEA (30'+15' Q&A)

11:15 – 11:30 h Break

- **Round table: "On the use of UQ in the regulatory process"**– D. Gyepi-Garbrah (CNSC), D. Luxat (SNL), Y. Maruyama (JAEA), A. Tehrani (ONR); (10'/each+30' Q&A)

12:45 – 14:00 h Lunch break

14:00 SESSION 1: INTRODUCTION (60')

- **Overall presentation of the MUSA project** – L.E. Herranz, CIEMAT (45'+15' Q&A).

15:00 – 15:15 h break

15:15 SESSION 2: ESSENTIAL ELEMENTS (80')

- **Uncertainties database** – S. Beck, GRS (25'+15' Q&A)
- **Methodologies Part I: The starting point** – V.H. Sánchez, KIT (25'+15' Q&A)

16:45 h Meeting adjourn

May 11, 2023

9:30 SESSION 3: UQ APPLICATION (150')

- **First insights into UQ application: The PHEBUS-FTP1 case** – F. Mascari, ENEA (30'+15' Q&A)

10:15 – 10:30 h Break (15 min)

- **Application to in-reactor SA sequences** – S. Brumm, JRC (30'+15' Q&A)
- **Application to Spent Fuel Pools** – O. Coindreau, IRSN (30'+15' Q&A)

12:00 – 13:30 Lunch break

13:30 SESSION 4: SUMMARY & DISCUSSION SESSION (135')

- **Major insights from MUSA** – L.E. Herranz, CIEMAT (15'+15' Q&A)
- **Final uncertainties database: Reflections** – S. Beck, GRS (15'+15' Q&A)
- **Recommendations on methods** (20'+15') – V.H. Sánchez, KIT (15'+15' Q&A)
- **MUSA from the standpoint of AB & EUG** – M. Adorni, OECD/NEA; A. Tehrani, ONR; F. Robledo, CSN (45')

15:45 – 16:00 h Break (15 min)

- **The path forward: INNOMUSA** – L.E. Herranz, CIEMAT (15'+15' Q&A)
- **Final Open discussion** – All attendees (30')

17:00 Closure of the workshop

Annex II: Presentations

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MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

MUSA

Final Open Workshop

CIEMAT Madrid,10 & 11 May 2023

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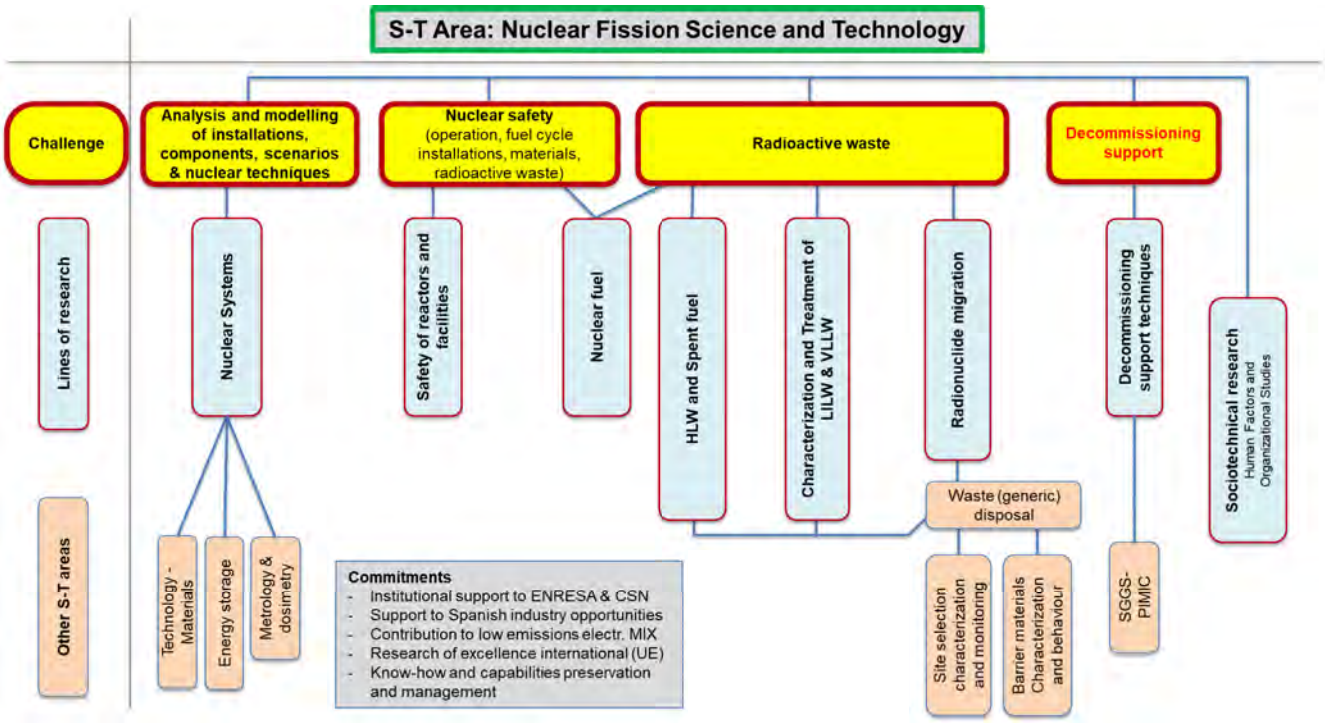
The Nuclear Fission Science and Technology Area



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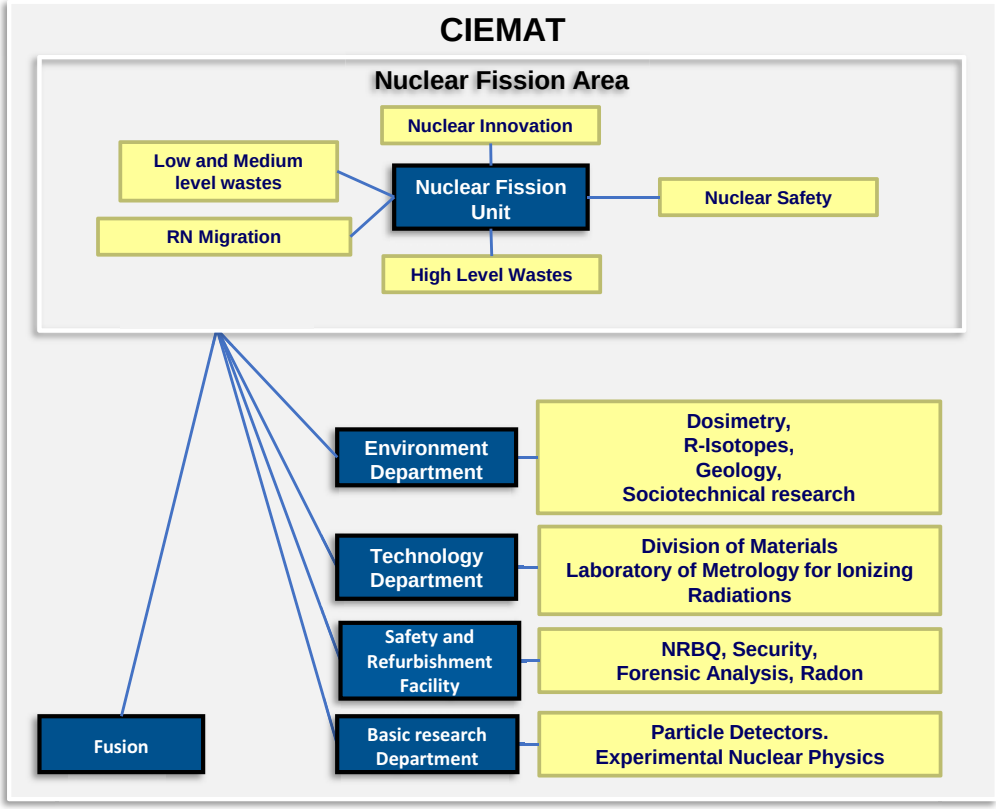
Nuclear Science and Technologies at CIEMAT



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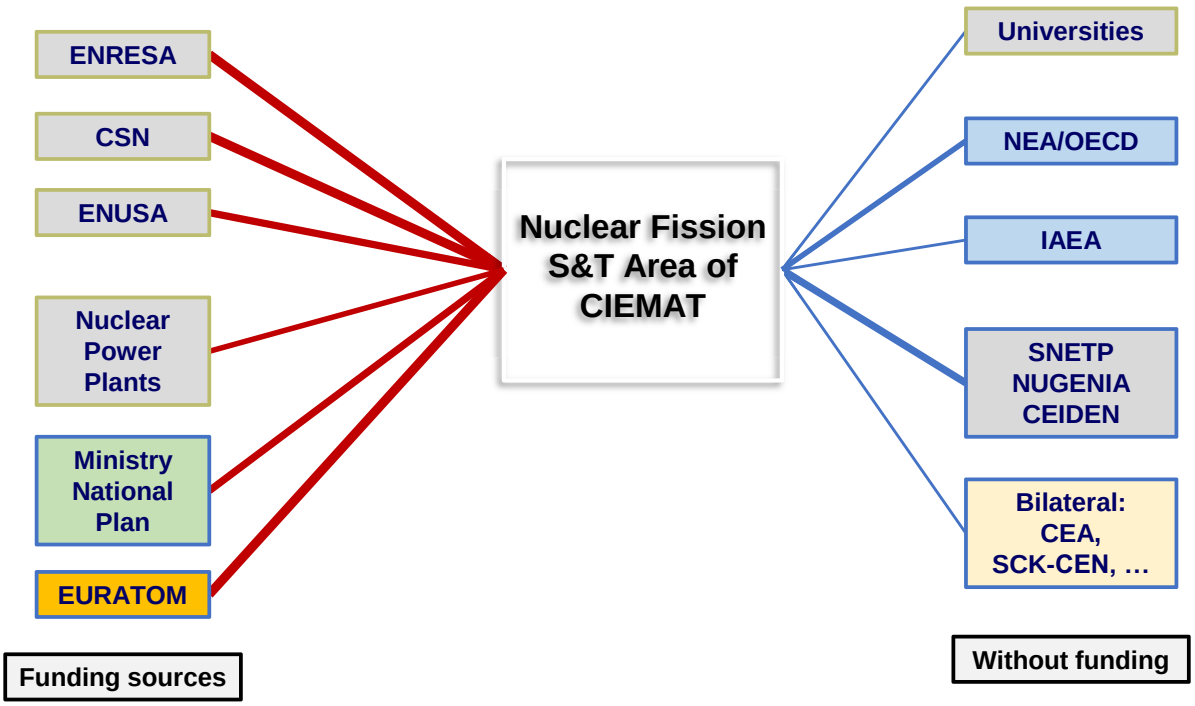
Collaboration and contract frameworks



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MUSA

Final Open Workshop

CIEMAT Madrid,10 & 11 May 2023

Uncertainties of Source Term in the Accident at the Fukushima Daiichi Nuclear Power Station (FDNPS)

MUSA Final Open Workshop (Hybrid)

May 10-11, 2023
CIEMAT, Madrid, Spain

Yu Maruyama

Sector of Nuclear Safety Research and Emergency Preparedness
Japan Atomic Energy Agency

Release timing and duration of radioactive materials to the environment

Degradation of confinement functions of NPS

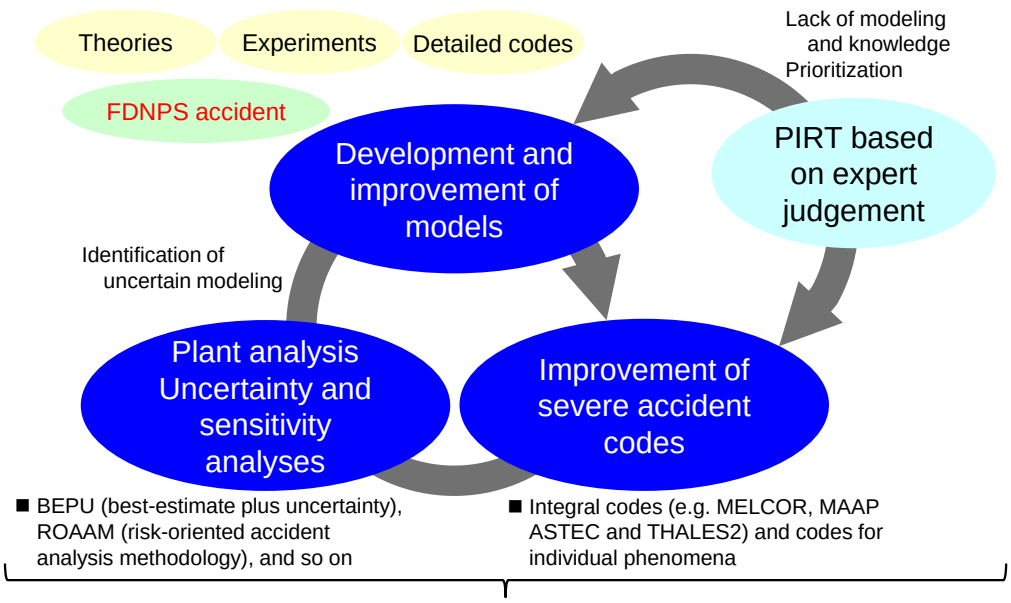
Amount and chemical and physical forms of released radioactive materials

Transport of radioactive materials in pathways from fuels (debris) to the environment

Source term and its uncertainty depend on accident scenarios.

- Assessment of effectiveness of management measures for severe accidents
- Offsite consequence analysis (level 3 PRA) with outputs of level 2 PRA
- Development of optimized emergency protective actions
- Training of emergency responders
- Comparison with numerical safety goals (performance goals) for release of radioactive materials to the environment

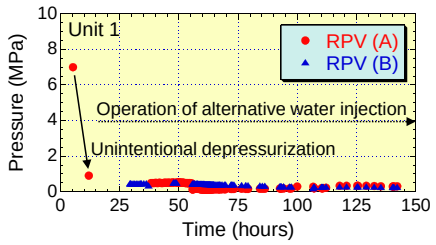
Best estimate and uncertainty band of source term are valuable information.



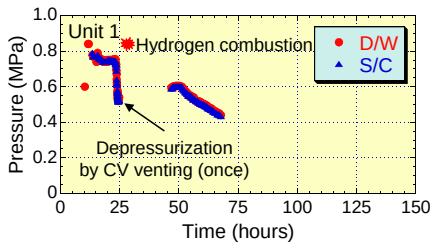
- State-of-the-art outputs for different reactor applications
- Continuous and efficient improvement of SA codes

- First severe accident of BWRs
- First multi-unit severe accident
- First severe accident induced by external natural hazards (common cause failures of key functions by external hazards)
- Recognition of threat of fuel damage in spent fuel pool
- **Long-term and large release** of radioactive materials into the environment
- **Different severe accident scenarios** in damaged three units

Reactor Vessel



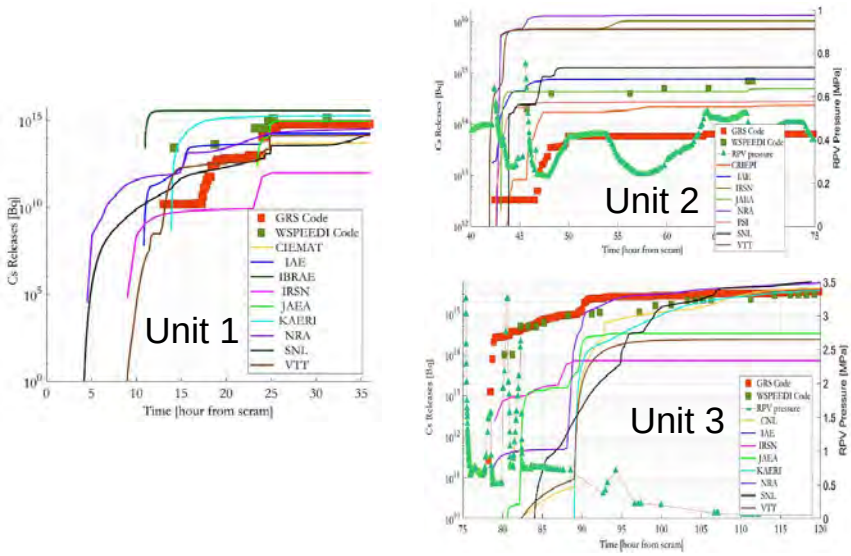
Containment Vessel



- Unintentional depressurization of the reactor vessel (RV) prior to lower head failure
  - Formation of leakage paths to the drywell
- Pressure increase in the containment vessel (CV) after the unintentional depressurization of the RV
- Operation of alternative water injection
- Pressure plateau in the CV at around 0.75 MPa
  - Leakage to the reactor building (RB) mainly through the CV top head flange
- Operation of CV venting through the suppression chamber (S/C)
- Hydrogen combustion in the RB

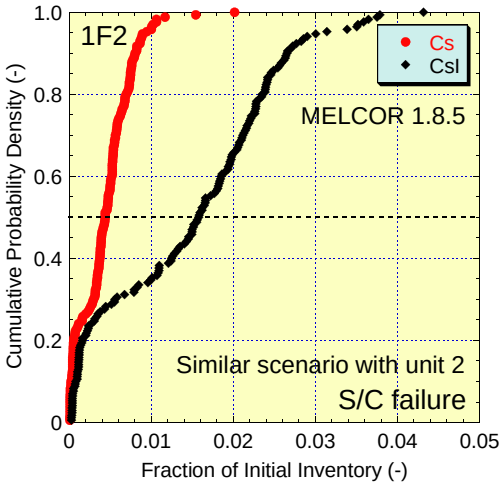
Outputs from OECD/NEA BSAF2 Project

- Analysis for Release of Cs to the Environment -

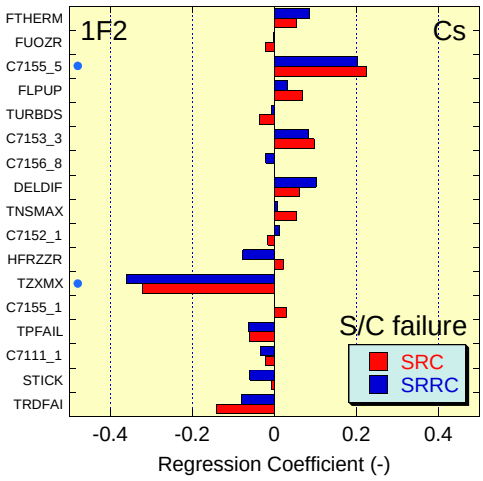


BSAF : Benchmark Study for the Accident at the Fukushima Daiichi Nuclear Power Station

Uncertainty Distribution



Regression Coefficient

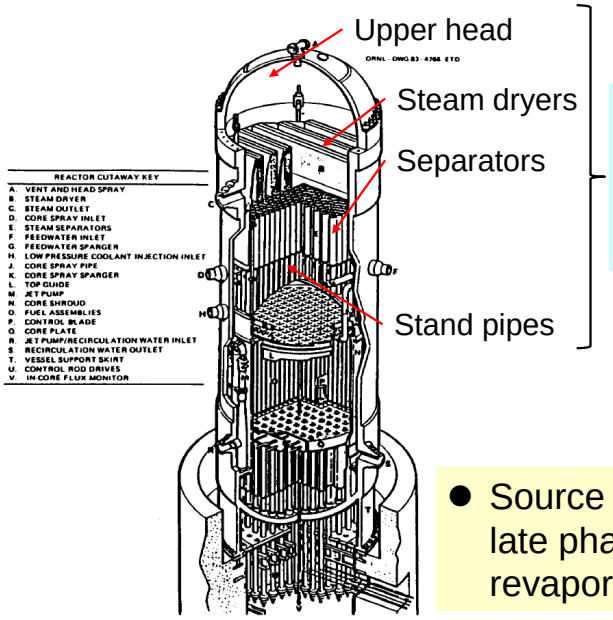


- Identification of parameters likely to be influential on source term
- Need of further analysis to quantify contribution of each parameters to uncertainty

- Formation of direct leakage pathways from reactor cooling system (RCS) to drywell (unclear mechanisms)
- Flow rate of alternative water injection, potentially changing thermal-hydraulic conditions in RCS
- Chemical behavior of FPs in RCS
- Influence of upper structures in reactor vessel on FP transport

- Chemical speciation of major FPs with high releasability from fuels such as cesium and iodine, taking into account influences of core structural materials
  - Identification of limitation and applicability of chemical equilibrium assumption and chemical reaction kinetics approach for expected chemical and thermal-hydraulic conditions

    - Aerosol physics
    - Condensation and revaporization
    - Chemisorption
    - pH of water pool

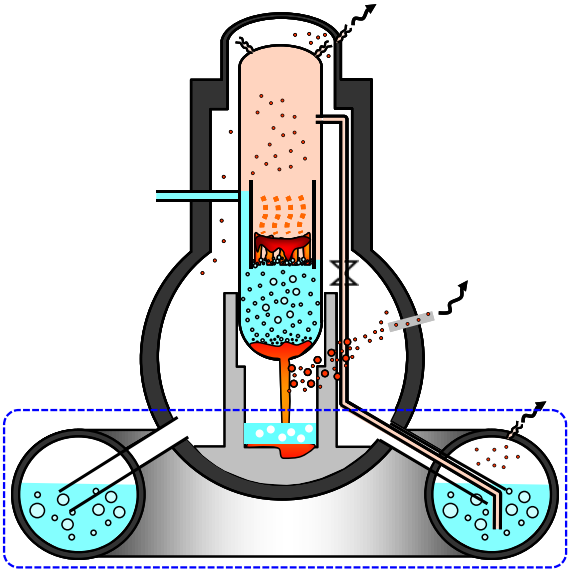


Large surface area of the upper structures for deposition and condensation of FPs

- Source for chemisorption and late phase release due to revaporization

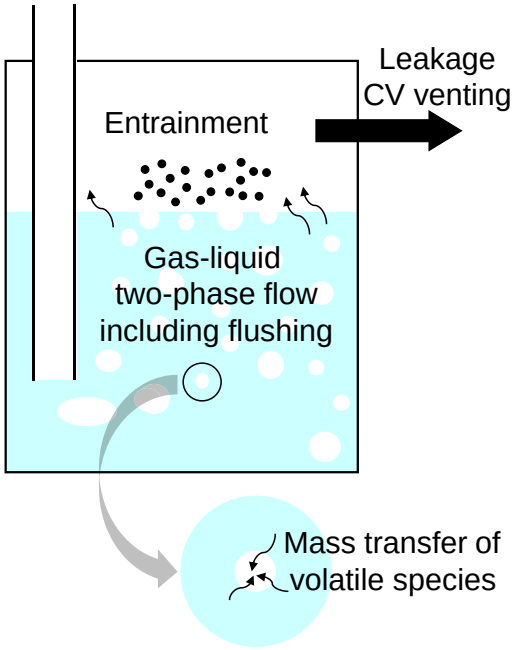
- Locations and areas of FP leakage pathways from containment vessel to reactor building
- Flow rate of alternative water injection, influencing pressure variation in containment vessel
- Pool scrubbing under high temperature conditions including boiling or flushing of water pool

- Thermal decomposition of organic materials in containment vessel such as sheaths and insulators of cables, paints and lubricating oil, and formation of gaseous organic iodine
- Revolatilization of iodine species dissolved in water pool
- Decontamination capability of reactor building
- Release of FPs through aquatic pathways including leaching of FPs

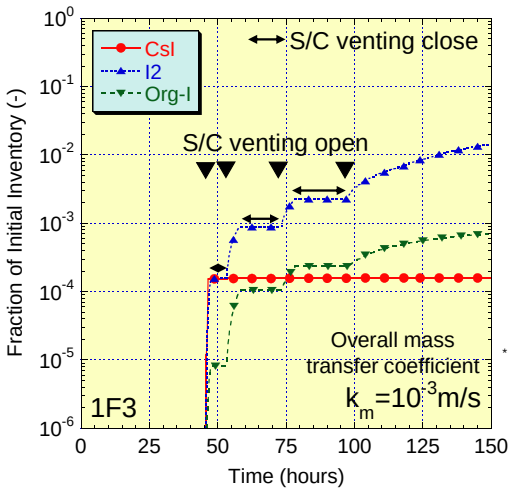


- Pool scrubbing under conditions beyond those of previous studies
  - High temperature of water pool to suppress steam condensation
  - Formation of very complex gas-liquid two-phase flow (difficulty to adequately characterize flow conditions and FP migration with various mechanisms in gas phase)

- Revolatilization of iodine species from water pool
  - Iodine chemistry in aqueous phase to form volatile species with impact of organic impurities
  - Gas-liquid mass transfer coefficients for volatile species and two-phase flow characteristics such as void fraction and interfacial area concentration
- Chemistry between iodine and organic materials in gas phase and on wall



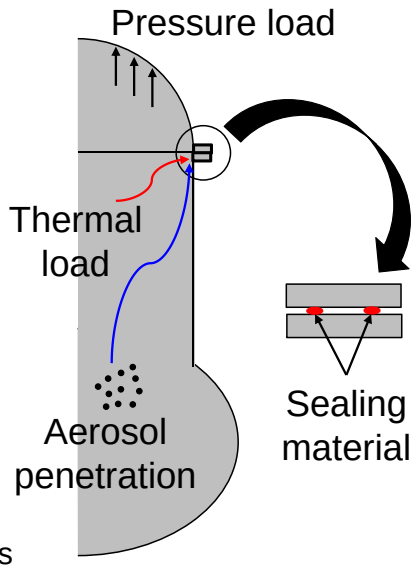
Iodine Release from S/C*



* Analysis performed prior to release of information that S/C venting was activated twice

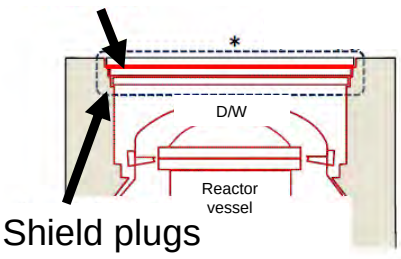
- Release of gaseous iodine from water pool of S/C due to operation of CV venting

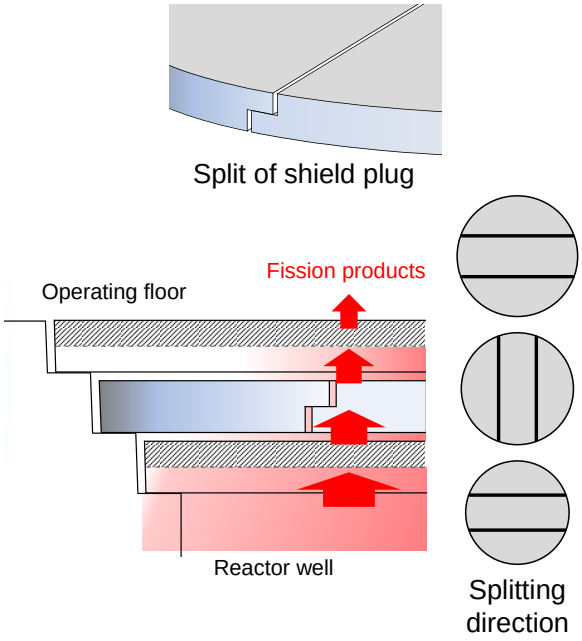
- Formation of leakage pathway at the CV top head flange
  - Leakage area and rate, depending on thermal-hydraulic conditions in drywell
  - Thermal (and chemical) degradation of sealing material

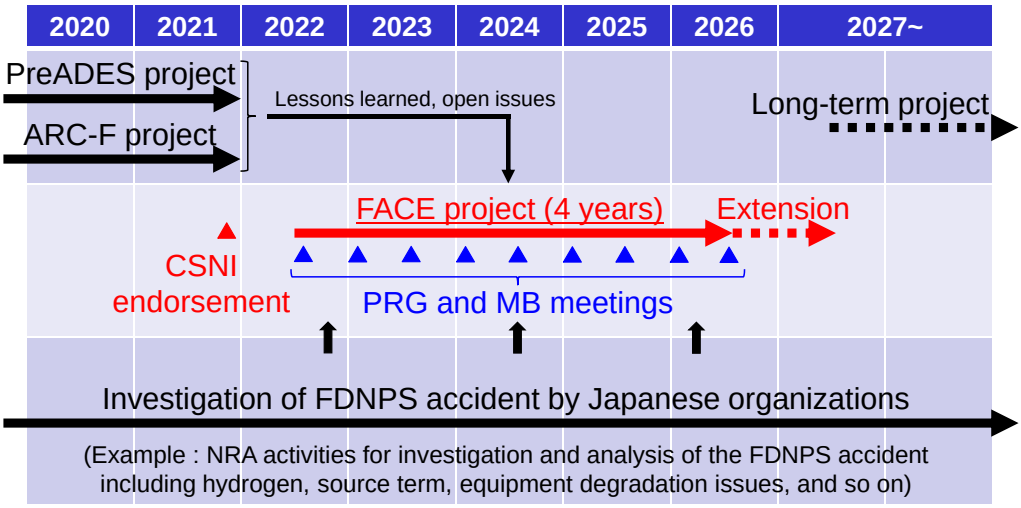


Other potential leakage pathways
- Degraded penetration

- Estimated radioactivity of Cs-137 in gap between top and mid covers
  - Unit 1 : 0.1-0.2 PBq
  - Unit 2 : 20-40 PBq
  - Unit 3 : 30 PBq







FACE : Fukushima Daiichi Nuclear Power Station Accident Information Collection and Evaluation

- **Scope 1** : In-depth discussions for accident progression and associated FP behavior and H_2 combustion
  - Interpretation of technical issues identified in recent (and future) FDNPS plant investigation
  - Quantification of uncertainties in severe accident modeling (melt progression, MCCI, FP and H_2 issues) taking into account those in boundary conditions
- **Scope 2** : Characterization of U-bearing particles and establishment of techniques for future fuel debris analysis for D&D
  - Study on plausible mechanisms for formation of U-bearing particles
  - International round-robin analysis activity with debris simulants
  - Contribution to understanding of accident progression
- **Scope 3** : Collection and sharing of data and information

- Source term and its uncertainty are crucially important information for various applications associated with the continuous improvement of reactor safety.
- A large amount of radioactive materials were estimated to be released to the environment by the FDNPS accident.
- Based on the investigation of the FDNPS, and relevant simulations of the FDNPS accident, several findings on source term have been identified and a large uncertainty is considered to still exist in source term evaluation (e.g. boundary conditions and late phase remobilization of FPs).

- Key lessens learned from the accident at the FDNPS should be taken into account in improving methodologies for source term evaluation.
- Uncertainty quantification and sensitivity analyses are anticipated to be beneficial for effective and efficient modeling improvement.
- Worldwide expertise through international cooperation is greatly helpful for further understanding of the FDNPS accident scenarios and source term.

Canadian Nuclear Safety Commission | Commission canadienne de sûreté nucléaire

Canada

UNCERTAINTY QUANTIFICATION IN ANALYSIS AND MANAGEMENT OF REACTOR ACCIDENTS – A REGULATORY PERSPECTIVE

Presented by
S. Gyepi-Garbrah
Canadian Nuclear Safety Commission
May 10, 2023

e-Docs #

Presentation Outline

- Introduction
- Regulatory Perspective
- Uncertainties Quantification (UQ)
- Summary

e-Docs #

Introduction

- The safety goal of nuclear power plants is to prevent exposure of people and the environment to radioactivity
  - Risk of containment failure
  - Source term measurement is key
- Despite excellent simulation efforts, uncertainties may render accident progression and source term modelling and quantification a challenge
  - Alignment of collaborations to address challenges is needed
  - MUSA project objectives to assess and obtain a "common uncertainty assessment approach“ is timely

e-Docs #

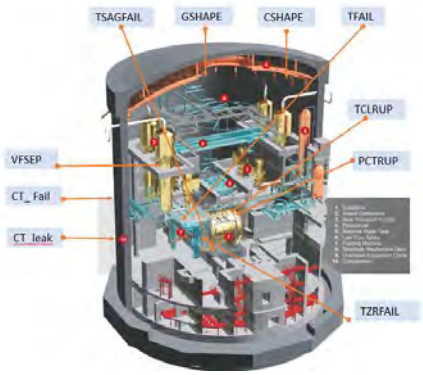
Use of UQ in the Regulatory Process

- Regulatory Requirements
  - CSA N290.16:16 – Requirements for beyond design basis accidents
  - CSA N286.7 – Quality assurance of analytical, scientific and design computer programs
  - REGDOC 2.4.1 – Deterministic Safety Analysis
  - REGDOC 2.3.2 – Accident Management
  - REGDOC 2.5.2 – Design of Reactor Facilities: Nuclear Power Plants
- Uncertainty Quantification
  - Methodology
  - Uncertain Parameters
  - Figure-Of-Merit
- Severe accident management oversight

e-Docs #

Uncertainty Quantification in CANDUs

par #	Uncertain parameters in the SA code	Definition of the UP
1	VFSEP	VFSEP value determines when phase separation occurs. It refers to the void fraction in the primary system above which the two-phase mixture characteristics no longer lead to the carrying of water over the highest point in the reactor coolant system.
2	TCLRUP	The temperature at which cladding fails if it hasn't already failed by ballooning, and allows fission product release
3	CSHAPE	The chi shape factor to account for non-spherical shapes of the aerosols.
4	GSHAPE	The gamma shape factor to account for non-spherical shapes in the aerosol coagulation calculations.
5	PCTRUP	Pressure at CV when catastrophic rupture occurs.
6	TFAIL	Condition allowing the perforation of Calandria Tube.
7	TSAGFAIL	Disassembly temperature of channel segment in dry calandria Vessel.
8	TZRFAIL	Failure temperature for pressure tube and calandria tube.
9	CT_leak	Containment leakage rate
10	CT_Fail	Containment failure Pressure



- Figures of Merit (FOM)
  - containment failure time
  - hydrogen in containment
  - caesium iodide source term to environment
- Risk-Informed Decision Making
  - Consummate with the risk with the facility
  - Implications for novel designs
  - Sound regulatory oversight for NPPs

e-Docs #

UQ in Severe Accident Domain

- Increase regulatory confidence in severe accident codes' predictions and enhance responses to a nuclear or radiological emergencies.
- Optimize the implementation of mitigation strategies and ranking important factors contributing to the global uncertainties
- Facilitates the identification of the suitable probability function that describes the behavior of FOM
  - Limitation? Lack of experiments?
- Quantification tool (Python Scripts for Uncertainties Quantification for MAAP-CANDU and MELCOR) can be used for a wide range of applications (CNSC)
  - Including SMRs novel technologies to evaluate their safety margins.

e-Docs #

Future Considerations

- Second phase of MUSA (INNOMUSA)
  - Claims of excellent safety features by new and novel designs (including SMRs)
    - Means of containment
    - Shutdown systems
    - Emergency core cooling
    - Accident Tolerant Fuels (pending)
- Harmonized methodology for uncertainties is essential
  - Bring value to the excellent work from MUSA
  - BEPU?

e-Docs #

Summary

- Uncertainties require continuous improvement and vigilance, making use of lessons learned and efforts to reduce them
  - MUSA finding is very vital for regulatory positions
- Measurement and quantification of uncertainties needs research and dialogue between regulators, designers, operators, and standards organizations for alignment
  - Experiments?
  - Well informed actions on severe accident management

e-Docs #

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Canada

Thank You! Questions?

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The MUSA Project: An Introduction

Luis E. Herranz (CIEMAT)

MUSA Open Workshop, Madrid 10-11 May, 2023 (Hybrid meeting)

MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

sustainable innovation

Background: The USTA Project

- **The seed: The Source Term Workshop** (Marseille, May 2015)
  - STINF (Source Term INFrastructures).
  - USTA (Uncertainties in Source Term Assessments).
- **The USTA development:**

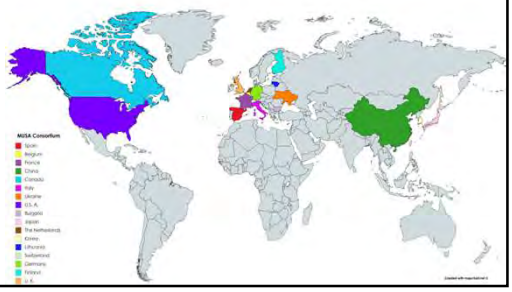
- **The USTA EC Evaluation:**

Evaluation Result

Total score: 13.00 (Threshold: 10)

Background: The MUSA « Believers »

- **Research Centres:** CEA, CIEMAT, ENEA, JRC-Petten, KAERI, KIT, LEI, PSI, VTT
- **TSOs:** BEL V, GRS, INRNE, IRSN, JAEA, SSTC NRS
- **Universities:** TUS, UNIPI, UNIRM1, VMU
- **Utilities:** CNPRI, ENERGORISK, TRACTEBEL, EPRI
- **Vendor:** Framatome
- **Regulators:** USNRC, CNSC
- **Consulting:** LGI, NINE, WOOD



Motivation: SA Radiography

- **Phenomenological domain**
  - A huge number of phenomena.
  - Multidisciplinary (thermal, fluid, mechanical, physical, chemical, …).
  - Strong feedback.
- **Boundary conditions**
  - Broad ranges (T, P, D, …).
  - Extreme values.
- **Timing & Extension**
  - Integration over long periods (fast & slow phenomena).
  - Full NPP scope (micro & macro scale; safeguards; human action).

Motivation: Undeniable Facts

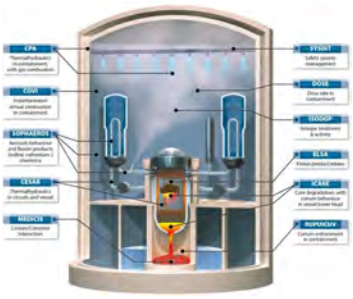
- **The Fukushima accident!!** → **Mitigation!!**
- **Source Term complexity**

$$J_i(t) = \underbrace{\int_0^{t_f} e(t)\cdot dt}_{\text{Th's!!}} \cdot \underbrace{I \cdot F \cdot F_i \cdot \int_0^{t} s(t')\cdot dt'}_{\text{Core degradation}} \cdot \underbrace{exp\left[-\int_{t'}^{t} \varepsilon(t'')\cdot dt''\right]}_{\text{Radioactive transport (Th's; NatMechs; Mitigation)}}$$

- **Source Term uncertainties!!** → **Emergency!!**
- **Around 40 years of BAU research** → **Data bases Codes**

Motivation: SA Codes

- **Capitalization of knowledge on severe accidents**
- **Major hypotheses, assumptions and approxs.**
- **Nature of models.**
- **Large uncertainties!**



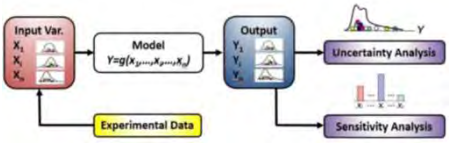
Motivation: The Current Situation

- **"Maturity"** of SA codes.
- Need to know SA codes **predictability.**
- **Optimization** of SA research (C/B).
- Major **computational resources!**

"The Age of UaSA in SA"

Motivation: UaSA
Uncertainty and Sensitivity Analysis

- **Major advantages:**
  - Avoidance of conservative assumptions.
  - Better identification of safety margins.
  - Quantification of likelihood of reaching given values.
  - **Insights into dominating uncertainties**
- **Innovative approaches necessary!**



Management & Uncertainties in Severe Accidents

(MUSA)

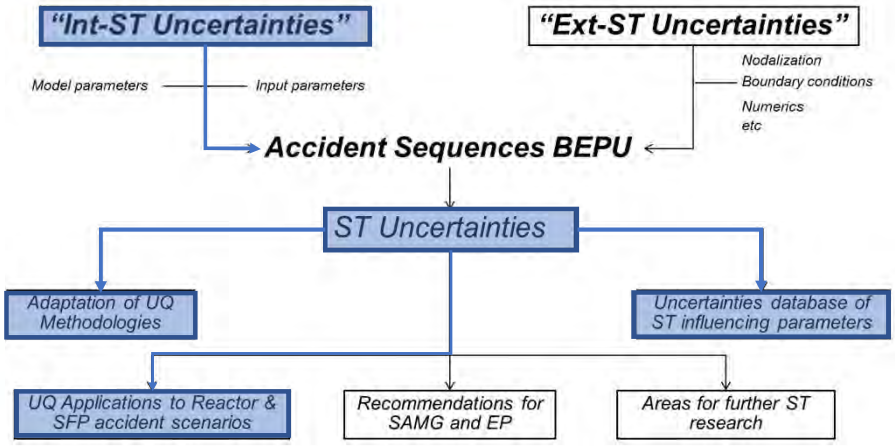
Framework: HORIZON-2020 (NUGENIA)

- "Update and development of simulation tools to improve safety features … and AM strategies for GEN II, GEN III and GEN III+".
- "… should address **technology gaps** … on issues still not yet completely covered by past … SA research".
- "… **ST re-assessments** should be done with a particular emphasis on innovative **accident management** strategies".
- "… The results should be reflected in the **SAMGs** and recommendations should be formulated to improve **EP&R** …".

Framework: Additional Value

- Use of **earlier investment** in safety research (codes & data).
- **Harmonization** of UaSA application in SA analyses.
- Encouraging **cooperation** and innovation (high competence).
- **Coordination** & complementarity with other "ventures" (IAEA).
- Fostering "timely and properly formulated" **dissemination**.

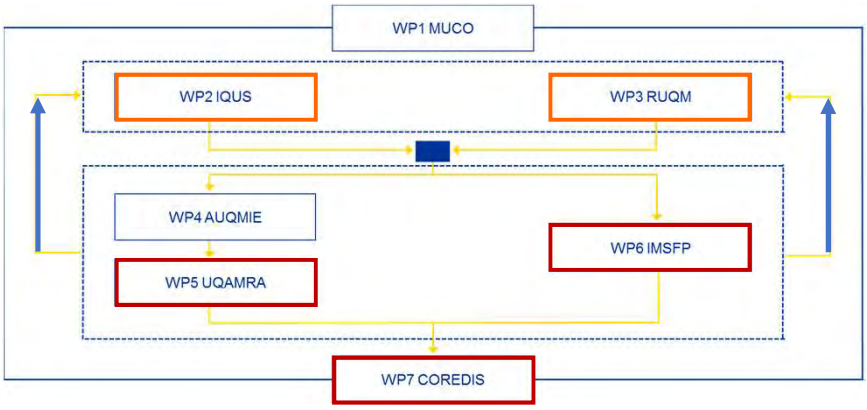
Conceptual Approach



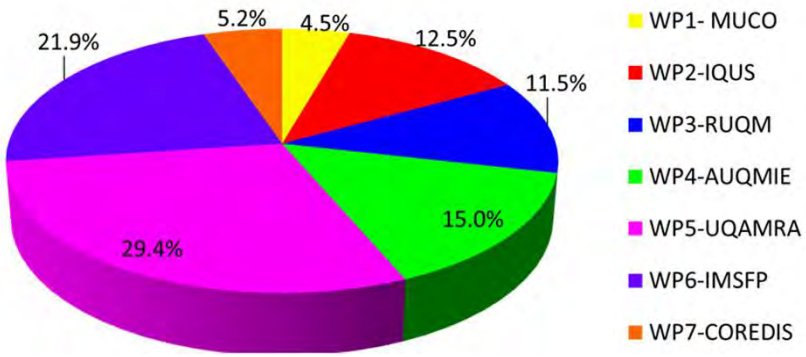
Project Articulation: WPs

- **WP1:** MUSA COordination **(MUCO)**
- **WP2:** Identification & Quantification of Uncertainty Sources **(IQUS)**
- **WP3:** Review of UQ Methodologies **(RUQM)**
- **WP4:** Application of UQ Methods against Integral Expts. **(AUQMIE)**
- **WP5:** UQ in A&M of reactor accidents **(UQAMRA)**
- **WP6:** UQ & Innovative Management of SFP Accidents **(IMSFP)**
- **WP7:** Communication and Results DISsemination **(COREDIS)**

MUSA Progress
Bases: Internal Networking

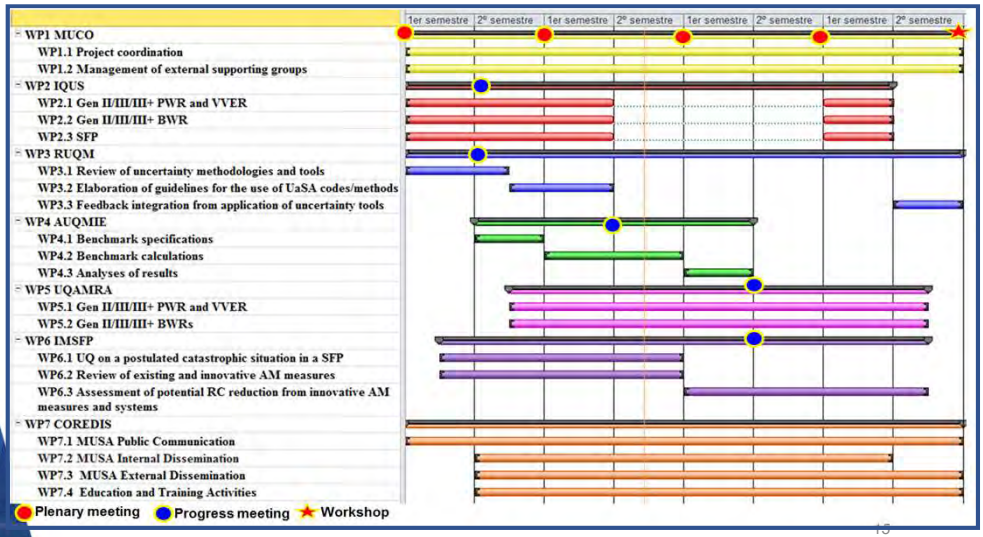


Workforce Distribution



TOTAL ABSOLUTE RESOURCES: 624.9(+) pm (68.5% funded)

MUSA Roadmap



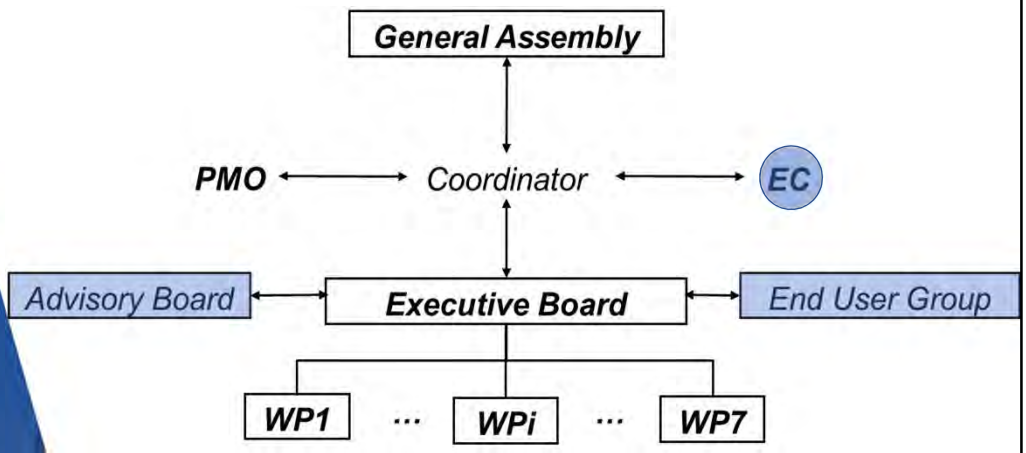
Expected Outcomes

- **A structured database** of uncertainties associated to ST influencing variables.
- Survey and **adapted-to-SA UaSA methods**.
- **Hands-on training & Identification of major challenges (IExp).**
- **Guidelines** for a systematic application of UaSA methods to SA scenarios.
- **Databases of accident scenarios (R&SFP) analyses**.
- Specific insights into the **effect of SAMs (existing/innovative) on scenarios.**
- **A Roadmap** for further development: **INNOMUSA**
- **Major issues** worth investigating on ST: **SEAKNOT**

Deliverables

D1.1	Online workspace	LGI	3
D1.2	Project Quality Plan	LGI	3
D1.3	Data Management Plan	LGI	3
D1.4	Advisory Board recommendations	CIEMAT	6
D1.5	End User Group requests	CIEMAT	6
D1.6	Progress report 1	CIEMAT	24
D1.7	Progress report 2	CIEMAT	36
D2.1	DRAFT Major sources of uncertainties during severe accidents in LWR and SFP affecting the ST	GRS	18
D2.2	Major sources of uncertainties of severe accidents in LWR and SFP affecting the ST	GRS	42
D3.1	Review of uncertainty methodologies and tools applicable to SA codes for the prediction of ST	KIT	18
D3.2	Guidelines for the use of uncertainty tools for SA codes to predict source term	KIT	48
D3.3	Best-practice Guidelines of uncertainty quantification performed within MUSA project	KIT	48
D4.1	UQ in integral SA experiments: Results and lessons learned on application to ST	ENEA	30
D5.1	Results of uncertainty assessment of ST released to the environment	JRC	48
D5.2	Best practices for the assessment of ST uncertainty when performing severe accident simulations with SAM actions using system codes	JRC	48
D5.3	Recommendations on R&D efforts for reducing ST uncertainty released to the environment	JRC	48
D6.1	Main uncertainties on accident progression and FP release in an SA in an SFP	IRSN	48
D6.2	Review of SAM measures for SFP accident ST Mitigation and proposals of innovative mitigation measures and systems for an SA in an SFP	IRSN	48
D6.3	Assessment of potential benefits from innovative mitigation systems for an SA in an SFP	IRSN	48
D7.1	Communication and dissemination strategy	UNIPI	4
D7.2	Learning modules from MUSA COREDIS	UNIPI	44
D7.3	Report on communication and dissemination activities	UNIPI	48
D7.4	Report on Education and training activities	UNIPI	48

BEYOND MUSA FRONTIERS



Thank you for your attention!

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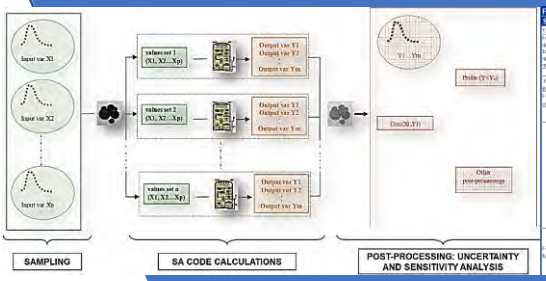
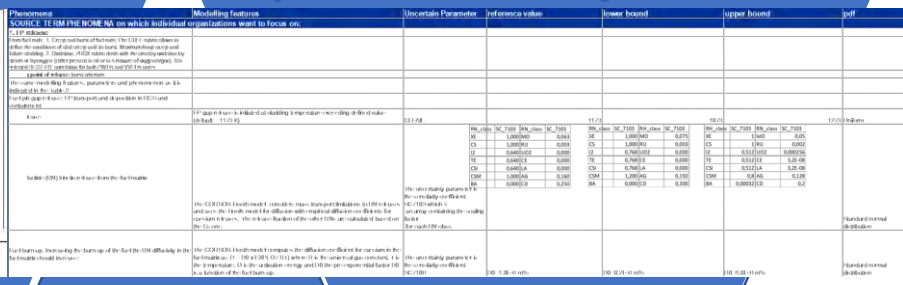
Management and Uncertainties in Severe Accident

Project Coordinator: Prof. Luis E. Herranz - CIEMAT Madrid

Methodologies

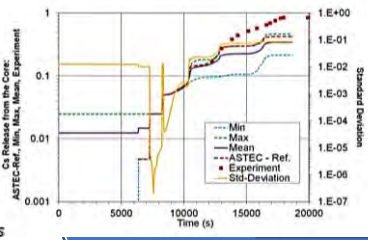


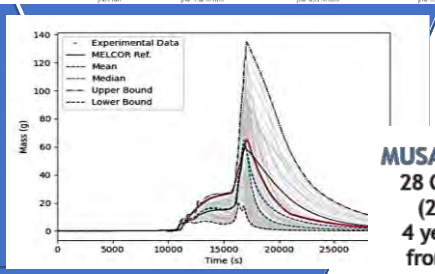
Input Uncertainty Database



FPT1

SOURCE TERM





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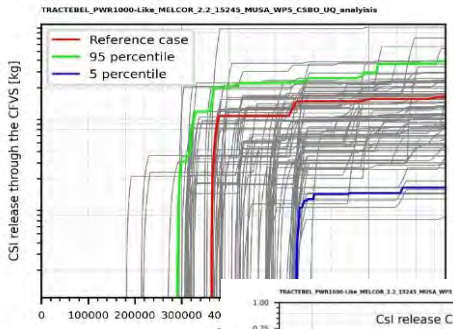
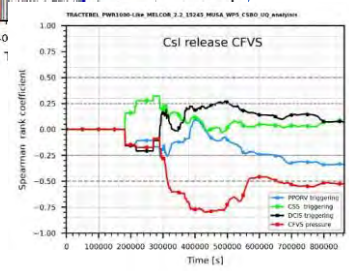
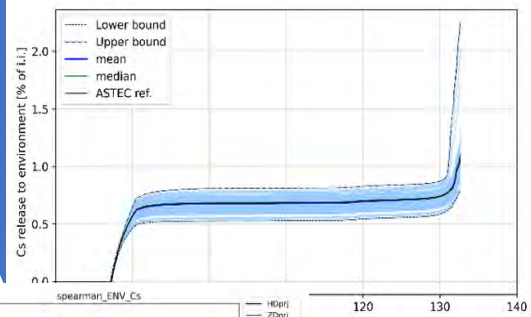
MUSA Consortium
28 Organizations
(25% non-EU)
4 years duration
from June 2019
630 person months
overall costs
€ 5,768,452.50

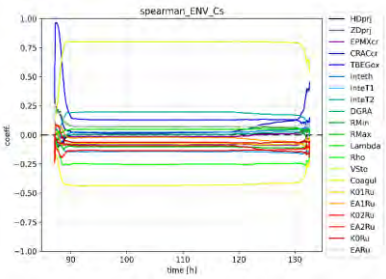
Reactor Sequence





SFP Scenario





INNOMUSA

Consolidated Methodologies

Systematic Appliction

Robust & Reliable Database

Extension to WC-SMRs, ATFs

Innovation in Management and Uncertainties in SAs

Uncertainties database

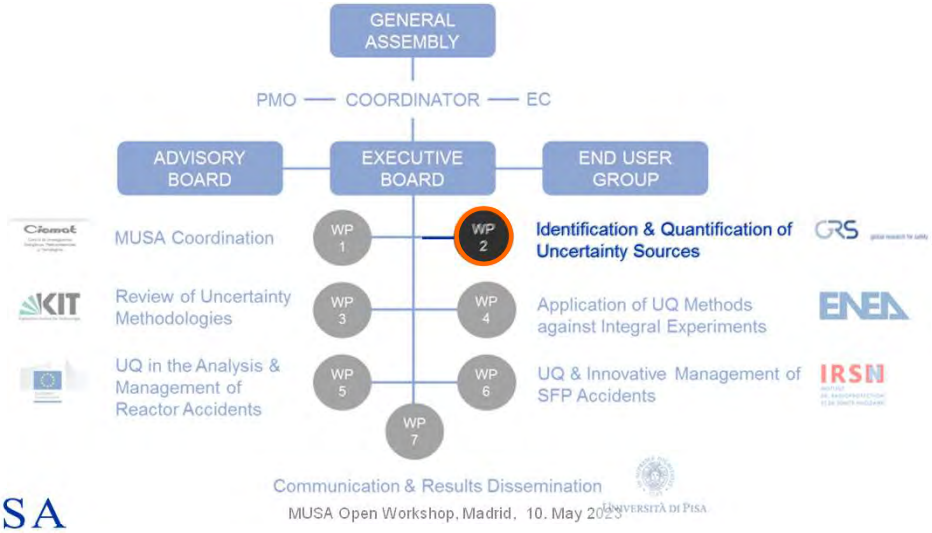
10. May 2023

Sara Beck (GRS), Olivia Coindreau (IRSN), L.E. Herranz (CIEMAT)

MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

Outline

- Objectives
- Methodology
  - Source Term related Figures of Merit
  - Phenomena
  - Uncertainties
- Database



WP 2 Objectives

- WP 2 objectives as described in the GA:
  - Identifying and partially quantifying the major sources of uncertainties of any type of processes and phenomena during SAs affecting the ST
  - It entails both uncertainties in the existing models and uncertainties due to the lack of specific models in the codes.
  - It extends its domain to the entire SA with the focus on ST and includes application to SAM measures for LWR types (GEN II and GEN III) and the SFP.
- The main objectives in the present WP2 are to address the following two aspects:
  - Identification and quantification of the major sources of uncertainties of any type on the prediction of severe accidents with regard to the ST in reactor (WP5) as well as SFP (WP6) severe accidents.
    In addition support for WP4 is needed for the definition of uncertain parameters etc.
  - Providing the basis for the assessment of the uncertainties in the SA prediction on the timely / effective implementation of SAM measures in GEN II and GEN III plants,
    a) PWR/VVER/CANDU, b) BWR, and c) in the Spent Fuel Pool (SFP)

WP 2

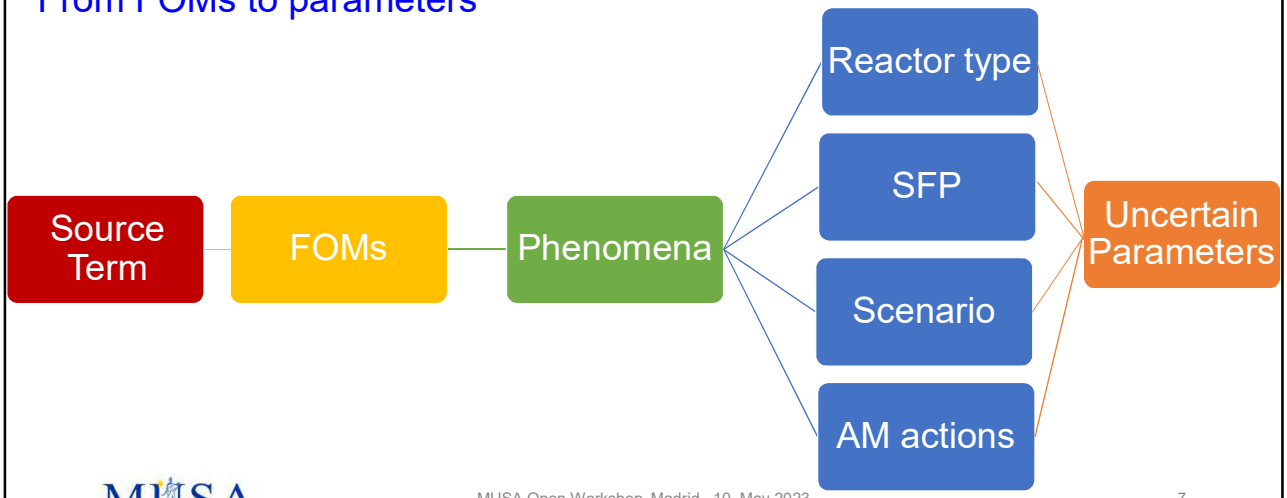
- Task 2.1 Selection of severe accident phases and phenomena
- Task 2.2 Consideration of requirements from SA codes and UQ methods
- Task 2.3 Determination of uncertain variables, parameters and models to be used

WP 2

- The WP is structured in three sub-WPs according to the application domain (reactor designs of GEN II/III/III+ are within the MUSA scope): PWR; BWR; SFP.
  - Sub-WP2.1: GEN II/III/III+ PWR, VVER and CANDU (led by GRS)
    - Partners involved: CEA,CIEMAT, BelV, Energorisk, ENEA, EPRI, INRNE, IRSN, KIT, SSTC, Tractebel , TUS, USNRC, VTT, CNSC
  - Sub-WP2.2: GEN II/III/III+ BWR (led by CIEMAT)
    - Partners involved: CIEMAT, EPRI, LEI, PSI, USNRC, VTT, Jacobs
  - Sub-WP2.3: SFP (led by IRSN)
    - Partners involved: CEA, CIEMAT, INRNE, Energorisk, IRSN, LEI, PSI, SSTC, TUS, USNRC

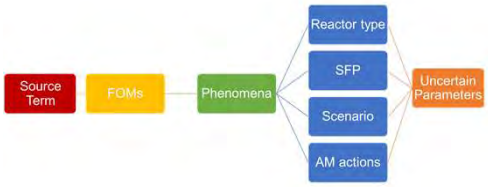
Methodology

From FOMs to parameters



Methodology

- Identification of Source Term (ST) related Figures Of Merit (FOM) needed to assess the capability of SA codes when modelling
  - a) reactor severe accident scenarios
  - b) SFP (Spent Fuel Pool) severe accident scenarios.
- A directory with the important uncertain phenomena affecting the source term has been built as a guide to identify uncertain parameters, which will be characterized by the uncertainty range (lower and upper bound) and probability density function.
- A **database** in form of a “knowledge-based matrix” containing the selected variables, parameters and models and its uncertainty ranges applied by the code users within the uncertainty and sensitivity in WP5 for PWR/VVER/CANDU and BWR and in WP6 for SFP was built.

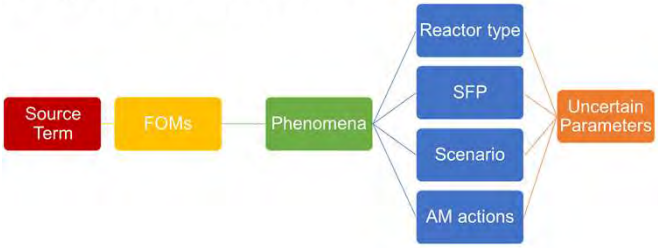


Methodology

- Selection of Severe Accident Phases and Phenomena
  - Break down phenomena in manageable phases and the often interacting phenomena occurring during an SA into their differing level of importance on the ST (see database)
  - NPP type and SA scenario specific phenomena are taken into account
  - Specific engineered safety features and technical means of SAM that might significantly affect the ST
- Selection of key target variables and radionuclides as ST Figures of Merit (FOM)
- Definition of uncertain parameters and models, also based on the SA codes and uncertainty codes
- Selection of uncertain variables, parameters and models to be used by partners (feedback at the end of project)
- Knowledge-based matrix was developed in which individual parameters, variables and code models are associated with uncertainty margins, are stored with potential impact on ST estimates and SAM measures in various LWR types and the SFP

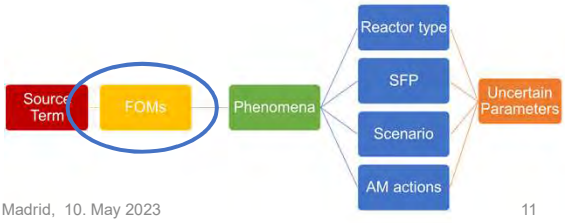
Methodology

- The database includes their uncertainty characterization, a reference value, lower and upper range limits and distribution/probability in the categories **“Source Term Phenomena”, “Other related Phenomena”**, **“Accident Scenario”** and **“Accident Management actions”**.



Step 1 – FOMs

- The **FOMs** selection has been based on a set of criteria:
  - focus on Source Term and, particularly,
  - on high-radiological radionuclides (NG, Cs, I and Ru; the latter particularly in SFPs); priority to be given to in-vessel FP release;
  - in SFP release will just address DECa (Design Extended Conditions) domain; gas and liquid leak paths considered;
  - timing of release to the environment is of outmost relevance; when available, gas and particulate nature of FPs (I) distinguished.



Step 1 – FOMs

- Additional Variables (AV) are needed to describe the analyzed severe accident scenarios and are worth keeping track on, like the FOMs, but that should not be considered in the sensitivity analysis.
- **FP release from fuel/debris**:
  - NPP accident: Priority is on the release of FPs from the fuel/debris in the rector (in-vessel release) into the Reactor Coolant System (RCS) and further into the containment and/or the environment. FP release from the core melt in the cavity after RPV failure (ex-vessel release) into the containment along with Molten Core-Concrete Interaction (MCCI) has not the same significance. The **primary FOM** is the **release** of FPs from containment into the **environment** or from RCS into the environment in case of a SGTR sequence.
  - SFP accident: The release of **FPs from the damaged fuel** is considered only. Mitigation measures will be applied which prevent large fuel melting. So, the **primary FOM** is the **release** of FPs from **SFP building into environment**.

Step 1– FOMs

- FP release into the environment
  - NPP accident: The FOMs related to the ST into the environment should allow to **differentiate** between different **gaseous releases paths** and **releases** caused by **water leaks**. An indirect way of considering this is by including in the FOMs the FP distribution in gas phase and in sumps at the location released to the environment.
  - SFP accident: The FOMs related to the ST into the environment should allow to see the potential benefits of existing, contemplated or innovative **SAM mitigation measures and systems**.
- Units of FP variables
- Timing of the release to the environment - a major FOM.
- Treatment of Iodine - detailed Iodine chemistry models

FOMs

No	ST related FOM	Comments
1.1	Total FP & NG release (mass fraction [% ii]) into environment (time dependent or at one point in time): - from containment or in bypass scenarios from RCS for reactor scenarios - *from SFP building for SFP scenarios*	Release path: filtered, unfiltered, … might be necessary to be differentiated. Releases on water path might be treated separately. Time dependent or total FP release (at a given time) should be considered.
1.2	Total Iodine release (mass fraction [% ii]) in gaseous form to environment (Time dependent or at one point in time) - *relevant for SFP scenarios*	In case a detailed iodine chemistry model is used.
1.3	Onset time of FP release from fuel/core (in-vessel), from debris in cavity/MCCI (ex-vessel) and into the environment - *begin of release is relevant for SFP scenarios*	Might be difficult to determine if different release paths are modelled. A threshold should be defined: Containment pressure = design pressure
1.4	Total FP & NG released (mass fraction [% ii]) from fuel/core (in-vessel) (time dependent or at one point in time) - *relevant for SFP scenarios*	Both affects the in-containment ST first.
1.5	Total FP & NG released (mass fraction [% ii]) from debris in cavity/MCCI (ex-vessel) (time dependent or at one point in time) - *not relevant for SFP scenarios*	
1.6	Total FP & NG airborne in the containment (mass fraction [% ii] and amount in [kg] or concentration [kg/m³]) (time dependent or at one point in time) of: - containment for reactor scenarios - *SFP building for SFP scenarios*	Important to distinguish FP distribution in the containment.
1.7	Total FP solved (mass fraction [% ii] and amount in [kg] or concentration [kg/m³]) in water pools (time dependent or at one point in time) of: - containment sump / wet well / other pools for reactor scenarios - *SFP water pool for SFP scenarios*	Units to be finally decided; in any case mas fractions should be provided. Probably only time dependent FP content can be used; total FP content (at a given time) does not make much sense. 3rd FOM in list could be moved to AVs if needed to limit the number of FOM, but then the "FP mass balance" is incomplete
1.8	Total FP (mass fraction [% ii] and amount in [kg] or concentration [kg/m²]) deposited on structures (time dependent or at one point in time): - containment walls and structures for reactor scenarios - *SFP building walls for SFP scenarios*	

FOMs

1.9	Total FP and NG (mass fraction [% ii]) into RCS or into SG secondary in case of bypass scenario (time dependent or at one point in time) - *not relevant for SFP scenarios*	May be differentiated between solved and deposited FPs. Probably only time dependent FP content can be used; total FP content (at a given time) does not make much sense.
	Evolution of the cumulated activity of a list of isotopes (to be defined) for SFP scenarios	To compute radiological consequences
No	SAM specific FOM	**Comments**
2.1	Times of containment*/SFP building vent*	If relevant
2.2	Time of hydrogen ignition by igniters	If relevant
2.3	Time of containment*/SFP building spray*	If relevant
2.4	Time of water-ingress/injection into: - reactor cavity / quenching of melt pool for reactor scenarios - *In the pool for SFP scenarios*	If AM measure
2.5	One more scenario / plant type spec. FOM	

Additional Variables (AVs) – reactor cases

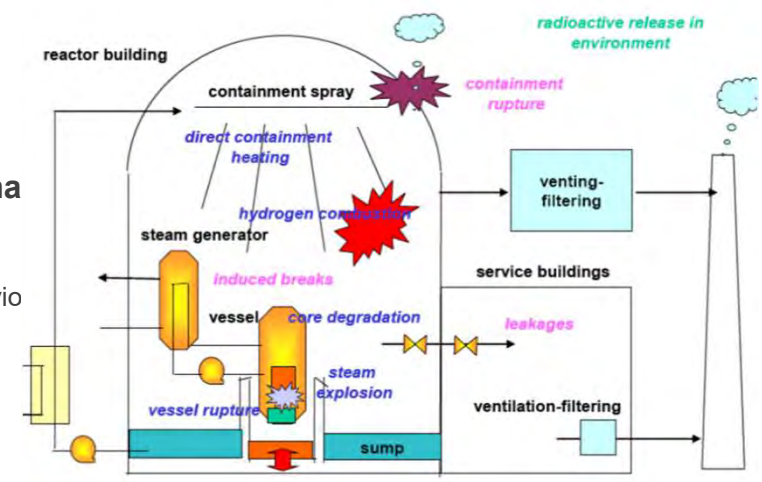
No	*Fission Products*	Comments
F.1	Total FP deposited (mass fraction [% ii]) inside RCS (time dependent or at one point in time):	Important to distinguish FP distribution between RCS and containment.
F.2	Total FP & NG release (mass fraction [% ii]) into containment (time dependent or at one point in time):	Important to distinguish FP distribution in the containment.
No	*Reactor circuit (reactor scenarios)*	**Comments**
R.1	Primary system pressure / depressurization	Might not be needed, scenario dependent, AM measure
R.2	Secondary system pressure	
R.3	Max. core/fuel and core outlet temperature	Important to understand in-vessel core degradation and loads to RPV
R.4	Fraction of failed/molten fuel/CR	
R.5	Mass of core melt relocated into lower plenum	
R.6	Mass of H_2 produced in-vessel	Indicator of strength of core degradation
R.7	Time of lower head failure	Important to distinguish in- and ex-vessel phase. Time could as well be derived from "Mass of core melt relocated into containment"
	Containment (reactor scenarios)	**Comments**
C.1	Containment pressure or temperature	Might not be needed, scenario dependent.
C.2	Mass of core melt relocated into reactor cavity	Important to understand ex-vessel/MCCI and loads to containment
C.3	Mass of H_2/CO produced ex-vessel by MCCI	Indicator of strength of MCCI / ongoing MCCI
C.4	Accumulated mass of H_2/CO in containment or recombined/burned mass of H_2/CO	Could be difficult if PARs are installed
C.5	Mass of core melt due to MCCI	Important to understand ex-vessel/MCCI

Additional Variables (AVs) – SFP

No.	SFP building	Comments
S.1	Pressure in the SFP building	
S.2	Temperature in the SFP building	
S.3	Relative humidity in the SFP building	
S.4	Dose rate in the SFP building	
S.5	O_2 partial pressure in the SFP building	
S.6	H_2 partial pressure in the SFP building	
S.7	Mass of water in the SFP	
S.8	Fraction of failed/molten fuel assemblies/rack	
S.9	Maximum fuel temperature	
S.10	Mass of H2 produced	

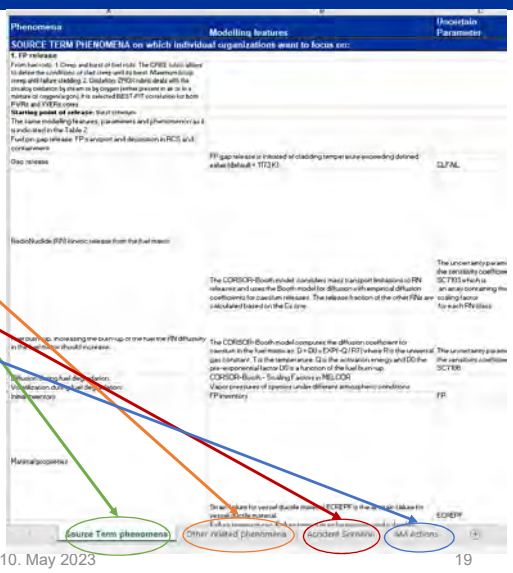
Accident Phases & Categories

- Break down the SA sequence into
  - **Manageable phases**:
    - In-vessel
    - Ex-vessel
  - **Categories of phenomena**
    - Thermal hydraulic (THY)
    - Core degradation (CD)
    - Fission Product (FP) Behavio
    - Molten Core Concrete Interaction (MCCI)



Database

- Source Term phenomena
- Other related phenomena
- Accident scenario
- AM actions

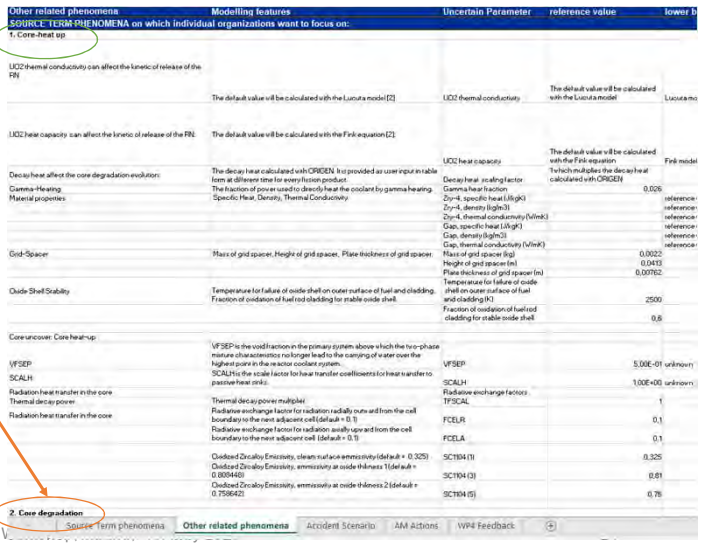


Database

- Source Term phenomena
  1. Core
     a) FP release
  2. RCS
     a) FP transport/deposition in RCS
     b) FP chemistry in RCS
  3. RCB (Reactor Containment Buildung)
     a) FP transport/deposition in containment
     b) FP chemistry in containment
     c) FP release from corium/debris in containment (Ex-vessel)
     d) Pool scrubbing
     e) FP and systems (sprays, FCVS, etc.) interactions
        i. FP scrubbing and deposition in filters under containment filtered venting

Database

- Other related phenomena
  1. Core-heat up
  2. Core degradation
  3. In-core thermalhydraulics
  4. Corium downward motion
  5. Corium slumping
  6. Corium/debris transfer to cavity
  7. Spreading and MCCI
  8. Containment thermalhydraulics
  9. Containment leak
  10. Stratification of suppression pool
  11. FCI
  12. Hydrogen/CO
  13. Heat transfer with environment
  14. FP scrubbing and deposition in filters under containment filtered venting

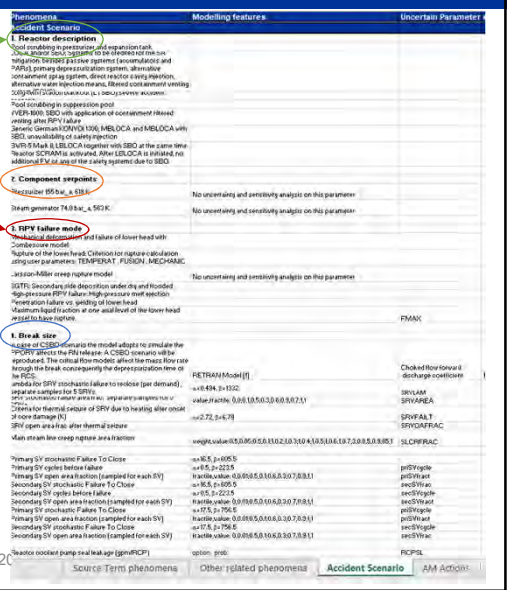


Other related phenomena	Modelling features	Uncertain Parameter	reference value	lower b
SOURCE TERM PHENOMENA on which individual organizations want to focus on:				
1. Core-heat up				
UO2 thermal conductivity can affect the kinetic of release of the FIN				
	The default value will be calculated with the Lucuta model [2]	UO2 thermal conductivity	The default value will be calculated with the Lucuta model	Lucuta mo
UO2 heat capacity can affect the kinetic of release of the FIN:	The default value will be calculated with the Fink equation [2]:			
		UO2 heat capacity	The default value will be calculated with the Fink equation	Fink model
Decay heat affect the core degradation evolution:	The decay heat calculated with ORIGEN. It is provided as user input in table form at different time for every fission product.	Decay heat scaling factor	To which multiplies the decay heat calculated with ORIGEN	
Gamma-Heating	The fraction of power used to directly heat the coolant by gamma heating.	Gamma heat fraction	0,026	
Material properties	Specific Heat, Density, Thermal Conductivity	Zry-4, specific heat (J/kgK)		reference
		Zry-4, density (kg/m3)		reference
		Zry-4, thermal conductivity (W/mK)		reference
		Gap, specific heat (J/kgK)		reference
		Gap, density (kg/m3)		reference
		Gap, thermal conductivity (W/mK)		reference
Grid-Spacer	Mass of grid spacer, Height of grid spacer, Plate thickness of grid spacer.	Mass of grid spacer (kg)	0,0022	
		Height of grid spacer (m)	0,0413	
		Plate thickness of grid spacer (m)	0,00762	
Oxide Shell Stability	Temperature for failure of oxide shell on outer surface of fuel and cladding. Fraction of oxidation of fuel rod cladding for stable oxide shell.	Temperature for failure of oxide shell on outer surface of fuel and cladding (K)	2500	
		Fraction of oxidation of fuel rod cladding for stable oxide shell	0,6	
Core uncover: Core heat-up				
VFSEP	VFSEP is the void fraction in the primary system above which the two-phase mixture characteristics no longer lead to the carrying of water over the highest point in the reactor coolant system.	VFSEP	5,00E-01	unknown
SCALH	SCALH is the scale factor for heat transfer coefficients for heat transfer to passive heat sinks.	SCALH	1,00E+00	unknown
Radiation heat transfer in the core		Radiative exchange factors		
Thermal decay power	Thermal decay power multiplier	TFSCAL	1	
Radiation heat transfer in the core	Radiative exchange factor for radiation radially outw and from the cell boundary to the next adjacent cell (default = 0.1)	FCELR	0,1	
	Radiative exchange factor for radiation axially upw and from the cell boundary to the next adjacent cell (default = 0.1)	FCELA	0,1	
	Oxidized Zircaloy Emissivity, clean surface emmissivity (default = 0.325)	SC1104 (1)	0,325	
	Oxidized Zircaloy Emissivity, emmissivity at oxide thickness 1 (default = 0.805468)	SC1104 (3)	0,81	
	Oxidized Zircaloy Emissivity, emmissivity at oxide thickness 2 (default = 0.759642)	SC1104 (5)	0,76	
2. Core degradation				

Source Term phenomena | Other related phenomena | Accident Scenario | AM Actions | WP4 Feedback

Database

- Accident scenario:
  1. Reactor description
  2. Component setpoints
  3. RPV failure mode
  4. Break size
  5. Design leak
  6. CFVS decontamination factor
  7. Flooding of the SG
  8. Containment failure mode
  9. CVFV decontamination factor
  10. SAM
  11. Break
  12. Calculation parameters



Phenomena	Modelling features	Uncertain Parameter
Accident Scenario		
1. Reactor description		
Pool scrubbing in pressurizer and expansion tank		
Other minor SBLC scenarios to be checked for the six		
sequences: Failure of passive systems (accumulators and		
PARs), primary depressurization system, alternative		
containment spray system, direct reactor cavity injection,		
alternative water injection means, filtered containment venting		
SBO with failure of diesel generators (LOOP)		
Pool scrubbing in suppression pool		
(VEPR-1000) SBO with application of containment filtered		
venting after RPV failure		
Generic German KONVOI (1300) MBLOCA and MBLOCA with		
SBO, unavailability of safety injection		
SWR 5 Mark II LBLOCA together with SBO at the same time		
Reactor SCRAM is activated. After LBLOCA is initiated, no		
additional EW or any of the safety systems due to SBO.		
2. Component setpoints		
Pressurizer 155 bar, a 618 K	No uncertainty and sensitivity analysis on this parameter	
Steam generator 74.0 bar, a 543 K	No uncertainty and sensitivity analysis on this parameter	
3. RPV failure mode		
Mechanical deformation and failure of lower head with		
Corebissure model		
Rupture of the lower head. Criterion for rupture calculation		
using user parameters: TEMPERAT , FUSION , MECHANIC		
Larson-Miller creep rupture model	No uncertainty and sensitivity analysis on this parameter	
(SGTR) Secondary side depressurization under dry and flooded		
high-pressure RPV failure: High-pressure melt ejection		
Penetration failure vs. yielding of lower head		
Maximum liquid fraction at one axial level of the lower head		
vessel to have rupture		FMAX
4. Break size		
In case of CSBO scenario the model adapts to simulate the		
SRV/PRV affects the FIN release. A CSBO scenario will be		
reproduced. The critical flow models affect the mass flow rate		
through the break consequently the depressurization time of		
the RCS.	RETRAN Model [1]	Choked flow forward discharge coefficient
Lambda for SRV stochastic failure to reclose (per demand) ,	x=8.434, b=1332	
separate samples for 5 SRVs		SRVLAM
SRV stochastic failure area fraction, separate samples for 5	value,fractile, 0,0,0,1,0,5,0,3,0,6,0,8,0,7,1,1	SRVAREA
SRVs		
Criteria for thermal seizure of SRV due to heating after onset		SRVFAILT
of core damage (K)	x=2.72, b=6.78	SRVOAFFRAC
SRV open area frac after thermal seizure		
Main steam line creep rupture area fraction	weight,value,0,5,0,05,0,0,5,0,1,0,2,0,3,0,4,0,5,0,6,0,7,0,8,0,9,0,95,1	SLCRFFRAC
Primary SV stochastic Failure To Close	x=16.5, b=605.5	
Primary SV cycles before failure	x=8.5, b=22.5	prISVcycle
Primary SV open area fraction (sampled for each SV)	fractile,value, 0,0,0,0,5,0,1,0,6,0,5,0,7,0,8,1,1	prISVfract
Secondary SV stochastic Failure To Close	x=16.5, b=605.5	secSVfrac
Secondary SV cycles before failure	x=8.5, b=22.5	secSVcycle
Secondary SV open area fraction (sampled for each SV)	fractile,value, 0,0,0,0,5,0,1,0,6,0,5,0,7,0,8,1,1	secSVfract
Primary SV stochastic Failure To Close	x=17.5, b=756.5	prISVcycle
Primary SV open area fraction (sampled for each SV)	fractile,value, 0,0,0,0,5,0,1,0,6,0,5,0,7,0,8,1,1	prISVfract
Secondary SV stochastic Failure To Close	x=17.5, b=756.5	secSVcycle
Secondary SV open area fraction (sampled for each SV)	fractile,value, 0,0,0,0,5,0,1,0,6,0,5,0,7,0,8,1,1	secSVfrac
Reactor coolant pump seal leak rate (gpm/RCP)	option, prob	RCPSL

Source Term phenomena | Other related phenomena | Accident Scenario | AM Actions

Phenomena

Phenomena	Modelling features	Uncertain Parameter
FP release from the fuel		
Initial inventory	FP inventory in the fuel given in the input; decay not always accounted for	Concentrations of different radionuclides in fuel
Gap release	FP gap release is initiated at cladding temperature exceeding defined value (MELCOR default = 1173 K)	Cladding failure temperature; uniform
FP diffusion inside the fuel grain	Diffusion is calculated using experimentally determined diffusion coefficients and activation energies for Cs, and the grain size. Release of other FPs is calculated based on Cs diffusion using scaling factors	Scaling factors for different radionuclide classes; Cs
		Ba
		Te
		Mo
		Xe
		I2
		CsI
		CsM
		Ru
		UO2
		Ce
		La
		Ag
		Cd

Phenomena

Phenomena	Modelling features	Uncertain Parameter
FP release from the fuel		
FP transport in the fuel	Grain size is used to calculate the diffusion transport of fission products in the fuel	Lower bound of the grain size distribution
		Upper bound of the grain size distribution
		Geometrical diameter
Fuel burn-up	RN diffusivity in the fuel matrix should increase with increasing burn-up; this is reflected in the diffusion coefficient D being a function of fuel burn-up	Diffusion coefficient for low and high burn-up fuel (sensitivity coefficient SC7106 in MELCOR)
Volatilization during fuel degradation	Vapor pressures are given as constant values for the duration of the calculation	Speciation of different radionuclides and their vapour pressures
	Different speciation of Cs can be selected	Chemical form of Cs
	Initial fraction of iodine as I2 can be given as a function of time in cycle	Chemical form of iodine

Phenomena

Phenomenon	Modelling features	Uncertain Parameter
3.1.2. FP transportation/deposition in RCS		
Aerosol class number	Number of particle size classes	class_si
Aerosol particle diameters	R_min – particle minimum geometrical radius (m) , R_max particle maximum geometrical radius (m).	"R_min" "R_max"
Aerosol density	Particle mean density (kg/m3)	Rho
Chi shape factor	The chi shape factor allows to account for non-spherical shapes of the aerosols in Stokes' Law for gravitational settling.	CSHAPE
Gamma shape factor	The gamma shape factor allows to account for non-spherical shapes in the aerosol coagulation calculations.	GSHAPE
Collision efficiency	The aerosol collision efficiency. A value of .33 represents the Prupacher-Klett model, which is the currently favored model. A value of 1 represents the FUCHS model.	FE0

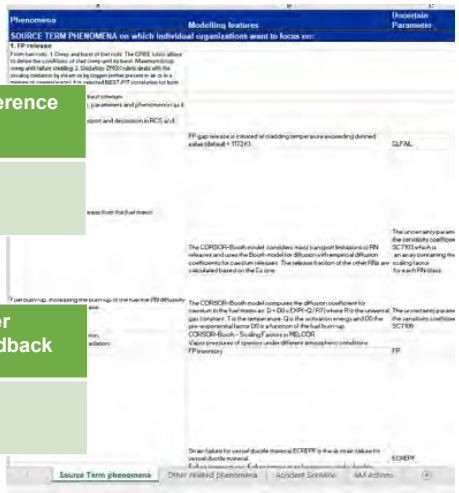
Phenomena

Phenomenon	Modelling features	Uncertain Parameter
3.1.2. FP transportation/deposition in RCS		
Aerosol class number	Number of particle size classes	class_si
Seed radius	The initial seed radius for the hygroscopic aerosol growth calculation	XRSEED
FP release into RRC	Gap release into RCS	correlations of cladding rupture
	Particle mean thermal conductivity	Lambda
	Average specific heat of the aerosol	speacheat
	Number of classes of particles	class_si
	R_min particle diameters	R_min
	R_max particle diameters	R_max
	Aerosol density	rho
FP release into RRC	FP release from fuel to gap	initial fuel inventory
FP release into RRC	conditions for gap release	initial gap inventory
FP release into RRC	gap release into RCS	number of failed rods

Structure of database

Phenomena	Modelling features	Uncertain Parameter	reference value	lower bound	upper bound	pdf	reference

reactor type	SA sequence	SA code	Organization	Comments	Review	User feedback



Database

Database

- ST related phenomena
  - ~ 400 UPs (Uncertain Parameters)
- Other related phenomena
  - ~ 150 UPs

Uncertainties database for SFP (1/5)

Uncertainty sources divided in 5 categories*:

1) **Modelling uncertainties**
2) **Initial conditions**
3) **Boundary conditions (scenario)**

SFP design and accidental scenario will be set in WP6.1

4) **Boundary conditions (systems / SAM)** → impact of systems will be addressed in WP6.3
5) **Mesh, numerics** → mesh and numerics investigated separately

Uncertainties database for SFP (2/5)

Table of phenomena, closely linked to the models developed in most SA codes, divided in 7 groups:

1. **Thermal-hydraulic in the pool**
2. **Power generation**
3. **Heat transfer**
4. **Fuel assemblies behavior and degradation**
5. **FP release and transport**
6. **Thermal-hydraulic in the SFP building**
7. **Material properties**

Phenomena close to those that occur in reactor scenarios: ⇨ SA can be considered as sufficiently mature in terms of phenomena addressed and validation conducted ⇨ u.p. provided in the reactor table have usually been considered and put in the table of u.p.
Phenomena significantly different from those that occur in reactor scenarios

Uncertainties database for SFP (3/5)

<u>Phenomena significantly different from those that occur in reactor scenarios [SOAR NEA 2015]:</u>

FAs stored in storage racks and the walls of the storage cells may incorporate neutron-absorbing material	▪ Not axisymmetric geometry	Sensitivity study
	▪ Radiative heat transfer in SFP geometry	Sensitivity study
	▪ Significant ≠ of radioisotopic inventory between FAs	-
	▪ Neutron-absorbing material	Uncertainty Quantification?
FAs contained in a large structure	▪ 3D flow pattern	Sensitivity study
Much lower decay power	▪ Stratified configuration	-
	▪ T° rise slower than in the reactor case: can affect chemical interaction	Uncertainty Quantification?
At atmospheric pressure, surrounded by air	▪ Large amount of non-condensable gas: can affect condensation and vaporization process	Sensitivity study
	▪ ↗ oxidation rate of Zr cladding in air or steam/air mixtures	**Uncertainty Quantification**
	▪ Wider range of atmosphere composition: can affect FP release, especially Ru	Uncertainty Quantification?
Generally no containment, the cladding is the only barrier	▪ Importance of the gap inventory for the radiological consequences	Uncertainty Quantification?

⇨ **For most of these phenomena, the uncertainty quantification can not be achieved by the propagation of input uncertainties since:**

- **Input uncertainties are not properly quantified**
- **There is no suitable modelling**

Uncertainties database for SFP (4/5)

Table of phenomena, closely linked to the models developed in most SA codes, divided in 7 groups:

1. **Thermal-hydraulic in the pool**
2. Power generation
3. **Heat transfer**
4. **Fuel assemblies behavior and degradation**
5. **FP release and transport**
6. Thermal-hydraulic in the SFP building
7. **Material properties**

Phenomenon	SA code	Uncertain parameter	Distribution	
FP release	AST	DGRA: Average fuel grain diameter	Uniform distribution [2] Lower bound: 10 µm Upper bound: 14 µm	[2, 5]
	MEL	RN1_GAP02: CLFAIL: Gap release temperature	Uniform distribution [9] Lower bound: 1073 K Upper bound: 1273 K Triangular distribution [1] 1173 K +/- 200 K	[9] [1]
	MEL	RN1_CSC Xe (7103): CORSOR-Booth scaling factors	Uniform distribution [1] Lower bound: 2 Upper bound: 2	[1]
	MEL	RN1_CSC Cs (7103): CORSOR-Booth scaling factors	Uniform distribution [1] Lower bound: 2 Upper bound: 2	[1]
	MEL	RN1_CSC Ba (7103): CORSOR-Booth scaling factors	Triangular distribution [1] $3.20\ 10^{-4}$ - 0.4	[1]
	MEL	RN1_CSC I2 (7103): CORSOR-Booth scaling factors	Triangular distribution [1] 0.51 - 1.60	[1]
	MEL	RN1_CSC Te (7103): CORSOR-Booth scaling factors	Triangular distribution [1] 0.51 - 1.60	[1]
	MEL	RN1_CSC Ru (7103): CORSOR-Booth scaling factors	Triangular distribution [1] $2.50\ 10^{-3}$ - $4.0\ 10^{-1}$	[1]
	MEL	RN1_CSC Mo (7103): CORSOR-Booth scaling factors	Triangular distribution [1] 0.05 - 0.5	[1]
	MEL	RN1_CSC Ce (7103): CORSOR-Booth scaling factors	Triangular distribution [1] $3.20\ 10^{-4}$ - $4.0\ 10^{-1}$	[1]
	MEL	RN1_CSC La (7103): CORSOR-Booth scaling factors	Triangular distribution [1] $3.20\ 10^{-4}$ - $4.0\ 10^{-1}$	[1]
	MEL	RN1_CSC UO2 (7103): CORSOR-Booth scaling factors	Triangular distribution [1] $2.56\ 10^{-3}$ - $1.20\ 10^{-3}$	[1]
	MEL	RN1_CSC Cd (7103): CORSOR-Booth scaling factors	Triangular distribution [1] 0.20 - 1.0	[1]
	MEL	RN1_CSCAg (7103): CORSOR-Booth scaling factors	Triangular distribution [1] 0.125 - 0.8	[1]
	AST	FPEVOL: Cs FP gap release at cracking occurrence	Uniform distribution [10] Ref: 0.005 Lower bound: ref - 20% Upper bound: ref + 20%	[10]
FP aerosol transport & deposition	AST	RMin: Particle minimum geometrical radius	Uniform distribution [4, 10] Ref: $1.0\ 10^{-6}$ m Lower bound: ref - 20% Upper bound: ref + 20% Normal distribution [6] Lower bound: ref - 10% Upper bound: ref + 10%	[4, 10] [2, 6]
	MEL	dmin: particle diameter, lower bound	Triangular distribution [1] $1.\ 10^{-6}$ - $2.\ 10^{-7}$	
	AST	RMax: Particle maximum geometrical radius	Uniform distribution [4, 10] Ref: $2.0\ 10^{-6}$ m Lower bound: ref - 20% Upper bound: ref + 20% Normal distribution [6] Ref: $2.0\ 10^{-6}$ m Lower bound: ref - 10% Upper bound: ref + 10%	[4, 10] [2, 6]
	MEL	dmax: particle diameter, upper bound	Triangular distribution [1] $5.\ 10^{-6}$ - $2.\ 10^{-5}$	
	AST	lambda: Particle mean thermal conductivity	Normal distribution [5] Ref: 3.5 W/m/K Lower bound: ref - 50%	[2, 5]

Partner who provided the PDF. References can be found in Appendix

Parnter(s) who used the PDF for the UaSA

Different PDF have provided/used

PDF has been provided but not used

Small extract from the table of u.p.

Uncertainties database for SFP (5/5)

Conclusions:

- Participants have listed the u.p. available to the user in the SA codes and filled the table with the names of the u.p., their description and their probability density function (PDF) - Usually, it was extracted from the reactor table
- 5 tables have been elaborated with all PDF provided and the list of participants that have used these PDF for the UaSA
- For some u.p., uncertainty distributions provided by the partners are different

⇨ **Additional and substantial work would be necessary to determine why different PDF have been provided and if important uncertain parameters are missing**

⇨ **It must be kept in mind that some uncertainty sources can not be accounted with the probabilistic propagation**

Database

- Consolidation and critical review of uncertainty database by partners
- Merging user feedback of WP 4&5&6
  - Partner´s feedback of information gained during the application of the uncertainty and sensitivity analysis in WP 4, 5 and 6 in the database is consolidated

Discussion of the database

- Not modeled phenomena is not included
- Impact of systems
- During the review process user feedback from WP 4 & 5 & 6 shows some differences to ranges given in the database or even more uncertain parameters added
- User feedback integrated in database

Major difficulties found

- Identification of missing phenomena
  - Did we include all important phenomena?
- Description of uncertain parameters is often based on expert knowledge
  - References sometimes are missing
- Reaching agreement for uncertainty bands after the application exoeriences

Synthesis & Insights

- A huge and defendable uncertainty database was created
- Methodology applied
  - 1. Identifying FOMs affecting the ST
  - 2. Identifying uncertain phenomena linked to ST
  - 3. UP depending on:
    - Reactor type / SFP
    - Accident sequence
    - AM measures
- It includes a complex and valuable knowledge
- First of a kind in this comprehensiveness for source term and for the length of accident scenarios, different plant types and codes
- Includes expert knowledge and references from literature from a huge expert group participating in MUSA

Synthesis & Insights

- FOMs must be reduced to focus and make UaSA easier to handle
- User feedback of the application WPs is taken into account
- Consolidation of the database during the project
- The uncertainty database is an important and valuable start in looking closer and more focused into the most important uncertainties
- After the revision process alongside of the project, for future project and with the knowledge of MUSA, the methodology could be changed to focus on important uncertainties

Thanks for your attention and your participation!

MUSA Ucertainty Quantification Methodologies

The Starting point

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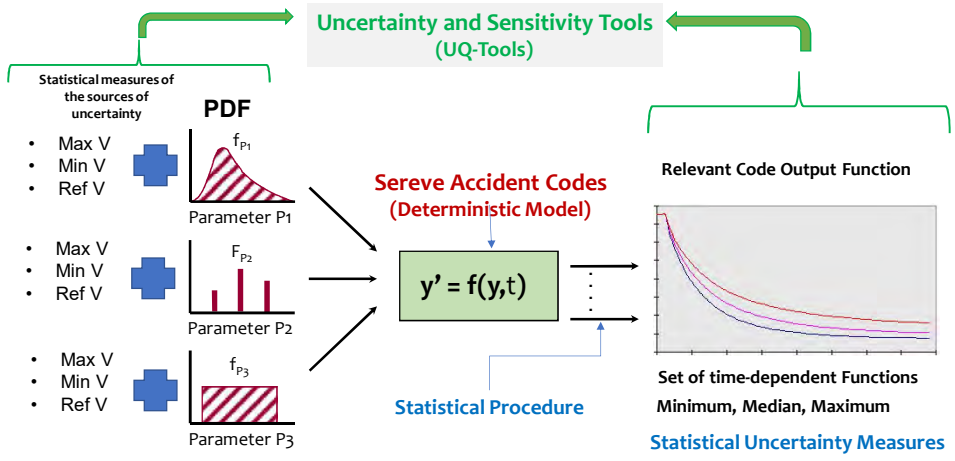
MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

Content

- Before MUSA
- UQ-Tools and Interfaces to SA at Beginn of WP4
- UQ-Tools and Interfaces to SA at Beginn of WP5/WP6
- Final Remarks

Before MUSA

Uncertainty Propagation: Overall Approach



Ref. R. Macian; Uncertainty and Sensitivity Evaluation for Best Estimate Coupled Calculations. FJOH-SS Lecture. August 2011

Experience of U&S-quantification of DBA-tools before MUSA (1/2)

- System thermal hydraulic codes e.g. RELA5, CATHARE, ATHLET, RETRAN, APROS, etc.
- BEMUSE (2003-2008): evaluation of the practicability and reliability of BE-methods including uncertainty evaluations in applications to reactor safety
- PREMIUM (2012-2015): benchmarking of methods of UQ of physical model parameters and application to the models involved in reflooding scenarios simulation
- SAPIUM (2017-2019): A Systematic Approach for Input Uncertainty Quantification
  - Develop a systematic approach that clearly compiles the different practices and offers a shared
  - understanding about "appropriate" practices for (model) input uncertainty quantification
  - Reduce user effect and increase the agreement among experts on recommended practices as well as on remaining open issues for further developments
- Multiphysics and multiscale OECD UAM LWR Bemchmark: N, TH (system TH, subcahnnel TH), TM (ongoing)
  - Phase I:Multi-Scale Standalone Neutronics Static Phase
  - Phase II:Core Phase – Introduce Other Physics in the Core and Time Dependence
  - Phase III: System Phase – Introduce Multi-Physics and Core-System Coupling

Experience of U&S-quantification of DBA-tools before MUSA (2/2)

- Computational Fluid Dynamics (CFD)
  - Monte-Carlo type methods:
    - high number of runs
    - not viable for industrial CFD nowadays
  - Meta-model elaboration
    - Polynomial Chaos Expansion (PCE)
  - Deterministic sampling:
    - Propagates uncertainty from the "**first statistical moments**" of input parameters PDFs instead of directly from PDFs
      - DFs of the input parameters are often not known or just assumed
      - whereas mean values, or standard deviations can be known
    - by appropriate choice of "state points" and "ponderation", it is possible to achieve uncertainty propagation with a limited number of calculations
  - OECD activities:
    - UQCFD: NEA Benchmark Exercise: Computational Fluid Dynamic Prediction and Uncertainty Quantification of a GEMIX Mixing Layer Test

Experience of MUSA-Partners (1/3)

- Experience in UA for DBA-tools in many partners
- Limited UA of SA-codes and SA-sequences
  - IRSN: SUNSET: ASTEC estimation of radiological ST for a French PWR reactor
  - KIT, LEI: URANIE: ASTEC U&S quantification in predicting H2-source term in QUENCH-06 and -08 tests
  - ENEA: DAKOTA: U&S quantification of MELCOR in predicting H2-production in a PWR, ST of CSTF-AB1 test, and in-pool FP-retention in a BWR-SBO
  - LEI:
    - SUSA U&S quantification of ASTEC and COCOSYS applied to PHEBUS FPT1 and FPT2 experiments, respectively
    - SUSA U&S quantification of RELAP/SCDAPSIM analysing QUENCH-03 and -06 tests

Experience of MUSA-Partners (2/3)

- Few experience applying UQ-tools to SA-codes covering full SA-sequence (in-vessel, ex-vessel, containment) to predict the radiological source term (ST)
  - IRSN: ASTEC/SUNSET, LOF-sequence in PWR
  - GRS: ATHLET-CD/COCOSYS/SUSA, SBLOCA in-vessel and containment ST

Experience of MUSA-Partners (3/3)

- Experience in HPC-applications of UQ/SA-codes in predicting radiological source term
  - IRSN: explored use of HPC using ASTEC/SUNSET
  - KIT: explored use of HPC cluster (ForLHR II) of KIT using ASTEC/URANIE for ST-prediction of a German PWR
- Data assimilation tools (MOCABA, NEMM)
  - MOCABA: first application to SA in connection with ASTEC
  - NEMM: no experience related to SA and UQ

UQ-Tools and Interfaces to SA at Beginn of WP4

WP4: Starting UQ/SA-codes used in MUSA

Grouped by UQ-tools

WP4: UQ/SA Tools

UQ Tool	SA Code
DAKOTA/Python scripts	MELCOR2.2
DAKOTA	MELCOR2.2
DAKOTA /SNAP	MELCOR2.2
DAKOTA/SNAP, MATLAB script	MELCOR2.2
DAKOTA/SNAP	MELCOR2.2
DAKOTA	MELCOR1.8.6
DAKOTA, Python, associated packages	MAAP5.05
UQ Tool	**SA Code**
SUSA4.2	AC²
SUSA4.0	MELCOR2.2
SUSA4.2	RELAP/SCDAPSIM mod3.4
UQ Tool	**SA Code**
SUNSET	ASTEC2.2b
SUNSET	ASTEC2.2b
SUNSET	ASTEC2.2b
UQ Tool	**SA Code**
Python Tools	MELCOR 2.2
Python in-house Tool	MELCOR 2.2
Scripts	MELCOR2.2
UQ Tool	**SA Code**
RAVEN	MELCOR2.2
URANIE	ASTEC2.1

Grouped by SA-tools

WP4: UQ/SA Tools

WP subgroup	Uncertainty tool	
PWR Gen III	SUNSET	ASTEC
	DAKOTA	MELCOR
	DAKOTA	MAAP 4.0.7
	DAKOTA	MELCOR 2.2
	DAKOTA	MELCOR
PWR Gen II	Python-based KATUSA	ASTEC
	URANIE	MELCOR
	DAKOTA	MELCOR
	DAKOTA	MELCOR
	DAKOTA, Python	MELCOR
	SUSA	AC2
	SUNSET, Python	ASTEC
	Python scripts	MAAP 5.05
	Python scripts	MELCOR
	Genpara, MOCABA	See KIT
	IUA2.0	RELAP/SCDAPSIM
VVER/CANDU	SUNSET	ASTEC
	Python scripts	MAAP
	NEMM method	MELCOR
	SUNSET	ASTEC
	SUSA	MELCOR
	DAKOTA	MELCOR
BWR	SUSA	RELAP/SCDAPSIM
	RAVEN	MELCOR
	DAKOTA	MELCOR
	RAVEN	MELCOR
	DAKOTA, Python	MELCOR

At MUSA start: UQ tools and Interfaces

- Developed for different computer architectures:
  - Linux: SUNSET, URANIE
  - Windows: SUSA
  - Linux/Windows: DAKOTA, RAVEN
- Different interfaces between UQ /SA codes
  - GUI based on Excel: SUSA/ATHLET-CD and AC²
  - Java-based GUI SNAP: DAKOTA/MELCOR
  - Java-based GUI Interface: SUNSET/ASTEC
  - Python-based interface: URANIE/ASTEC
  - Python-based interface: RAVEN/MELCOR

At MUSA start: HPC Capability of UQ/SA tools

- GUI based on Excel: SUSA/ATHLET-CD and AC²
  - no
- Java-based GUI SNAP: DAKOTA/MELCOR
  - Good parallel capability
- Java-based GUI Interface: SUNSET/ASTEC
  - no
- Python-based interface: URANIE/ASTEC
  - Sequential or parallel
- Python-based interface: RAVEN/MELCOR
  - no

Limitations of Interfaces

- GUI based on Excel: SUSA/ATHLET-CD and AC²
  - Only Windows
- Java-based GUI SNAP: DAKOTA/MELCOR
  - Some limitations in the case of failed calculations that can be overcome with the new Python directed job-stream capability in SNAP, model parameters if they are part of the input only, additional scripts may be needed for specific pre- and post-processing
- Java-based GUI Interface: SUNSET/ASTEC
  - LHS is based on independence of UP
  - Better results than SRS if response is dominated by only some of the input variables or if response is a monolitic function of each of ist arguments
  - Global sensitibity coefficients check the influence of a parameter over all the variation interval of the parameters; **local info is missed**
- Python-based interface: URANIE/ASTEC
  - URNAIE requires a lot of external tools for installation which ar platform dependent
- No GUI for RAVEN/MELCOR: Python outpout parser (binary plot/CVS)
  - GUI not yet available

UQ-Tools and Interfaces to SA at Beginn of WP5/WP6

MUSA: At beginn of WP5 and WP6: New toos for UQ and coupling of UQ/SA-codes

- Based on WP4 experience, new tools / extension of interfaces developed for WP5
- MUSA new Interface:
  - UNIROME: Phyton script RAVEN/MELCOR
  - TBL: Python script /DAKOTA
  - PSI: Python script /DAKOTA
- MUSA New UQ-tools:
  - KIT: KATUSA/ ASTEC
  - CSNS: PSUQM2/ MAAP
  - IRSN: R+ Python Scripts /ASTEC
  - EPRI: Python Script /MAAP

WP5 UQ/SA-Codes Applied for Plant Analysis

- WP5 UQ
  - Subgroup 5.1:
    - VVER 1000: 5
    - French PWR 900: 2
    - French PWR 1000: 2
    - PWR Surry: 2
    - PWR konvoi: 2
    - PWR-1100: 1
    - PWR 4 Loop: 1
    - APR1400: 1
    - HPR1000: 1
    - CAP1400: 1
    - CANDU-6: 1
  - Subgroup 5.2:
    - BWR4 Mark1: 3
    - BWR 5: 1
    - ABWR: 1

WP subgroup	Uncertainty tool	
PWR Gen III	SUNSET	ASTEC
	DAKOTA	MELCOR
	DAKOTA	MAAP 4.0.7
	DAKOTA	MELCOR 2.2
	DAKOTA	MELCOR
PWR Gen II	Python-based KATUSA	ASTEC
	URANIE	MELCOR
	DAKOTA	MELCOR
	DAKOTA	MELCOR
	DAKOTA, Python	MELCOR
	SUSA	AC2
	SUNSET, Python	ASTEC
	Python scripts	MAAP 5.05
	Python scripts	MELCOR
	Genpara, MOCABA	See KIT
	IUA2.0	RELAP/SCDAPSIM
VVER/CANDU	SUNSET	ASTEC
	Python scripts	MAAP
	NEMM method	MELCOR
	SUNSET	ASTEC
	SUSA	MELCOR
	DAKOTA	MELCOR
BWR	SUSA	RELAP/SCDAPSIM
	RAVEN	MELCOR
	DAKOTA	MELCOR
	RAVEN	MELCOR
	DAKOTA, Python	MELCOR

UQ Tools used:
- DAKOTA: 10
- SUNSET: 4
- SUSA: 3
- Python Scripts: 3
- RAVEN: 2
- URANIE: 1
- Python KATUSA: 1
- **IUA2: 1**

Data assimilation:
- NEMM: 1
- MOCABA: 1

WP6 UQ/SA Tools applied to Spent Fuel Pools (SFP)

SA code	Uncertainty tool	SFP design	Building model	Number of UPs
DAKOTA	MELCOR	BWR FU-4	No	15
DAKOTA	MELCOR	BWR FU-4	Yes	8
DAKOTA	MELCOR	BWR FU-4	No	15
SUNSET	ASTEC	BWR FU-4	Yes	7
SUNSET	ASTEC	BWR FU-4	Yes	12
SUNSET	ASTEC	BWR FU-4	Yes	7
SUNSET	ASTEC	BWR FU-4	Yes	n.a.
SUSA	RELAP/SCDAP	BWR FU-4	No	25
SUSA	MELCOR	BWR FU-4	Yes	24
RAVEN	MELCOR	BWR FU-4	Yes	25
R + Python script	ASTEC	BWR FU-4	Yes	18
RAVEN + Python script	ASTEC	BWR FU-4	Yes	21

End of MUSA: Status of UQ and UQ/SA-Codes

- New UQ-tools:
  - CNSC: PSUQM2 used with MAAP
  - KIT: KATUSA based on Python used with ASTEC
  - IRSN: R+Python Scripts used with ASTEC
  - EPRI: Python tool used with MAAP
- Improved UQ-tools
  - GRS: New GUI version based on Visual Basic for SUSA/AC2
  - UNIROME: Python parser replaced by Python interface for MELCOR/RAVEN interface
- Improvements of GUI-capabilities with Python scripts (LINUX/Windows)
  - PSI: DAKOTA/MELCOR
  - TRACTBEL: DAKOTA/MELCOR
  - PSI: DAKOTA/MELCOR
- Capability to consider correlation of UPs: SUSA, SUNSET, URANIE, KATUSA, EPRI Python tool

Final Remarks

Final remarks

- First quantification of U&S-tools predicting SA-sequences with different Severe Accident codes
  - Unique expereince gained
- MUSA: Very **heterogeneous analysis** in WP5/WP6 regarding
  - Selected FOMs, number of FOMs
  - Number of UPs
  - Number of runs
  - Number of SA-sequences
  - **Only few partners** performed the analysis of full SA-sequences including all phases (FP-release and transport into the Containment and ENV)
- Hence, comprehensive, systematic, and more homogenous quantitification of the SA-Codes‘s uncertainty for specific reactor designs and SA-sequence with different UQ-tools is needed
  - To develop recommendations, guidelines, etc.

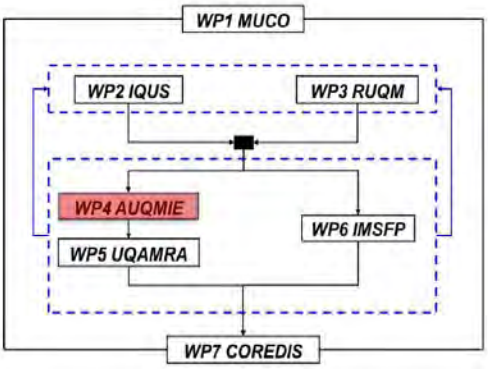
MUSA WP4: APPLICATION OF UNCERTAINTY QUANTIFICATION METHODS AGAINST INTEGRAL EXPERIMENTS (AUQMIE)

F. Mascari[1], O. Coindreau[2], Sara Beck[3] , S. Paci[4]
[1]ENEA, Italy.
[2]IRSN, France
[3]GRS, Germany
[4]UNIPI, Italy

MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

MUSA framework

- One of the main targets of MUSA is to move beyond the state-of-the-art regarding the predictive capability of SA analysis codes by combining them with the best available or improved UQ tools.
- The achievement of the overall objective is assured by a consistent and coherent work program, reflected by the technical WP, which includes:
  - WP1, MUSA COordination and project management (MUCO),
  - WP2, Identification and Quantification of Uncertainty Sources (IQUS),
  - WP3, Review of Uncertainty Quantification Methodologies (RUQM),
  - WP4, Application of UQ Methods against Integral Experiments (AUQMIE),
  - WP5, Uncertainty Quantification in Analysis and Management of Reactor Accidents (UQAMRA),
  - WP6, Innovative Management of SFP Accidents (IMSFP), and
  - WP7, COmmunication and Results DISsemination (COREDIS).



Introduction on WP4

- WP4, led by ENEA (Italy), is aimed at applying and testing UQ methodologies, against the internationally recognized PHEBUS FPT1 test.
- Considering that FPT1 is a simplified experiment but remains a representative SA scenario, the main objective of the WP4 is to train project partners to applicate UQ to SA analyses.
- WP4 is also a collaborative platform for highlighting and discussing results and issues arising from the application of UQ methodologies, already used for design basis accidents, or in MUSA used for SA analyses.
- WP4 application:
  - Creates the technical background useful for the MUSA full plant and spent fuel (WP4 and WP5).
  - Provides a first contribution for MUSA best practices and lessons learned (WP3).

MUSA

Objectives of the WP4

- Application of Uncertainty Quantification (UQ) Methods against Integral Experiments (AUQMIE) WP is aimed at *applying and testing UQ methodologies, investigated in WP3, against the internationally recognized PHEBUS FPT1 test.*
- Along the WP4:
  - UQ application trained the project Partners gaining experience in the Uncertainty and Sensitivity Analyses (UaSA);
  - Provided a platform of discussion for proposing solutions if some issues arise during the UaSA applications.
- The experience gained along the WP4 will be used as a technical background for the full plant (WP5) and SFP (WP6) UaSA application.

MUSA

WP4 Structure and role of the parners

- Sub-WP4.1Benchmark specifications
  - Lead by IRSN:
    - Olivia Coindreau : olivia.coindreau@irsn.fr
  - Partners involved: CIEMAT, CEA, CNSC, ENEA, ENERGORISK, EPRI, GRS, INRNE,IRSN, KIT, LEI, PSI, SSTC, TUS, UNIPI, UNIRM1, USNRC, VTT
- Sub-WP4.2 Benchmark calculations
  - Led by GRS and ENEA:
    - Sara Beck: sara.beck@grs.de; Fulvio Mascari
  - Partners involved: CIEMAT, CNPRI, CNSC, ENEA, ENERGORISK, EPRI, GRS, INRNE,IRSN, KIT, LEI, PSI, SSTC, TUS, UNIPI, UNIRM1, USNRC, VTT
- Sub-WP4.3 Analyses of results
  - Led by UNIPI:
    - Sandro Paci: sandro.paci@unipi.it
  - Partners involved: CIEMAT, CEA, CNPRI, CNSC, ENEA, ENERGORISK, EPRI, GRS , INRNE,IRSN, KIT, LEI, PSI, SSTC, TUS, UNIPI, UNIRM1, USNRC, VTT

MUSA

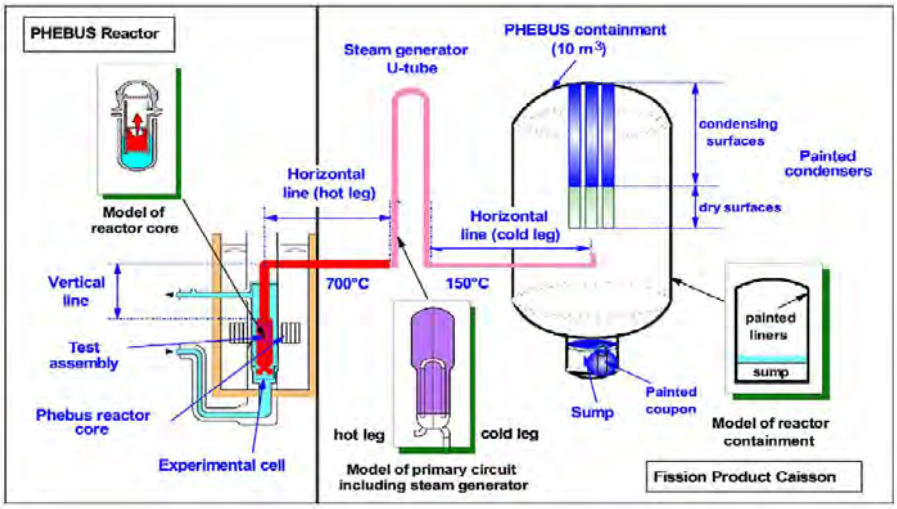
PHEBUS-FPT1

- The PHEBUS Fission Product (FP):
  - Program was initiated in 1988;
  - Main objective of studying the release, transport and retention of fission products in an in-pile facility under conditions representative of a severe accident in a light water reactor.
- Second test of the program (FPT1), carried out on 26 July 1996 in the Phébus facility at Cadarache (France)
  - Degradation of a 1 m long fuel bundle that consists of 18 irradiated fuel rods (about 24 GWd/tU), two fresh fuel rods and a silver-indium-cadmium control rod.
- The degradation of the fuel was realized by a progressive increase of the nuclear power, up to the formation of a molten pool in the lower part of the bundle,
  - made of about 2 kg of mixture (i.e. corium) urania, zirconia and related FP and actinides.
- The test comprises:
  - Fuel degradation phase;
  - Aerosol phase;
  - Washing phase and a chemistry phase.

MUSA

PHEBUS-FPT1

The objectives of the Phébus FP experimental programme and main findings Bernard Clément, Roland Zeyen, ANE 61 (2013) 4-10



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PHEBUS-FPT1

- Considering:
  - Resources available for the WP4,
  - Previous ISP 46 activity

  a code benchmark against the experimental data is not in the scope of the exercise.

- However, representative experimental data have been used :
  - Have full and credited details of the scenario and
  - Allow to calibrate the nodalization for the reference case before developing the uncertainty application.

- This allows to:
  - Focus the WP4 exercise on the uncertainty application and
  - Investigate how to address the issues that can arise in the UaSA methodologies application to simplified, but still representative, SA scenarios

- As agreed among the WP4 partners, the first two phases of the experiment (namely the degradation and the aerosol phases) have been the focus of the exercise, and washing and chemistry phases have been excluded.

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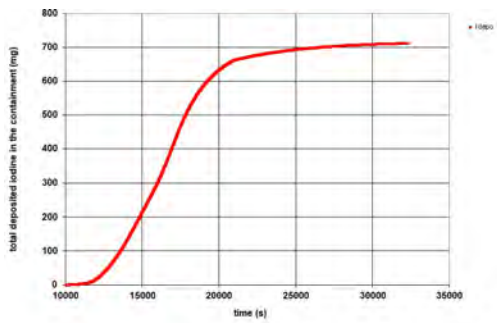
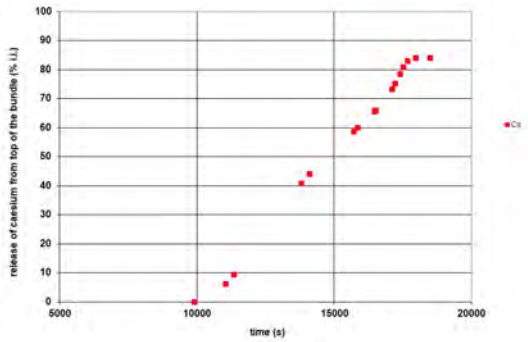
WP4 Figures of Merit

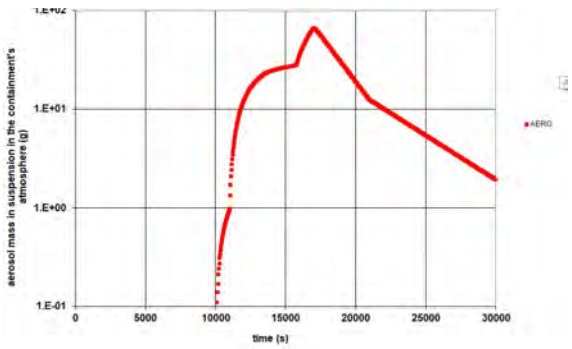
- FOMs, ST focused, that have been identified in the WP2 for the reactor case application and that have been considered relevant for the WP4:
  - Release of iodine from top of the bundle [% of i.i.]
  - Release of cesium from top of the bundle [% of i.i.]
  - Cesium retention in the circuit [% of Cs released from the core]
  - Aerosol amount in the containment atmosphere [g]
  - Total gaseous iodine amount in the containment atmosphere [g]
  - Total iodine aerosols amount in the containment atmosphere [g]
  - Total deposited/adsorbed iodine amount in the containment [g]

MUSA





Element	Experimental fractional retention
Cs	0,476 ± 0.107



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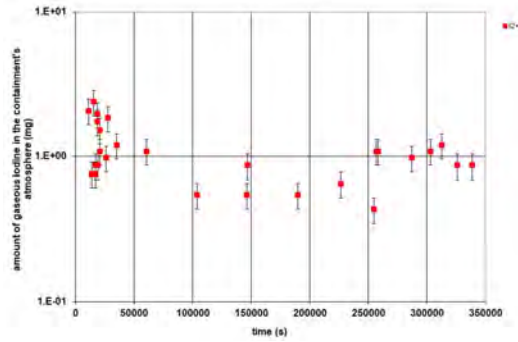

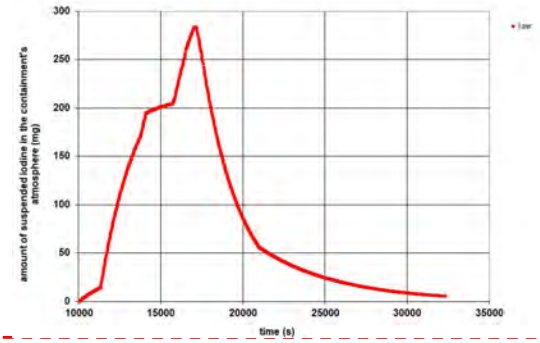

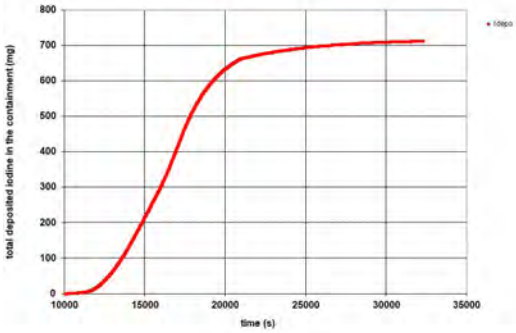

Contributing Partners, SA codes and UTs

Partner	Severe accident code	Uncertainty tool
CIEMAT	MELCOR 2.2	DAKOTA
CNSC	MELCOR 2.2	Python scripts
ENEA	MELCOR 2.2	DAKOTA
Energorisk	MELCOR 1.8.6	DAKOTA within SNAP
EPRI	MAAPv5.05	Python w/associated packages, DAKOTA
GRS	AC²	SUSA 4.2
INRNE	ASTEC 2.2	SUNSET
KIT	ASTEC 2.2	URANIE 4.1
LEI	ASTEC V2.2.b.	SUNSET V2.1
	RELAP/SCDAPSIM mod3.4	SUSA 4.1
PSI	MELCOR 2.2	DAKOTA within SNAP
SSTC	MELCOR 2.2	SUSA 4.0
Tractebel	MELCOR 2.2	Python in-house tool
TUS	ASTEC 2.2b	SUNSET
UNIPI	MELCOR 2.2	DAKOTA within SNAP / MATLAB script
UNIRM1	MELCOR 2.2	RAVEN v2.1
USNRC	MELCOR 2.2	DAKOTA
VTT	MELCOR 2.2	DAKOTA within SNAP

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Computing environment adopted by WP4 partners

Partner	Operative systems	RAM	CPU Characteristics
CIEMAT	Windows 10	32 GB	I7 11700k (8 cores at 5.0 GHz)
CNSC	Win10-1803 5.06	8 GB	Intel R core i7 CPU1.90GHz 2.11GHz
ENEA	Windows 10	32 GB	Intel® Xeon® Silver 4108 CPU @ 1.80GHz, 1796 MHz, 8 Core(s), 16 Logical Processor(s)
Energorisk	Windows 10	16 GB	Intel(R) Core(TM) i9-9900K CPU
EPRI	Windows 10	16 GB	Xeon 3.6GHz
GRS	PC-Windows 10/Unix server – Linux, x86_64		
INRNE	64-bit operating systems working under windows 10 Pro	8,00 GB	Intel® Core™ i5-9600K CPU @ 3,70 GHz 3,70 GHz
KIT	LINUX (Ubuntu 16.04)	16 GB	Intel® Core™ i7-6700 CPU @ 3.4 GHz
LEI	Windows 10 Pro	4 GB	2.80 GHz
	Windows 10 Pro	8 GB	i7-8750H CPU @ 2.20GHz
PSI	Windows 10	16 GB	Intel i7-8700 3.20 GHz
SSTC	Windows 10	16 GB	Intel Core i9-10900F, 2.8 GHz
Tractebel	Windows 64bit	32 GB	Intel®, Xeon®, Silver 4215 CPU 2,5 GHz
TUS	Windows 10, 64-bit Operating System, x64-based processor	4 GB	Intel® Core™ i5-3210M CPU @ 2,50GHz 2,50 GHz
UNIPI	Windows 10 Pro / Windows Server 2019 Datacenter	16 GB/64 GB	i9-10885H CPU / Xeon Gold 5218
UNIRM1	CENTOS 7	256 GB per node	2 x Xeon E5-Gold 6140 (each node, x 4 nodes)
USNRC	Linux (Red Hat Enterprise Linux 7.9)	32 GB	16 Core Xeon
VTT	Windows 10 laptop	8 GB	Intel Core i5-8365U processor (4 cores)

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Partner computational time for the reference case and UQ.

Partner	Computational time	
	Reference calculation	UQ
CIEMAT	5.6 h	59.24/54.2 h
CNSC	5 h	4.5 d
ENEA	8 h	5 d
Energorisk	1.5 h	10 h
EPRI	9-13 min	60-90 min
GRS	4.5 h	462.6 h
INRNE	39 min	1 d and 10 h
KIT	130 min	
LEI	39 min	70 h
	0.2 h	30-40 h
PSI	5.87 h	22.76 d
SSTC	15 min	5 days
Tractebel	1 h	3 h
TUS	60 min	
UNIPI	3-5 h	1.5 d
UNIRM1	8 h	37 h
USNRC	6 h	361 h
VTT	28 min	15 h

MUSA

WP4 common FOMs investigated

FOM / Partners	Release of iodine from top of the bundle	Release of caesium from top of the bundle	Caesium retention in the circuit	Aerosol amount in the containment's atmosphere	Total gaseous iodine amount in the containment's atmosphere	Total Iodine aerosol amount in the containment's atmosphere	Total deposited/ adsorbed iodine amount in the containment
CIEMAT	X	X	X	X	X	X	X
CNSC			X				
ENEA				X			
ENERGORISK	X	X					
EPRI	X	X		X		X	X
GRS	X	X				X	X
INRNE	X	X	X	X	X	X	X
KIT	X	X	X				
LEI-ASTEC	X	X	X	X	X	X	X
LEI-RELAPSCDAPSIM	X*	X*					
PSI			X	X			
SSTC					X		
TRACTEBEL		X	X	X			
TUS	X			X	X	X	X
UNIPI				X			
UNIRM1				X			
USNRC	X	X	X	X	X	X	
VTT	X	X	X			X	X

MUSA

Lessons learned

- The following points have been extensively discussed to extract the first lessons learned in WP4:
  - Identification and characterization of the input uncertain parameters;
  - Management of the failed calculations;
  - Coupling of the UT with the SA code;
  - Post processing of the data and the SA code.

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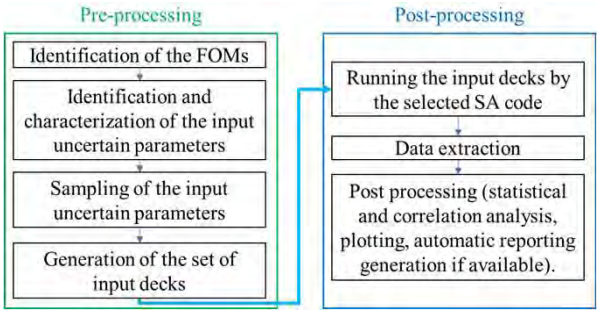
Example of main tasks to be performed to do an uncertainty analysis

- The application of a deterministic code, as SA code, together with an UT requires two main phases:
  - Pre-processing phase
  - Post processing phase.



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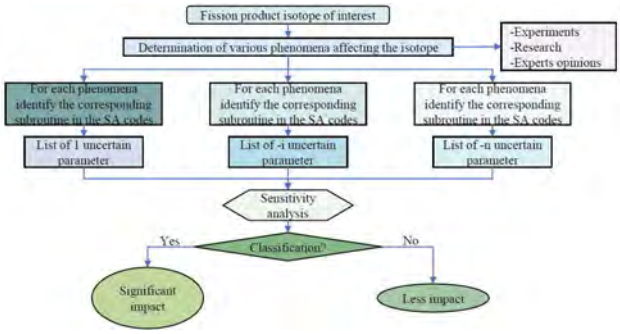
Identification and characterization of the input uncertain parameters

- The identification and characterization of the input uncertain parameters is a crucial task for the application of UA based on the probabilistic propagation of input uncertainties.
- Combination of extreme input uncertain parameter values should be investigated separately in order to understand if they generate outliers and if the obtained FOM behavior is physically acceptable.
- Also, the range of the input uncertain parameters can affect the correlation (e.g. linear, monotonic, etc.) with the FOM. Therefore, their selection should be done with care and the PDF and range should be based on references or engineering judgment. In general, experimental data, analytical data and expert judgement are necessary.



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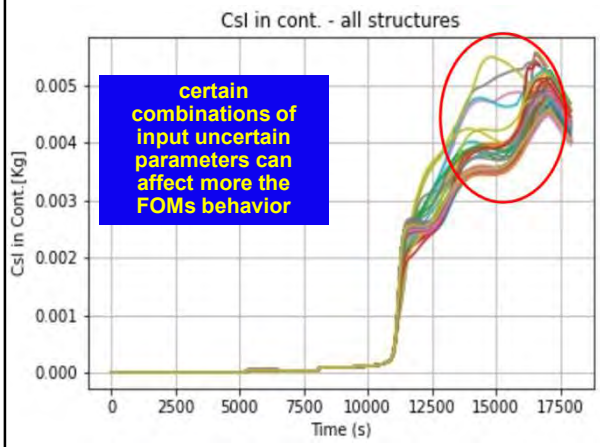
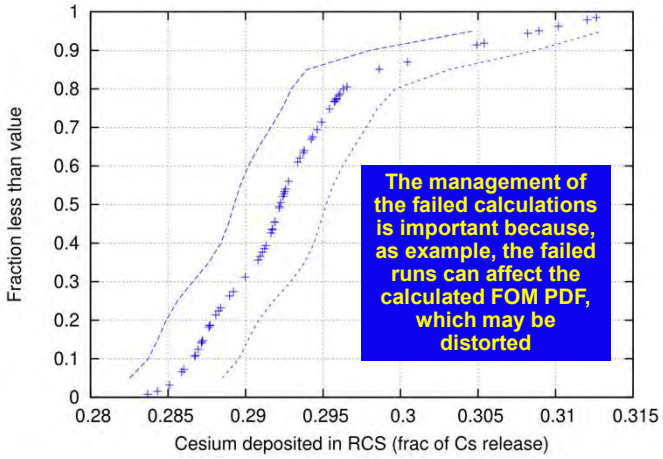
Management of the failed calculations





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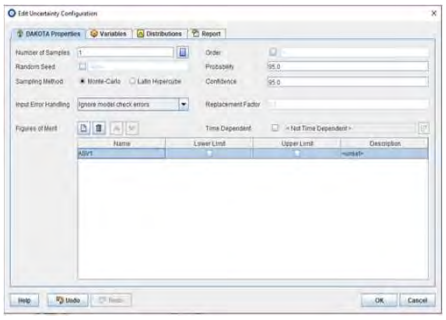
Coupling of the UT with the SA code

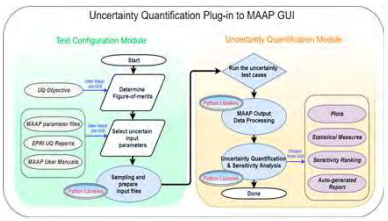
- The coupling of the UT with the SA code is a necessary step to automate the process;
- There is the need to balance the user flexibility and tool robustness.
- Scripting, even less user-friendly and time demanding, resulted extremely powerful and flexible to automate the UA process, also for selecting ad-hoc statistical and post-processing techniques.
- Every step should be:
  - Controllable,
  - Traceable/reproduceable and
  - It could be useful to detect potential errors during the implementation and alert the user.
- GUI have shown to be more user-friendly, but some limitation has been observed:
  - Post-processing capability,
  - Management of failed calculations

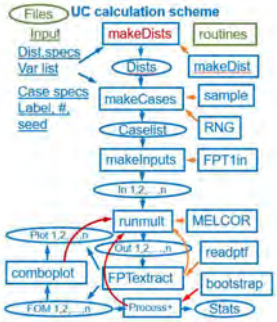
MUSA

Coupling of the UT with the SA code

Use of a Graphical User Interface (GUI) vs scripting

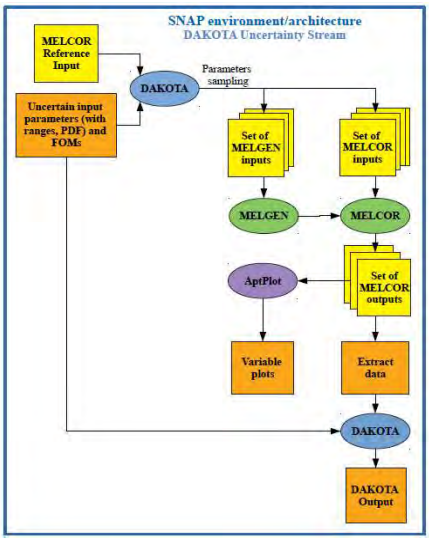






MUSA

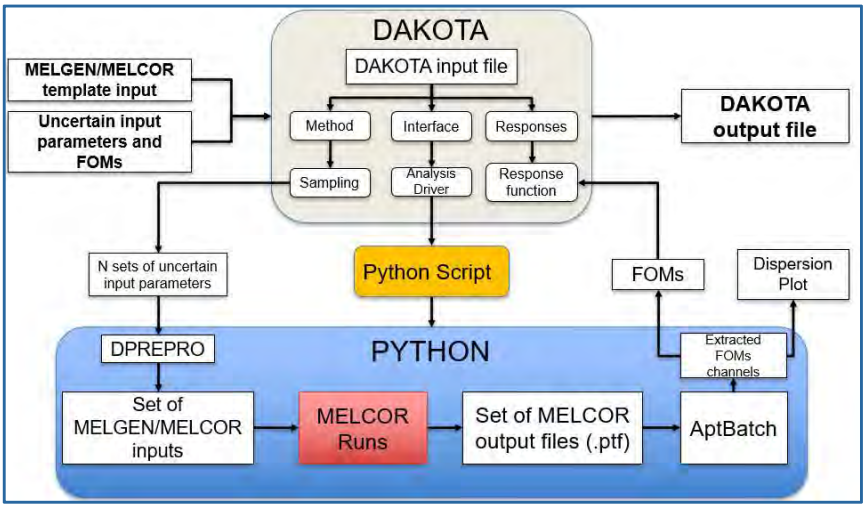
Coupling of the UT with the SA code



MELCOR/DAKOTA coupling in the SNAP environment/architecture workflow

MUSA

Coupling of the UT with the SA code



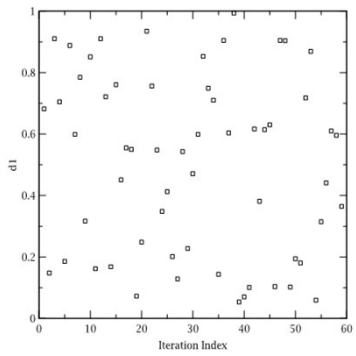
MELCOR/DAKOTA coupling with Python scripts workflow

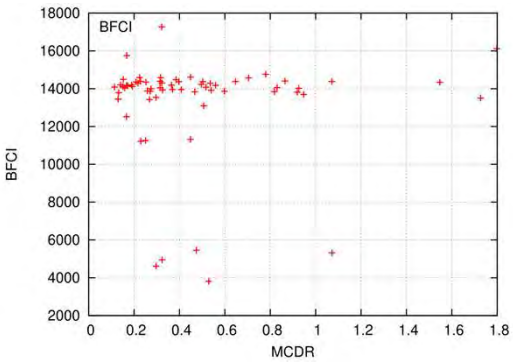
Post processing of the data

- The post processing of the data is a key element of the uncertainty application.
- The analyses can be done:
  - particular point of the FOM (e.g. the maximum value of the aerosol in the containment) or
  - time dependent.
- Time dependent analyses permits:
  - to analyze the statistical behavior of the FOM considered along the scenario evolution and permits
  - to compute the degree of statistical correlation in all phases of the transient:
    - Time dependent PDF is considered very useful and the explanation of the PDF variation with time can be an added value of the analyses.
- However, it should be underlined that the FOM time dependent analysis within the adopted methodology needs more discussion (e.g. number of calculations required).
- In relation to uncertainty/sensitivity analyses, some partners considered different threshold values to characterize the relationship between the uncertain input parameters and the FOM and a common consensus should be reached.

Post processing of the data

Characterization of the variate and the response data.



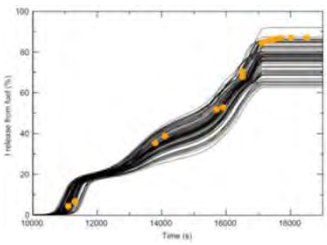


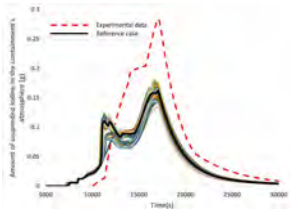
It show the parameter range is sampled in various code runs and gives an idea of the coverage of the sampling space

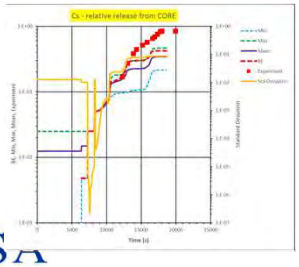
It is easy to visualize eventual correlation between the FOM and the input uncertain parameters and to visualize possible outlier values

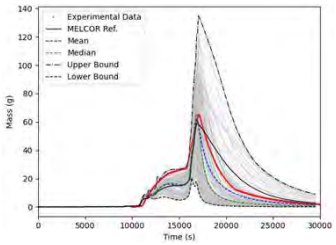
Post processing of the data

Dispersion plots to have a visualization of the spread of the results









MUSA

Post processing of the data

Single value statistical analysis

	average	standard deviation	min	max
'Outputs_variable#1' (FoM1)	74.83292	0.9349476	69.9418	75.4608
'Outputs_variable#2' (FoM2)	75.6778	0.9035606	70.9509	76.2846
'Outputs_variable#3' (FoM3)	44.69411	0.6258984	41.4658	45.2189
'Outputs_variable#4' (FoM4)	17.15974	0.6905951	14.6947	17.709
'Outputs_variable#5' (FoM5)	76.03427	7.690871	57.0591	84.0967
'Outputs_variable#6' (FoM6)	684.8632	29.19382	561.988	706.64
'Outputs_variable#7' (FoM7)	208.0369	20.16689	156.889	230.437

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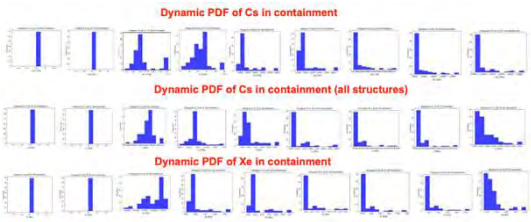
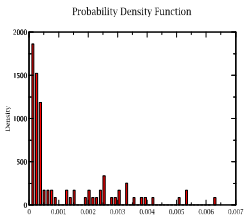
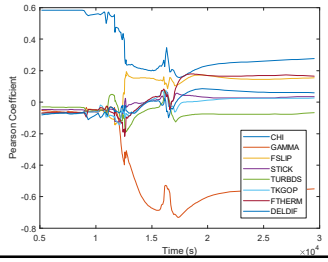
Post processing of the data

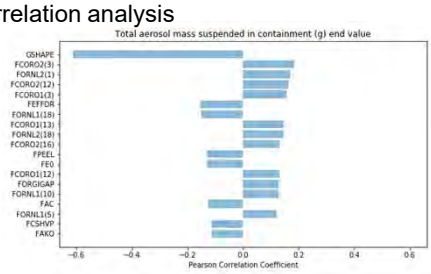
Time depended and and single value FOM empirical PDF





Time dependent and single value correlation analysis





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Coefficients adopted by the partners to characterize the input uncertain parameters relationship with the FOM.

Partner	Type of regression	Coeff used to rank the uncertain parameters	Threshold used to consider the contribution of the uncertain parameters
CIEMAT	Linear	Pearson, Spearman	p-value < 0.05 CC confidence interval (Fisher's Transformation)
CNSC	NA	NA	NA
ENEA	Correlation	Pearson, Spearman	Absolute value <0.2: low Absolute value ≥0.2 and <0.5: moderate Absolute value ≥0.5: significant
Energorisk	Correlation	Pearson, Spearman	Positive/negative values: between 0.9 and 1.0: very highly between 0.7 and 0.9: highly between 0.5 and 0.7: moderately between 0.3 and 0.5: low less than 0.3: little if any
EPRI	No information given.		
GRS	Correlation	SRCC	Absolute value < 0.2 → no statistical significance Note: Coeff. of determination for overall evaluation of the quality of the SA (the closer its value to one, the better)
INRNE	Linear Regression: Correlation technics	Pearson correlation coefficients	Positive/negative values 0.1-0.3: small; Positive/negative values 0.3-0.5: medium; Positive/negative values 0.5-1.0: large. (Cohen, 1988)
KIT	Correlation	Pearson	Absolute value <0.2: small/negligible Absolute value ≥0.2 and <0.5: moderate Absolute value ≥0.5: significant
LEI	Correlation	Spearman	Absolute value <0.2: negligible impact; ≥0.2: influencing parameter.
	Correlation	Spearman	Absolute value > 0.2
PSI	Correlation	Pearson, Spearman	Absolute value > 0.2
SSTC	Correlation	Pearson, Spearman	
Tractebel	Correlation	Pearson	P. Coefficient<|0.30| Low degree |0.30| < P. Coefficient<|0.50| Moderate degree P. Coefficient>|0.50| Significant degree
TUS	Correlation	Pearson coefficients	Absolute value 0.1-0.3 / low Absolute value > 0.3 until 0.5 / middle Absolute value > 0.5 / high
UNIPI	Correlation	Pearson, Spearman	abs value: <0.2: almost negligible >0.2 and <0.3: weak >0.3 and <0.5: moderate >0.5 and <0.7: strong >0.7: very strong
UNIRM1	Correlation	Spearman (Pearson for comparison)	abs value: <0.2: almost negligible ≥0.2 and <0.3: weak ≥0.3 and <0.5: moderate ≥0.5 and <0.7: strong ≥0.7: very strong
USNRC	No information given.		
VTT	Correlation	Pearson	

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Main conclusions from WP4 exercise

- The probabilistic method to propagate input uncertainties has been adopted by all the partners with different SA codes and UT.
- In general, the direct application of UQ methodologies developed e.g. in nuclear thermal-hydraulics or thermo-mechanics could be more challenging for SA.
  - Some considerations are needed for example:
    - Possible large number of uncertain input parameters (e.g. due to some limitations of geometric prototypical experimental facilities with prototypical material),
    - Possible higher failure rate of code runs,
    - Possible presence of cliff-edge effects etc.
- Scripting was needed to couple SA codes and UT in most applications
  - it required major efforts for its development than GUI adoption.
  - it provided more flexibility, in terms of post-processing capabilities, compared to GUIs which, despite being user-friendly, presented certain limitations.

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Main conclusions from WP4 exercise (continued)

- The proper choice of the input uncertain parameters and their characterization (range and PDF) is a crucial task, that should be based in general on a sound background (e.g. experimental and analytical data, references, engineering judgment, etc.).
  - Complexity and multi-physics nature of the phenomena occurring in SA and their interconnection might lead to a large set of uncertainty input parameters.
- Certain combinations of input uncertain parameters can affect more the FOMs behavior, generating possible outliers that should be investigated.
  - Results showed that SA codes could be sensitive to the choice of the input uncertain parameter and the related range.
  - the choice of values not varied (i.e. not sampled) in the UQ can influence the stability of the calculations.
- Computational time is a key element to perform UaSA and for plant applications the use of clusters, and eventually the implementation of GUI in clusters, may be necessary.

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Main conclusions from WP4 exercise (continued)

- Several post-processing approaches have been tested.
  - In general, the interpretation of results from sensitivity or correlation analysis is not always straightforward due to the possible large number of uncertain input parameters.
- There is the need for a statistically solid handling of failed calculations within the adopted methodology.
  - In the WP4 exercise different approaches have been proposed by the partners, but consensus should still be reached on this point.
- The differences in partners' nodalizations and UaSA applications do not allow to draw a comprehensive conclusion on the uncertainty of the various FOM.
  - However, according to the partners results, it has been collected a list of input parameters mostly correlated with various FOMs according to Pearson and Spearman coefficients.

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Thank you for your kind attention

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This paper reflects only the author's view, and the European Commission is not responsible for any use that may be made of the information it contains.

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Uncertainty Quantification: Application to in-reactor Severe Accident sequences

S. Brumm, JRC (Petten),
as work package coordinator

MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

Content

- Motivation and groundwork
- Elements of the approach
- Insights and results
- Major challenges
- Conclusions

Acknowledgement

- Partners contributing

- Co-coordinators in the work package:
  F. Gabrielli (KIT), P. Groudev (INRNE), P. Ou (CNPRI)

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Motivation of reactor applications work package

- Demonstrate the application of BEPU analysis in the Severe Accident context
- Challenge/educate the Severe Accident community
- Investigate implications for/from SAM actions

- How?
  - 2/3 of MUSA resources in the application work packages, 30% in WP5

MUSA

The groundwork for MUSA reactor applications

WP5: Uncertainty Quantification in Analysis and Management of Reactor Accidents
24 partners

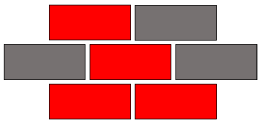
WP6: Innovative Management of SFP Accidents
15 partners

WP4: Application of UQ Methods against Integral Experiments
18 partners

WP2: Identification and quantification of Uncertainty Sources
18 partners

WP3: Review of Uncertainty Quantification Methodologies
20 partners

The groundwork for MUSA reactor applications 2/2



- All partners brought their knowledge of severe accident modelling and analysis into the project
- Before entering WP5, most partners had explored
  - how to define the uncertainty sources
  - how to use their specific UQ tool
  - how to deal with typical problems of a BEPU analysis for the Phebus FPT-1 severe accident simulation
- The EUG of the project made recommendations on preferable accident scenarios and SAM actions
- MUSA is explicitly looking at Source Term figures-of-merit, and there at environment release

Partners choices in WP5 (1/2)

- MUSA allowed the 'broadest possible' variety of choices
  - Reactor types: PWR Gen II+III, VVER, CANDU, and BWR
  - SA codes: AC^2, ASTEC, MAAP, MELCOR, RELAP/SCDAP
  - UQ tools: Dakota, Raven, Sunset, SUSA, Uranie, (KATUSA, MOCABA)

  - Risk-dominant accident scenario: SBO, LOCA, SGTR
  - Assumptions on availability of emergency systems and SAM actions

  - Definition of parameter uncertainty in the modelling, i.c./b.c., SAM actions
  - Selection of ST-related Figures-of-Merit
  - Post-processing of data and presentation of results

Partners choices in WP5 (2/2)

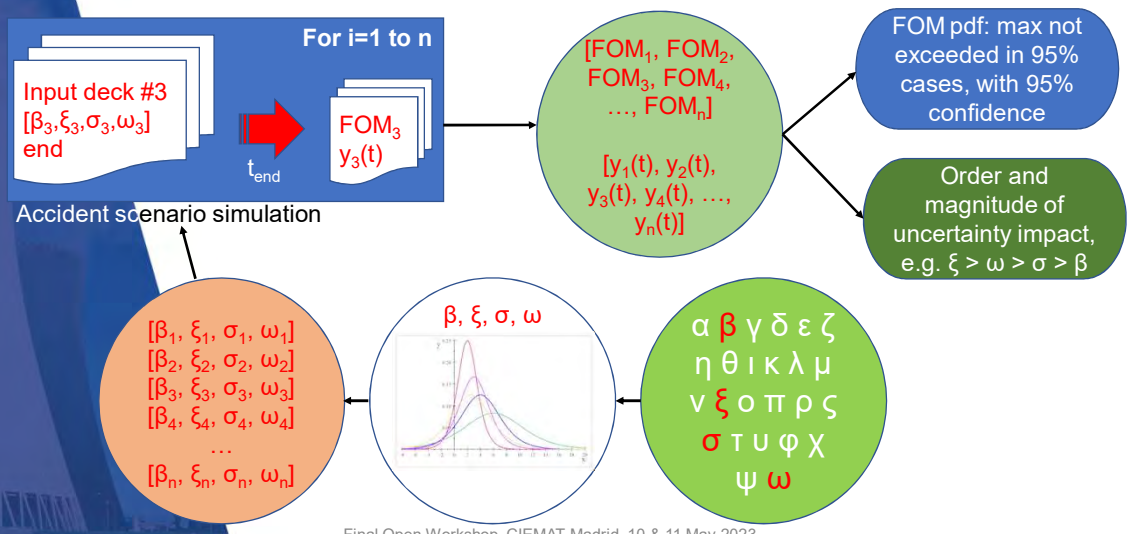
- Consequences of the 'broadest possible variety' approach
  - Maximum trust in the partners for innovative freedom
  - The need for many meetings as a forum for exchange: 4 subgroups established along reactor type, 8 meetings/subgroup
  - Possibly a lack of guidance that some partners would have appreciated
  - Many partners said that they invested a larger effort than planned

  - A great variety of results; few cases where results could be compared
  - Some innovative results
  - Recurring challenges of applying BEPU analysis

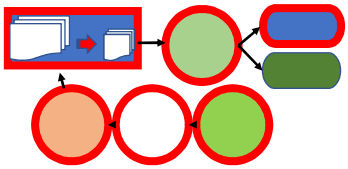
Elements of the approach

- Selection of uncertain parameters in the input deck
- Definition of uncertain-parameter pdf
- Sampling of parameter values according to pdf
- Propagation of uncertainty by running SA code
- Code results for all runs provide a sampled output
- Based on proper assumptions, statistical methods can be applied to the sampled output
  - Uncertainty analysis: establishment of tolerance limits
  - Sensitivity analysis: impact of input uncertainty on FOM

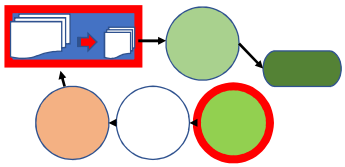
Elements of the approach - graphical



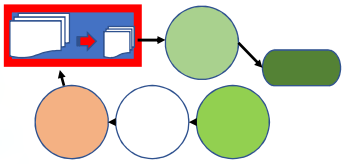
Categories of partners' analyses



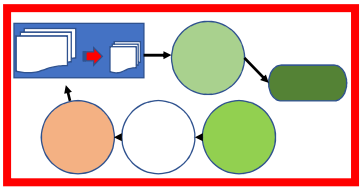
Tolerance limits (1-2)



Modelling improvements (~3)



Scenario investigations (~7)



BEPU method exploration

Insights and results introduction

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D5.1 – Results of uncertainty assessment of Source Term released to the environment

- All partners have carried out uncertainty and sensitivity analyses for their case, and have identified and solved challenges on the way
- The 8 cases shown in the following are a personal selection, and can only reflect a fraction of the work done
- The work, including the reports of all partners on their contribution, will be summarised in 3 public deliverables of the work package

Documented contributions to WP5

Organisation	Reactor	SA scenario	SAM strategy
CNPRI	HPR1000	LLOCA	
KAERI	APR1400	C-SGTR induced by SBO	
KIT	KONVOI	MB-LOCA plus SBO	Filtered venting
BELV	PWR-1000	LB-LOCA	
ENEA	PWR-900	SBO	
CIEMAT	PWR (Surry)	SBO	
PSI	PWR-1100	SBO plus SGTR	Fixed-time SG re-flooding
GRS	KONVOI	MB-LOCA plus SBO	
IRSN	PWR-900	SBO plus loss of aux. FW	Fixed-time sump flooding, CFVS
EPRI	PWR (Surry)	ELAP w/o+ w/ mitigation	Un-mitigated vs. AC restored at RPV failure
TRACTEBEL	PWR-1000	SBO	UA for triggering CSS, DCIS, PPORV, CFVS
FRAMATOME	KONVOI	MB-LOCA plus SBO	Filtered venting
ENSO	PWR 4-loop	LT-SBO at low pressure	
INRNE	VVER-1000	LB-LOCA 850mm, SBO	Core quenching at SAMG criterion
CNSC	CANDU-6	LB-LOCA; SBO	
N.IN.E	VVER-1000	LB-LOCA plus SBO	
TUS	VVER-1000	LB-LOCA 300mm, SBO	
SSTC	VVER-1000	SBO	UA for Pressurizer PORVs
Energorisk	VVER-1000	LB-LOCA plus SBO	
LEI	BWR5-LIKE	LB-LOCA plus SBO	
JAEA	BWR4 Mark1	SBO	UA for CFVS, DC water injection
VTT	BWR4 Mark1	SBO	Fixed-time wet-well venting
SAPIENZA	BWR4 Mark1	SBO	Pressure-based wet-well venting
JACOBS	ABWR-LIKE	SBO	UA for triggering/flow rate of High-Pressure Core Flooder

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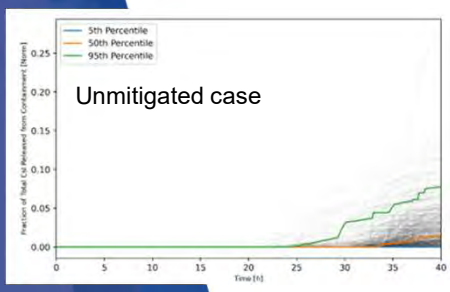
Insights and results (1/8)

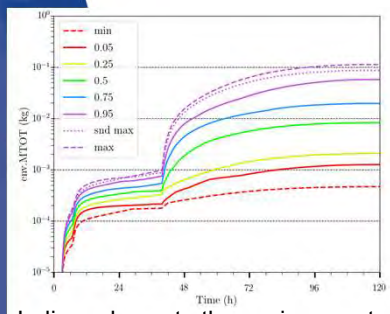


Fraction of CsI released to the environment

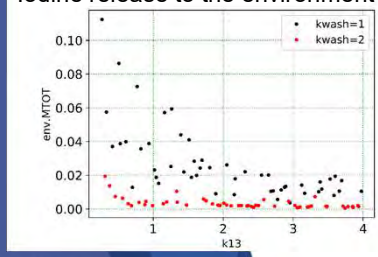
- PWR (Surry), ELAP w/ and w/o SAM (AC restored at RPV failure)
- 232 UIP, database of parameter uncertainty, 500 runs, no crashes
- Using Wilks, the confidence of the and tolerance limit for CsI could have been calculated, e.g. for t_{end}=40h
- Impact of model form switches
  - Sideward relocation in core enabled y/n
  - Mass and energy transfer between gases and pools in cont. is calculated y/n
- … followed by aerosol properties

EPRI

Insights and results (2/8)



Iodine release to the environment

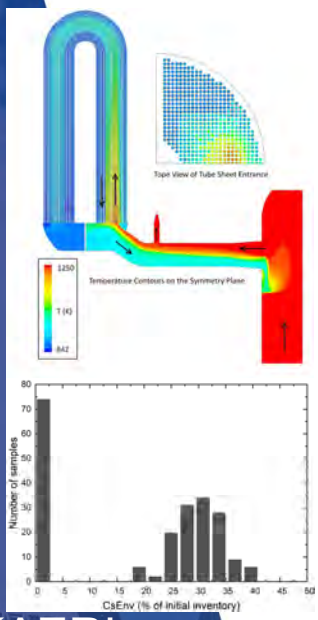


k13: CH3I radiolysis in gaseous phase

- PWR-900, SBO plus loss of aux. FW (Fixed-time sump flooding, CFVS)
- Focus on FP transport in containment
- Base case all-modules calculation
- Analysis innovative in simulating the ex-vessel phase, and parameterizing boundary conditions from in-vessel phase
- Substantial reduction of computational effort
- One governing UIP is model form switch “kwash”

IRSN

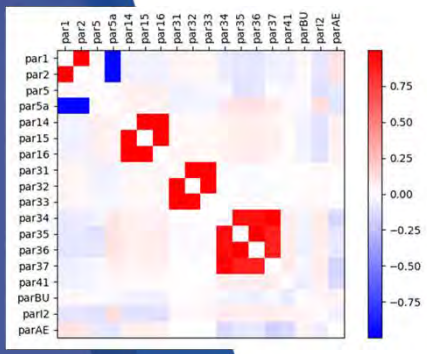
Insights and results (3/8)



- Competing creep failure of hot leg and SGTs following an SBO in an APR1400
- SAM action: depressurize secondary, uncertain delay on valve triggering time
- Bifurcation of results:
  - SGTR first,
  - HL/SL rupture first and w/ SGTR
  - HL/SL rupture w/o SGTR => no release
- Governing uncertainty for Cs release to environment:
  - Mixed steam fraction in SG inlet plenum
  - Depressurization delay (SAM action)

KAERI

Insights and results (4/8)



Corrected UIP correlation matrix

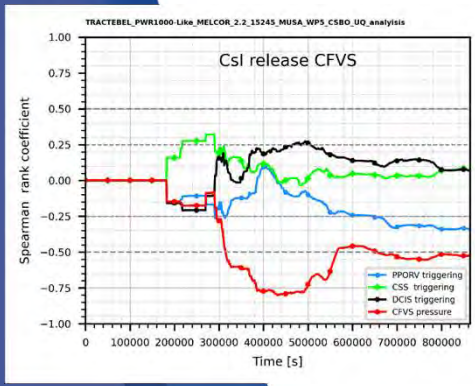
- KONVOI, MBLOCA+SAM (CFVS)
- Application of Iman-Conover method to re-order sampled values, to reflect correlation among some UIP
- Suggestion the pre-correlation measure can lead to less code crashes
- Parameter uncertainties dominating Iodine release
  - Fuel burn-up
  - Containment leakage
  - Filter efficiency
  - Aerosol properties (containment)
  - Aerosol behavior (containment)

KIT/Framatome

Insights and results (4bis/8)

- par1/par2 are surface-to-volume (S/V) correction factors for the fuel pellet that reflect effects of the pellet's surface roughness, and of limited steam access to the pellet; the correlation is positive
- The increase of the mean diameter of the grain (par5a) should correspond to a reduction of the S/V ratio of the fuel pellets; par5a is negatively correlated to par1 and par2
- Concerning integrity of the fuel pin, an increase of the temperature threshold for the dislocation of the cladding (par14) should be consistent with the increase of the temperature threshold of the dislocation of the oxide layer (par15) and then of the minimum limit for the thickness of the oxide layer (par16). These 3 parameters are assumed to be pre-correlated.
- As to the aerosols produced, an increase of the minimum particle radius (par34) is expected to be directly pre-correlated with the maximum particle radius (par35). Furthermore, par34 should be directly pre-correlated with the shape factor of the particles (par36 and par37), since a large particle radius should make the particle shape approaching a sphere (par36=1 and par37=1)

Insights and results (5/8)



- PWR 1000, complete SBO, 10 days
- Available: passive accumulators
- SAM action by PPORV, CSS, DCIS, CFVS
- Discrete triggering times, pressure
- Uncertainty in CsI release through the CFVS is dominated by
  - PPORV delay, that affects the activation of the accumulators
  - CFVS activation pressure

Tractebel

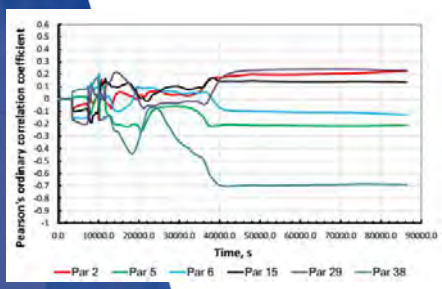
Insights and results (5bis/8)

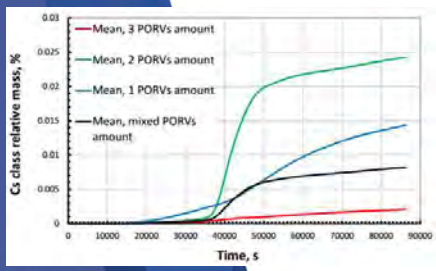
- Definition of SAM action uncertainty

11	PPORV opening time PRZ Power Operated Relief Valves	CET +700s	TIME=CET+[700.,1000., 1200., 2000., 3000., 4000., 5000.]	random/ choice	SCENARIO	WP2
12	CSS triggering time	Time= VF	Time = VF+ [0.0, 5000.,10000., 15000.,20000., 25000., 30000., 40000., 1.0E6]	random/ choice	SCENARIO	WP2
13	DCIS triggering time Direct Cavity Injection System	Time= VF+1800s	Time = VF+1800+ [0.0, 5000.,10000., 15000.,20000., 25000., 30000., 40000., 1.0E6]	random/ choice	SCENARIO	WP2
14	CFVS opening pressure	P=4,5 bar_a	[4.0E+5, 4.5E+5, 5.0E+5, 5.5E+5, 6.0E+5]	random/ choice	SCENARIO	WP2

Tractebel

Insights and results (6/8)

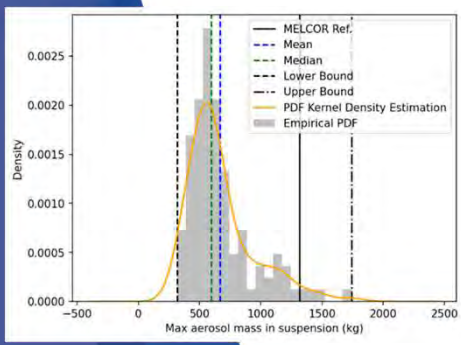




- VVER-1000, SBO
- FOM: Cs release to the environment
- SAM actions:
  - PORV
    - no. available (1,2,3) (Par 38)
    - Delay 0-2700s after CET>450°C
  - CFVS: opening pressure setpoint
- Cs release dominated by PORV availability
- When running BEPU analyses for fixed no. of PORV, 2 PORVs mean Cs release is 70% higher than w/ 1 PORV

SSTC

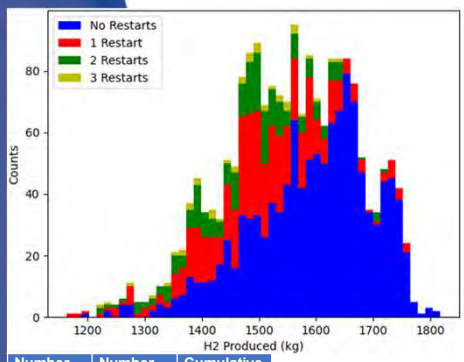
Insights and results (7/8)



- PWR-900, SBO
- FOM shown: peak value of the aerosol suspended mass in the containment's atmosphere
- Work highlights that non-standard FOM can be defined to address particular concerns (here: a danger potential)
- Dominating uncertainties
  - Aerosol agglomeration parameters gamma, chi

ENEA

Insights and results (8/8)



Number of Restarts	Number Passed	Cumulative Pass Rate (%)
0	1554	61.8
1	570	84.5
2	247	94.3
3	93	98.0

- Investigation into: bias caused by abandoning crashed simulations
- The figure shows bias in the sampled distribution of an output
- Many other partners checked only input variable values for visual signs of correlation with crashes

Jacobs

Major challenges

- Practical challenges
  - Computing effort (run time, data volume)
  - Code crashing and ways to recover
  - Coupling of UQ tools an SA codes => Python solutions
- Methodical challenges
  - Bias quantification (model simplification, recovering crashes, sampling, etc.)
  - Defining suitable uncertainty distributions
  - Post-processing/sensitivity analysis limited to linear correlations
  - At this stage, overstressing of tolerance limits

Conclusions on SAM

- SAM action uncertainty can readily be implemented in uncertainty propagation
- Uncertainty in SAM actions can provide insight into complex scenarios
  - SSTC on availability of PORVs
  - KAERI on competing creep failure of HL/SL and SGT
- Can help rank different actions the impact of their uncertainty on specific FOM
  - Tractebel analysing a scenario where PPORV, CFVS triggering uncertainty dominates DCIS, CSS

Conclusion: Impact of SAM uncertainty on BEPU analysis

- Reminder: SAM action with uncertainty are selected to mitigate ST release (even SAM actions with a fixed trigger drastically change the course of the accident)
- SAM action dominance in BEPU analysis is confirmed by results
- Dominance of SAM action hides the effect of other uncertain variables
- Whether SAM actions' uncertainty is included should be determined by the objective of an analysis

Conclusions

- A broad range of applications has been carried out
- The objective of an application should be clear to define the extent of the work
- Further work is required to fully explore, but also harmonise, BEPU application
- More proof is needed that assumptions of the statistical method are met => that the sampled FOM distribution is unbiased
- Thanks to all contributors to this work package – results are documented in 3 public deliverables

Thank you for your attention.

Questions?

MUSA

Uncertainty Quantification: Application to Spent Fuel Pool (SFP)

10-11 May 2023

Olivia Coindreau (IRSN), T. Lind (PSI) &
M. Massone (ENEA)

MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

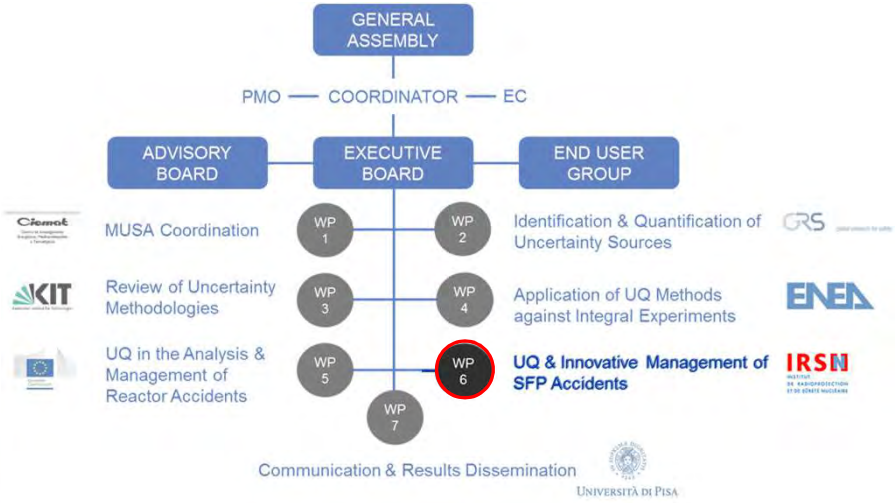
Content

- Motivation and groundwork
- Insights and results
- Conclusions

Motivations for SFP application

- To quantify and rank the uncertainties affecting SFP accident analyses, up to the RC, by applying UQ methodologies
- To review existing or contemplated SAM mitigation measures and systems in SFP worldwide
- To assess the possible benefits of mitigation measures in terms of reduction of radiological consequences

Groundwork, participants



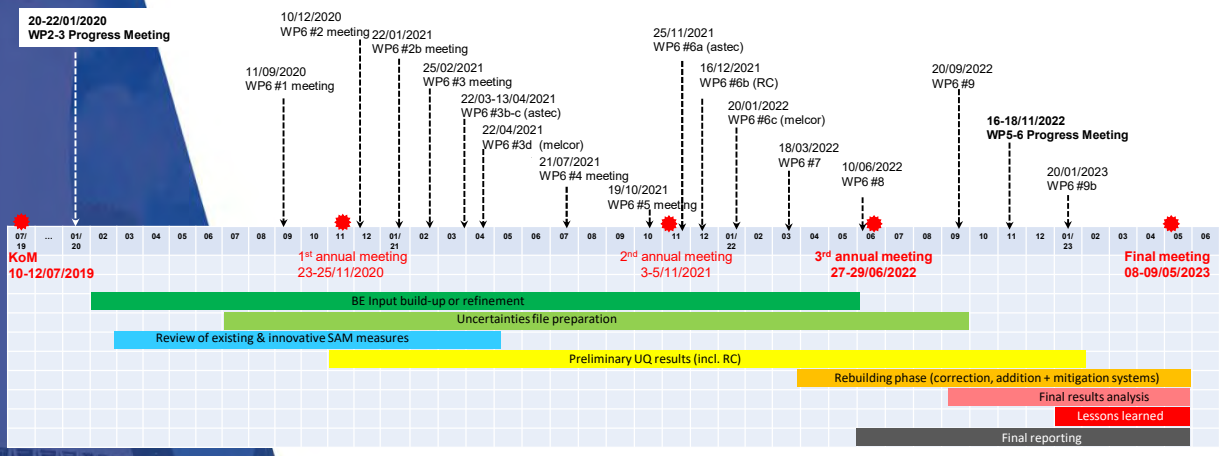
Groundwork, participants

Tools used (SA code uncertainty tool radiological consequences)

CIEMAT	MELCOR 2.2 DAKOTA
CEA	
ENEA	ASTEC RAVEN JRODOS
Energorisk	MELCOR DAKOTA
INRNE	ASTEC SUNSET
IRSN	ASTEC R SYMBIOSE
LEI-A	ASTEC SUNSET HOTSPOT
LEI-R	RELAP/SCDAPSIM SUSA
PSI	MELCOR 2.2 DAKOTA
SSTC	MELCOR SUSA
TUS	ASTEC SUNSET
UNIRM1	MELCOR 2.2 RAVEN MACCS
~~CNPRI~~	~~ASTEC SUNSET~~
~~CNSC~~	~~MAAP-CANDU / MELCOR~~
~~EPRI~~	~~MAAP5 DAKOTA~~
~~KAERI~~	~~MELCOR or in-house computer~~
USNRC	~~MELCOR~~

Reallocated to WP5
137,5 pm →109,5 pm

Overview of the meetings & planning



Main outcomes in WP6.1

To quantify and rank the uncertainties affecting SFP accident analyses by applying UQ methodologies ⇨ The different steps required to carry out the UaSA have been completed

- selection of an accidental scenario
- creation of an input deck and check of its consistency
- determination of uncertainty sources in models
- choice of key target variables as ST FoMs
- uncertainty quantification and sensitivity analysis with the use of UQ-tools to propagate input uncertainties

Main outcomes in WP6.1

- selection of an accidental scenario
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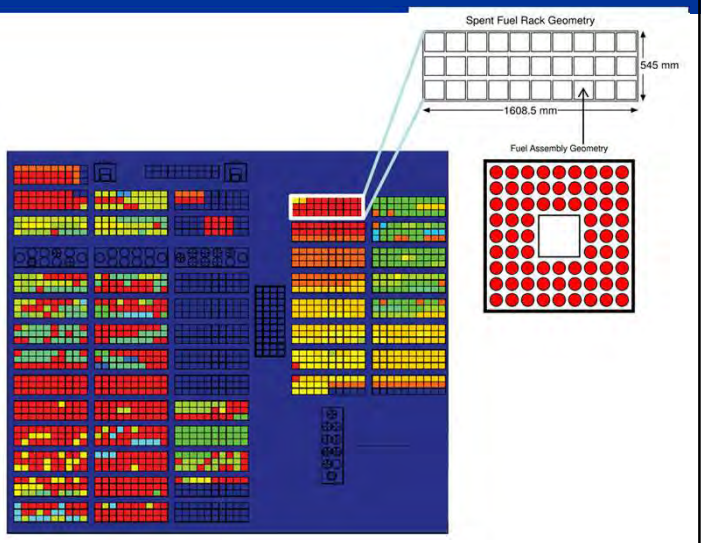
Selection of a scenario (1/3)

Geometry identical to the unit 4 of Fukushima Daiichi with simplifications*

Dimensions: 12.2 m × 9.9 m
Heat load: 2.4 MW
1535 FA: 548 hot (3,47 kW/FA), 783 cold (0,507 kW/FA), 204 non irradiated

Loss-of-cooling scenario with a computation starting at the onset of fuel uncovery and ending at the onset of fuel melting. The criterion to stop the computation is a fraction of relocated (liquefied or debris) greater than 1-3 %

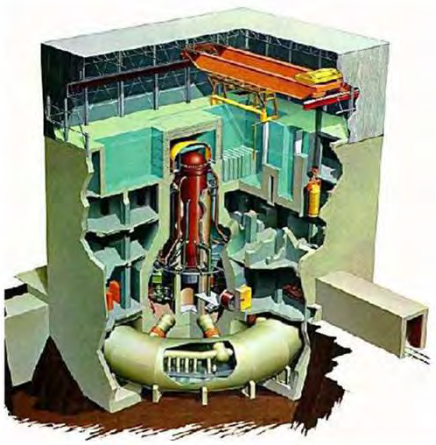
* See NUGENIA+ AIR-SFP project [May 2015-Sept 2016]



Selection of a scenario (2/3)

FP inventory: provided to the participants, assuming a cooling time for hot (resp. cold) FA's of 3.7 months (resp. 3.15 years), a burnup of about 21 MWd/kg (resp. 42 MWd/kg) with a remaining enrichment of about 2.03 % (resp. 0.77 %)

Modelling domain: only the pool or the pool and the building above the SFP (46 m length, 34.2 m width and 16.4 m height and a 10 m^2 opening of the fuel pool area outwards in order to avoid pressurization)



Selection of a scenario (3/3)

Conclusions:

- Simplified scenario based on the unit 4 of Fukushima Daiichi
- Approach for long-time discussed:

Modelling domain: each partner free to decide if its modelling includes or not the SFP building ⇨ **Conclusions of the UaSA will depend on this choice**

Temporal domain: as large FP releases are practically eliminated, the computation ends at the onset of fuel melting ⇨ as il will be shown later, it leads to **stop the computation during fast-transient heating and FP release: must be taken into account for the UaSA**

Main outcomes in WP6.1

- selection of an accidental scenario
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Elaboration and analysis of the reference case (1/5)

Some difficulties encountered during the elaboration of the input data deck:

- ✓ Setting the specified decay heat in MELCOR computations was not straightforward,
- ✓ The model for radiative heat exchanges in cores with sub-channels recently developed in ASTEC was not operational,
- ✓ Crash in MELCOR computations when using the SFP-BWR type of reactor (radiative model)

Diversity among partners:

- ✓ Modelling domain (building modeled or not)
- ✓ Ending criterion: 1 to 3% relocated fuel (liquefied or debris)

Objectives:

- ✓ Check the consistency of the input data deck before performing the UaSA, improve the input data decks, correct some mistakes
- ✓ Have a good understanding of the physical phenomena occurring during the accidental scenario
- ✓ All participants were asked to fill xls files with their results (but not a benchmark!)

	Maximum cladding T° at (h)				1% reloc. fuel (h)	Mass of water in the SFP at (h)				
	500 K	1000 K	1500 K	2000 K	end of the sim.	400 t	300 t	200 t	100 t	50 t
Institution name										

Start of (h)			At the end of the simulation						
H2 Prod°	Gap release	Mass relocation	Collapsed WL (m)	H2 prod° (kg)	Magma / debris (kg)	release from fuel (% I.I.)			RC metric (-)
						Cs	Ru	Sr	

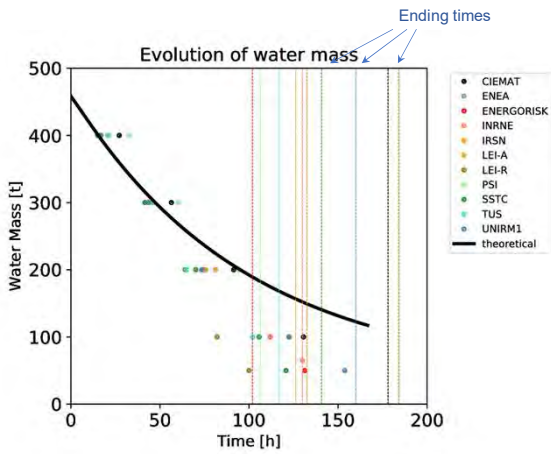
Elaboration and analysis of the reference case (2/5)

Before 50 h:

- ✓ Some results differ from the theoretical curve
- ✓ Differences can be due to **differences in heat loss and heat transfer modelling between the pool and the building**: importance of assumption made concerning the SFP building (inclusion or not & nodalization of the SFP building, …)
- ✓ **Axial nodalization** can significantly impact the results
- ✓ The **use of the 5 or 6 equations modelling for diphasic thermal-hydraulics in ASTEC computations** also impact the results
- ✓ Differences were observed between **MELCOR computations carried out with different decay heat modelling**

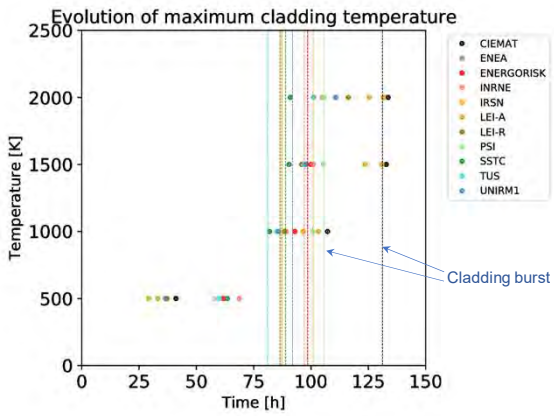
After 50 h:

- ✓ **Increase of ≠** between the theoretical curve and the computations: oxidation, material relocation, radiation, …come into play
- ✓ Differences between computations increase as well as more phenomena come into play



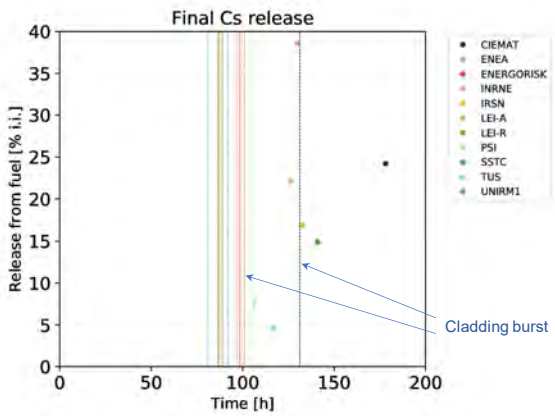
Elaboration and analysis of the reference case (3/5)

- ✓ The maximum **cladding temperature is stable until approx. 1 m of fuel assembly is uncovered.** Then, the temperature of the **uncovered part of the FAs increases regularly** in a first time
- ✓ **The burst of hot FAs' occurs** more than 80 h after the beginning of the transient
- ✓ The **heating of cold FAs' is strongly linked to the nodalization and radiative heat transfer** between hot and cold FAs (cladding of cold FAs burst or not)
- ✓ An **exponential temperature** rise is observed when the cladding has reached a temperature at which **oxidation starts to be significant** ⇨ loss of integrity
- ✓ Depending on the amount of relocated material and on the criterion chosen to stop the computation, the computation ends or continues ⇨ leads to **significant differences in computation end times**



Elaboration and analysis of the reference case (4/5)

- ✓ **First FP release (gap release) occurs when the cladding of hot fuel assemblies' bursts** (more than 80 h after the beginning of the transient)
- ✓ **Intensity of these first releases depend on the amount of FP put in the gap and the number of failed FAs**
- ✓ **Fast FP release** from the fuel matrix when the **exponential temperature rise is observed**
- ✓ If (relatively) high temperature are maintained for a long time without reaching the criterion ⇨ leads to significant differences in releases
- ✓ **Most of release occurs at the end of transient** and the final amount is strongly impacted by the criterion chosen to stop the computation.



Elaboration and analysis of the reference case (5/5)

Conclusions:

Analysis of the reference case computations has put in evidence differences between the results:

- In the **TH behaviour**, right from the beginning
- In **FA heating & degradation**… leading to different ending times
- In **FP release**… differences in the amount of FP released at cladding failure

These differences can be due to:

- **different nodalizations**: number of radial rings, number of axial meshing
- **different SA codes**
- **different physical modelling options** (within the same SA code)

⇨ **Establishing good quality reference case is an important part of UQ analysis**

⇨ **Some improvements have been done in the meantime by code developers**

Main outcomes in WP6.1

- selection of an accidental scenario
- creation of an input deck and check of its consistency
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- choice of key target variables as ST FoMs
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Determination of uncertainty sources (1/2)

As presented in SESSION 2:

- Uncertainty quantification limited to the **modelling uncertainties** in this part

- **SA codes have strong limitations** when they are applied to SFP:
  - ✓ one mean FP inventory distributed in the modelled groups of FAs (and possibly FP grouped by classes for the MELCOR code)
  - ✓ radiation model not operational for SFP configuration
  - ✓ 3D flow patterns & stratified configurations not properly simulated
  - ✓ models developed for conditions representative of reactor scenarios and not for SFP conditions (slower temperature rise and long-standing chemical interactions)

- **Only a part of the uncertainty can be evaluated**

determination of uncertainty sources (2/2)

1. Thermal-hydraulic in the pool
2. Power generation
3. Heat transfer
4. FAs behavior and degradation
5. FP release and transport
6. Thermal-hydraulic in the SFP building
7. Material properties

Organisation	SA code	UQ-tool	Nb of u.p.	1.	2.	3.	4.	5.	6.	7.
CIEMAT	MELCOR	DAKOTA	15				*	*		
ENEA	ASTEC	RAVEN + Python script	21	*			*	*		
Energorisk	MELCOR	DAKOTA	8			*	*			
INRNE	ASTEC	SUNSET	7				*	*		
IRSN	ASTEC	R + Python script	18				*	*		
LEI - ASTEC	ASTEC	SUNSET	12			*	*	*		
LEI - SCDAP	RELAP/SCDAP	SUSA	25			*	*			*
PSI	MELCOR	DAKOTA	15	*		*	*			
SSTC	MELCOR	SUSA	24	*		*	*	*		
TUS	ASTEC	SUNSET	7				*	*		
UNIRM1	MELCOR	RAVEN	25				*	*		

Main outcomes in WP6.1

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FoM

Criteria to chose the FOM (output variables)*:

- **ST driven ⇒ only variables linked to FP release into the environment have been selected**
- **Simple evaluation of radionuclides with greatest radiological impact ⇒ most contributing isotopes are Sr90, Cs137, Cs134, Ru106, Ce144, Sr89, Ba137m and Ru103**

List of FOM:

1. **Total release of Cs, Ru and Sr from fuel [mass fraction of the i.i.]**
2. **Onset time of FP release from fuel [h]**
3. **Total release into environment from SFP building of Cs, Ru and Sr** [mass fraction of the i.i.]**
4. **Total Ruthenium release in gaseous form to environment** [mass fraction of the i.i.]**
5. **Dose due to isotopes with the greatest radiological impact relative to that of total release of Cs137 [fraction]**

Main outcomes in WP6.1

- selection of an accidental scenario
- creation of an input deck and check of its consistency
- determination of uncertainty sources in models
- choice of key target variables as ST FoMs
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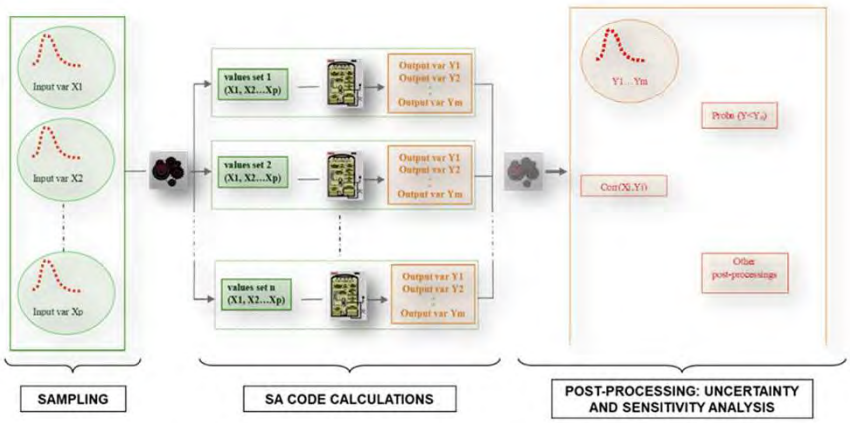
Uncertainty quantification (1/6)

Probabilistic propagation of input uncertainties (see SESSION 3)

- Propagation of input uncertainties
- Application of a statistical method to the data

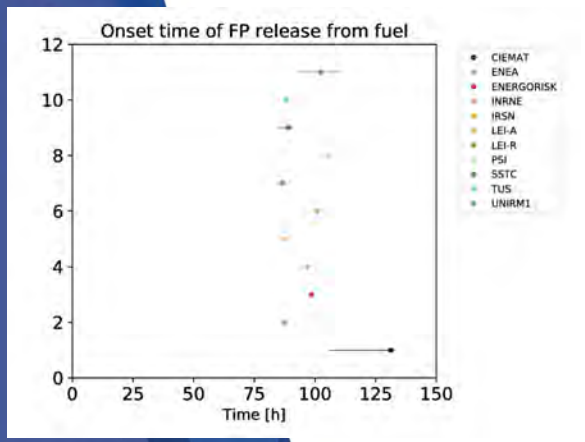


Uncertainty quantification(2/6)

Statistics indicators for the uncertainty analyses of the FoMs:

Dispersion plots	Evolution of a FoM for all runs: enables the visualization of the spreading of the results
Minimum, maximum values	At given transient times (generally the ending time) or as a function of time
Mean, median, standard deviation	
Cumulative density function (CDF), probability density functions (PDF)	At given transient times (generally the ending time)
Quantiles	Wilks formula: considering the number N of runs performed, we have the probability β (confidence level) that more than a fraction γ (probability content) lies between the min – max values ⇒ For a two-sided tolerance interval, a probability content and a confidence set to 95% and 95%, the minimum number of code runs is approximately 100

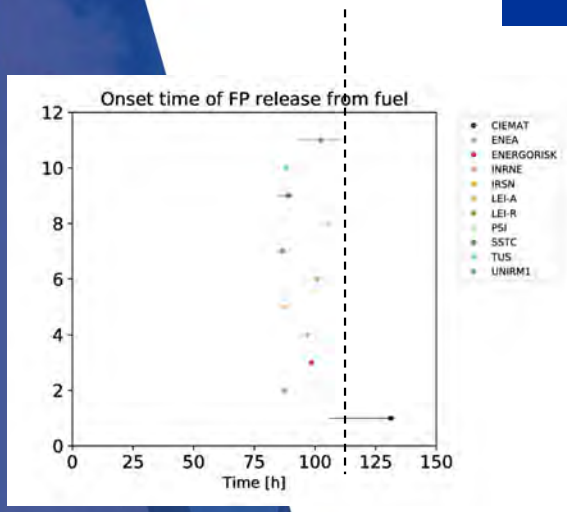
Uncertainty quantification (3/6)



- The **onset times of FP release** for the reference case are in **relatively good agreemeent** between the computations
- **But its uncertainty range strongly differ:**
  - ✓ very small when cladding rupture is computed by the code
  - ✓ more important when cladding failure temperature is an u.p.

⇨ **Some u.p. linked to the cladding burst modelling should have been considered**

Uncertainty quantification (4/6)

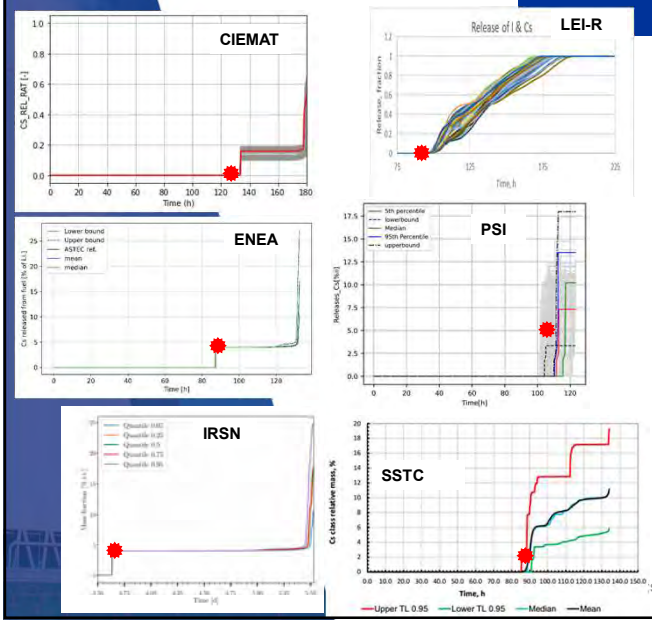


Despite cladding failure is in rather good agreement, **FP release soon after cladding rupture is not!**

- **Gap inventory and/or amount of failed rods are different**
- **The delay between onset time of FP release** (cladding rupture temperature) **& onset time of large FP release** (excursion temperature) are **significantly different** between the computations

Dispersion plots, min/max, mean & percentiles for Cs release from fuel

Uncertainty quantification (5/6)



- Simulations with a delay between the cladding rupture and the fast temperature rise: **uncertainty on Cs release very low at cladding rupture**
- If this delay is long, it raises question about FP release: use of the Booth diffusion model that describe FP diffusion through the fuel grain to the grain surface at high T°. **What about release at lower T° (FP in the intergranular zone)?**
- The **uncertainty increases at the end of the simulation**. In particular if:
  - u.p. linked to FA degradation affects the final thermal-behaviour
  - long-standing at high T° that drives Cs release
  - the fraction of relocated fuel to stop the calculation is important

Uncertainty quantification (6/6)

Conclusions:

- Due to the ending time selected, the computation stops during a fast temperature and FP release increase. **The statistical analysis at the final time can be very different from that performed during the long-lasting transient**.
  - ⇨ **Analysis of the whole sequence, and not only the final time step, is more meaningful**
- Use of the Wilks formula require some constrains [Porter, 2019] that are not met in SFP calculations**:**
  - ✓ code uncertainties are quantified and minimized
  - ✓ no calculation failures
  - ✓ all input parameters relevant for code results are considered
  - ✓ distribution of uncertain input parameters is well known
  - ⇨ **UQ performed in WP6 cannot be considered as quantitative**
- Even if not quantitative, uncertainty propagation enables:
  - ✓ to **quantify the spreading of SA code** responses when varying some input parameters
  - ✓ to see **how the dispersion evolves through the transient** and if a phenomenon gives rise to spreading
  - ✓ to see that the **variability in FP release timing coming from the UQ** is relatively small when compared to the variability between reference computations of all participants, indicating that **u.p. and/or models are missing**

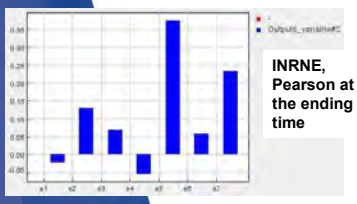
Sensitivity Analysis (1/6)

Statistics indicators for the uncertainty analyses of the FoMs:

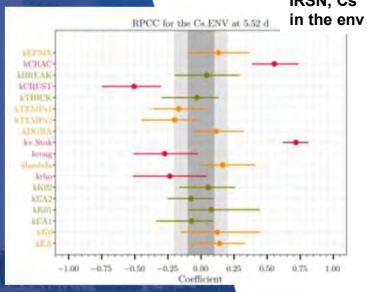
Correlation coefficients: **Pearson (values)** **Spearman (ranks)**	Statistical correlation between the u.p. and the FoMs: a correlation coefficient close to 1 (resp. -1) indicates a positive (resp. negative) linear dependence At given transient times or as a function of time
Scatter-plot of FOMs vs. input uncertain parameters	At given transient times
Simple (linear) and Polynomial regressions	
Advanced feature selection techniques	stepwise backward elimination, stepwise forward selection, and LASSO regularization

Sensitivity Analysis (2/6)

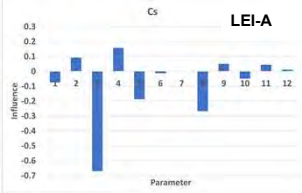
Spearman coefficient for Cs release from fuel



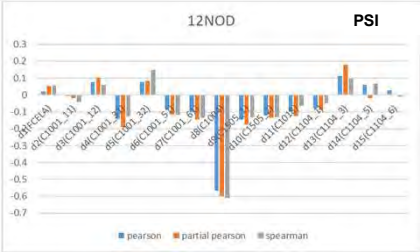
INRNE, Pearson at the ending time



IRSN, Cs in the env



LEI-A

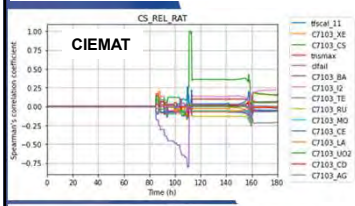


PSI

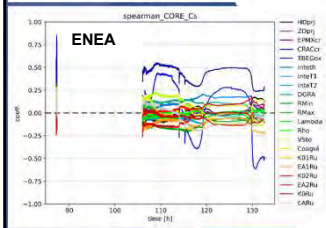
Some analyses carried out at the ending time…

Sensitivity Analysis (3/6)

Spearman coefficient for Cs release from fuel

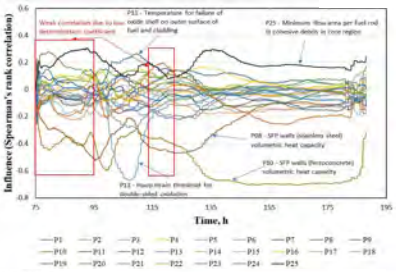


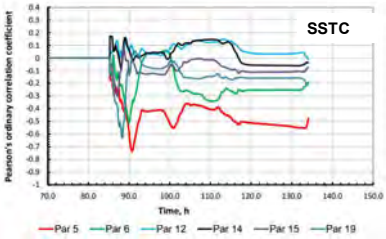
CIEMAT



ENEA

LEI-R

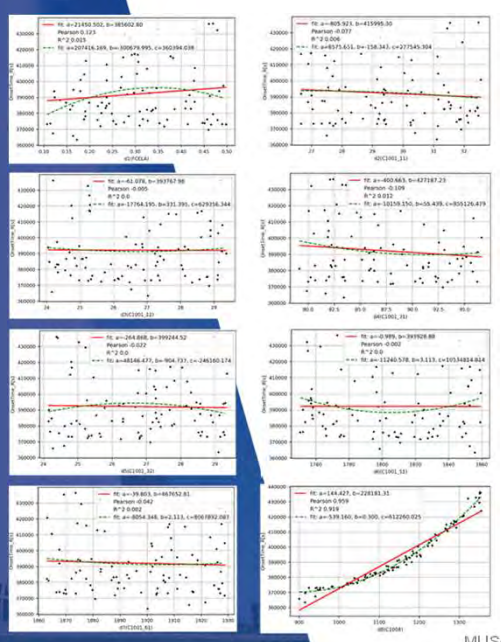




SSTC

- **The correlation coefficient strongly evolves with time** ⇨ analysis at the ending time (only) is very restrictive!
- **An u.p. can be the most important one but only for a while**
- Due to the diversity of u.p. considered, **difficult to have generic conclusions…**
- **The sensitivity to degradation parameters is not straightforward:** u.p. that drives degradation should be positively correlated to Tmax and consequently to FP release… it is true until fuel relocation in colder regions!
- **The analysis seems to be easier for release in env.**

PSI



Sensitivity Analysis (4/6)

Some unexpected dependencies/cliff-edge effect put in light, supported by:

- **the analysis of single realizations**
- **the analysis of scatter plots**

Sensitivity Analysis (6/6)

Conclusions:

- **No « silver bullet » to conduct the sensitivity analysis, the use of several techniques is recommended**:
  - ✓ **Pearson and Spearman correlation coefficients** usually used to characterize the statistical correlation between the uncertain input parameters and the FoMs
  - ✓ **Scatter plots of FOMs vs. input uncertain parameters** always recommended to confirm or not the analysis, to identify the uncertain input parameters responsible of outliers & to identify cliff-edge effects
  - ✓ Scatter plots are generally sparse: difficult to characterize the relationship between FOMs and uncertain input parameters, **single sensitivity calculation by varying only one input parameter** is recommended for supporting the analysis.

- **Sensitivity Analysis is a helpful technique with limitations that must be beard in mind:**
  - ✓ Spearman and Pearson coefficients have been used…
    - **useful to determine most significant parameters** and order the input factors
    - **but strong limitations:** more advanced methods should be envisaged to overcome this limitation
  - ✓ The results obtained are strongly linked to the u.p. investigated and of the FoM considered… but very helpful in:
    - **identifying unexpected dependencies**, investigating the reasons of such behaviour and having a deeper understanding of the accident progression
    - **putting in evidence discontinuities and/or cliff edge effect** in a FoM and to determine which input modelling parameters is responsible of this behaviour

Main outcomes in WP6.2 & WP6.3

To review existing or contemplated SAM mitigation measures and systems in SFP worldwide

To assess the possible benefits of mitigation measures in terms of reduction of radiological consequences

Main outcomes in WP6.2 & WP6.3

Existing accident management measures:

- Restoration of SFP cooling
- Restoration of SFP water level
  - Design and alternative sources
- Isolation of the leak
  - Of the leak, failed SFP, fuel pool area
- Pool area venting
  - To maintain low pressure
- Spray – also using alternative systems
- Injection of an absorber

⇨ **Water injection by spray systems investigated in WP6.3**

No country / organization indicated additional planned or considered accident management measures

Main outcomes in WP6.2 & WP6.3

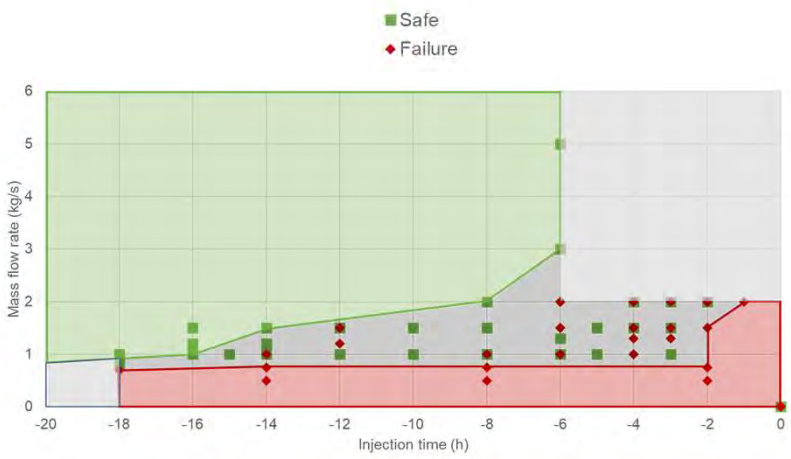
Sensitivity study on the SAM parameters:

- Determine a safe domain for injection time and mass flow rate
- Which flow rate and when to prevent cladding failure?

	Code used	Injection time (before failure)	Water flow rate	N. cases
ENEA	ASTEC 2.2.0.1 ASTEC 3.1	2 ÷ 14 h	0.5 ÷ 2.0 kg/s	20
INRNE	ASTEC 2.2.0.1	1 ÷ 16 h	1.0 ÷ 2.0 kg/s	12
IRSN	ASTEC	8 ÷ 12 h	1.0 ÷ 2.0 kg/s	10
LEI-A	ASTEC 2.2.0.1	0 ÷ 8 h	1.0 ÷ 2.0 kg/s	19
LEI-R	RELAP5/SCDAPSIM	0 ÷ 0.5 h	0.5 ÷ 2.0 kg/s	11
SSTC	MELCOR 2.2	5.9 ÷ 17.9 h	0.7 ÷ 5.0 kg/s	9
TUS	ASTEC 2.2b	3 ÷ 15 h	1.0 ÷ 2.0 kg/s	8

Main outcomes in WP6.2 & WP6.3

- 113 simulations performed by 5 institutions, covering large ranges of injection time and mass flow rate
- 1 kg/s injection is required regardless of the injection time - water injection should exceed evaporation
- Safe and failure regions have been identified
  - Unclear/unreliable results region has also emerged



https://authors.elsevier.com/a/1gn4x15hWOqpr7

Deliverables D6.1, D6.2 & D6.3

General Conclusions

- **We have learnt and shared a lot**: in uncertainties propagation, in the input data deck elaboration, in the physics of the accidental transient in the SFP
- This work has **raised questions about limitations, improvements still needed in SA when applied to SFP**
- We have faced challenges, for instance **High CPU Time** ⇨ need of HPC cluster
- Even if UQ is not quantitative, it gives interesting information
- The **UaSA is a long and iterative process**… what we would recommend is:
  - ⇨ UQ first with a maximum of u.p.
  - ⇨ Sensitivity analysis with less parameters

Thanks for your attention,

Thanks to all WP6 participants!

Uncertainties database for SFP (1/5)

Uncertainty sources divided in 5 categories*:

1) **Modelling uncertainties**
2) **Initial conditions**
3) **Boundary conditions (scenario)**

SFP design and accidental scenario will be set in WP6.1

4) **Boundary conditions (systems / SAM)** → impact of systems will be addressed in WP6.3
5) **Mesh, numerics** → mesh and numerics investigated separately

Uncertainties database for SFP (2/5)

Table of phenomena, closely linked to the models developed in most SA codes, divided in 7 groups:

1. **Thermal-hydraulic in the pool**
2. **Power generation**
3. **Heat transfer**
4. **Fuel assemblies behavior and degradation**
5. **FP release and transport**
6. **Thermal-hydraulic in the SFP building**
7. **Material properties**

Phenomena close to those that occur in reactor scenarios:

⇨ SA can be considered as sufficiently mature in terms of phenomena addressed and validation conducted

⇨ u.p. provided in the reactor table have usually been considered and put in the table of u.p.

Phenomena significantly different from those that occur in reactor scenarios

Uncertainties database for SFP (3/5)

Phenomena significantly different from those that occur in reactor scenarios [SOAR NEA 2015]:

FAs stored in storage racks and the walls of the storage cells may incorporate neutron-absorbing material	▪ Not axisymmetric geometry	Sensitivity study
	▪ Radiative heat transfer in SFP geometry	Sensitivity study
	▪ Significant ≠ of radioisotopic inventory between FAs	-
	▪ Neutron-absorbing material	Uncertainty Quantification?
FAs contained in a large structure	▪ 3D flow pattern	Sensitivity study
Much lower decay power	▪ Stratified configuration	-
	▪ T° rise slower than in the reactor case: can affect chemical interaction	Uncertainty Quantification?
At atmospheric pressure, surrounded by air	▪ Large amount of non-condensable gas: can affect condensation and vaporization process	Sensitivity study
	▪ ↗ oxidation rate of Zr cladding in air or steam/air mixtures	**Uncertainty Quantification**
	▪ Wider range of atmosphere composition: can affect FP release, especially Ru	Uncertainty Quantification?
Generally no containment, the cladding is the only barrier	▪ Importance of the gap inventory for the radiological consequences	Uncertainty Quantification?

⇨ **For most of these phenomena, the uncertainty quantification can not be achieved by the propagation of input uncertainties since:**

- **Input uncertainties are not properly quantified**
- **There is no suitable modelling**

Uncertainties database for SFP (4/5)

Table of phenomena, closely linked to the models developed in most SA codes, divided in 7 groups:

1. **Thermal-hydraulic in the pool**
2. Power generation
3. **Heat transfer**
4. **Fuel assemblies behavior and degradation**
5. **FP release and transport**
6. Thermal-hydraulic in the SFP building
7. **Material properties**

Phenomenon	SA code	Uncertain parameter	Distribution	
FP release	AST	DGRA: Average fuel grain diameter	Uniform distribution [2] Lower bound: 10 µm Upper bound: 14 µm	[2, 5]
	MEL	RN1_GAP02; CLFAIL: Gap release temperature	Uniform distribution [9] Lower bound: 1073 K Upper bound: 1273 K Triangular distribution [1] 1173 K +/- 200 K	[9] [1]
	MEL	RN1_CSC Xe (7103): CORSOR-Booth scaling factors	Uniform distribution [1] Lower bound: 2 Upper bound: 2	[1]
	MEL	RN1_CSC Cs (7103): CORSOR-Booth scaling factors	Uniform distribution [1] Lower bound: 2 Upper bound: 2	[1]
	MEL	RN1_CSC Ba (7103): CORSOR-Booth scaling factors	Triangular distribution [1] $3.20\ 10^{-1}$ - 5.4	[1]
	MEL	RN1_CSC I2 (7103): CORSOR-Booth scaling factors	Triangular distribution [1] 0.51 - 1.60	[1]
	MEL	RN1_CSC Te (7103): CORSOR-Booth scaling factors	Triangular distribution [1] 0.51 - 1.60	[1]
	MEL	RN1_CSC Ru (7103): CORSOR-Booth scaling factors	Triangular distribution [1] $2.50\ 10^{-1}$ - $4.0\ 10^{1}$	[1]
	MEL	RN1_CSC Mo (7103): CORSOR-Booth scaling factors	Triangular distribution [1] 0.05 - 5.5	[1]
	MEL	RN1_CSC Ce (7103): CORSOR-Booth scaling factors	Triangular distribution [1] $3.20\ 10^{-1}$ - $4.0\ 10^{1}$	[1]
	MEL	RN1_CSC La (7103): CORSOR-Booth scaling factors	Triangular distribution [1] $3.20\ 10^{-1}$ - $4.0\ 10^{1}$	[1]
	MEL	RN1_CSC UO2 (7103): CORSOR-Booth scaling factors	Triangular distribution [1] $2.56\ 10^{-1}$ - $1.20\ 10^{1}$	[1]
	MEL	RN1_CSC Cd (7103): CORSOR-Booth scaling factors	Triangular distribution [1] 0.20 - 1.0	[1]
	MEL	RN1_CSCAg (7103): CORSOR-Booth scaling factors	Triangular distribution [1] 0.128 - 0.8	[1]
	AST	FPEVOL-Cs: FP gap release at cracking occurrence	Uniform distribution [10] Ref: 0.005 Lower bound: ref - 20% Upper bound: ref + 20%	[10]
FP aerosol transport & deposition	AST	RMin: Particle minimum geometrical radius	Uniform distribution [4, 10] Ref: $1.0\ 10^{-6}$ m Lower bound: ref - 20% Upper bound: ref + 20% Normal distribution [6] Lower bound: ref - 10% Upper bound: ref + 10%	[4, 10] [2, 6]
	MEL	dmin: particle diameter, lower bound	Triangular distribution [1] $1.\ 10^{-6}$ - $2.\ 10^{-7}$	
	AST	RMax: Particle maximum geometrical radius	Uniform distribution [4, 10] Ref: $2.0\ 10^{-4}$ m Lower bound: ref - 20% Upper bound: ref + 20% Normal distribution [6] Ref: $2.0\ 10^{-4}$ m Lower bound: ref - 10% Upper bound: ref + 10%	[4, 10] [2, 6]
	MEL	dmax: particle diameter, upper bound	Triangular distribution [1] $5.\ 10^{-6}$ - $2.\ 10^{-5}$	
	AST	lambda: Particle mean thermal conductivity	Normal distribution [5] Ref: 3.5 W/mK Lower bound: ref - 50%	[2, 5]

Partner who provided the PDF. References can be found in Appendix

Parnter(s) who used the PDF for the UaSA

Different PDF have provided/used

PDF has been provided but not used

Small extract from the table of u.p.

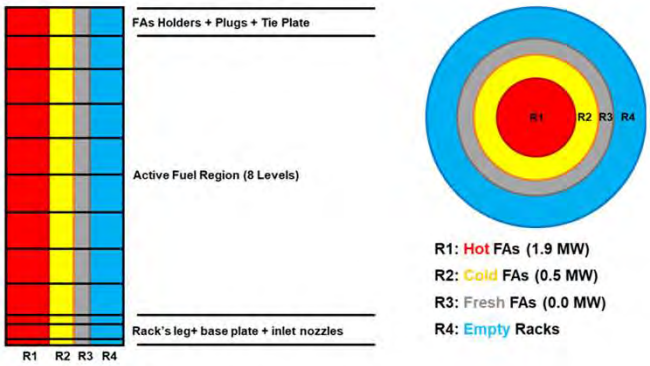
Uncertainties database for SFP (5/5)

Conclusions:

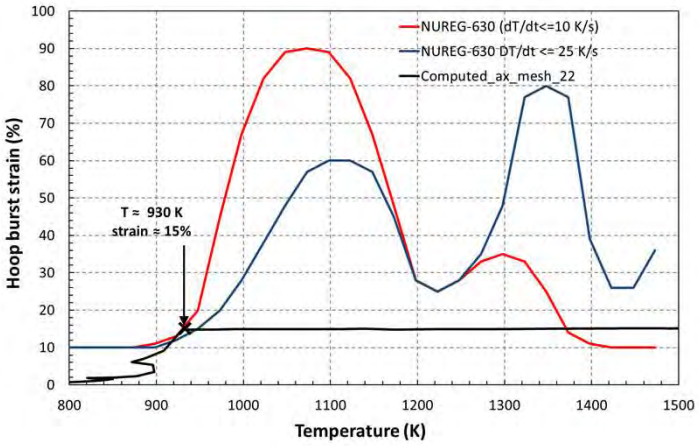
- Participants have listed the u.p. available to the user in the SA codes and filled the table with the names of the u.p., their description and their probability density function (PDF) - Usually, it was extracted from the reactor table
- 5 tables have been elaborated with all PDF provided and the list of participants that have used these PDF for the UaSA
- For some u.p., uncertainty distributions provided by the partners are different

⇨ **Additional and substantial work would be necessary to determine why different PDF have been provided and if important uncertain parameters are missing**

⇨ **It must be kept in mind that some uncertainty sources can not be accounted with the probabilistic propagation**



Configuration MUSA/SFP



Sensitivity Analysis (5/6)

Attend to rank u.p. & to determine governing uncertainties

⇨ Difficult for the reasons explained before

Input uncertain parameter	IRSN, metric at 5,52 days, RPCC
1.1.1	
1.3.1	
1.3.2	
3.1.2	
3.1.3	
3.1.4	
3.1.15	
3.2.1	
3.2.2	
4.1.2	
4.1.3	
4.2.2	
4.2.3	
4.2.4	
4.2.8	
4.2.9	
4.2.18	
4.4.2	
4.5.1	
4.5.10	
4.5.11	
4.5.12	
5.1.1	
5.1.2	
5.1.3	
5.2.2	
5.2.3	
5.2.4	
5.2.5	
5.2.6	
5.2.7	
5.6.1	
5.6.2	
5.6.3	
5.6.4	
5.6.5	
5.6.6	
Statistical significance	
	RPCC<0,1
	0,1<RPCC<0,2
	RPCC>0,2

RC

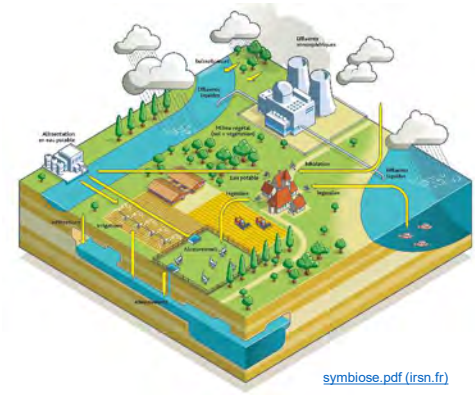
- **To develop the coupling between the SA code and the RC code**

1) SA computations: n ST
2) ST from SA code → input RC Tool
3) n RC computations
4) Post-processing

- **To have a global indicator and see how the uncertainty on the ST affects the uncertainty on the RC**

Can also be done thanks to the metric (dose relative to that of total release of Cs137 with the implicit assumption that dispersion affects all RNs equally):

$B = \text{Sum}\ (I_i\ R_i\ D_i)\ /\ (I_{Cs137}\ D_{Cs137})$



symbiose.pdf (irsn.fr)

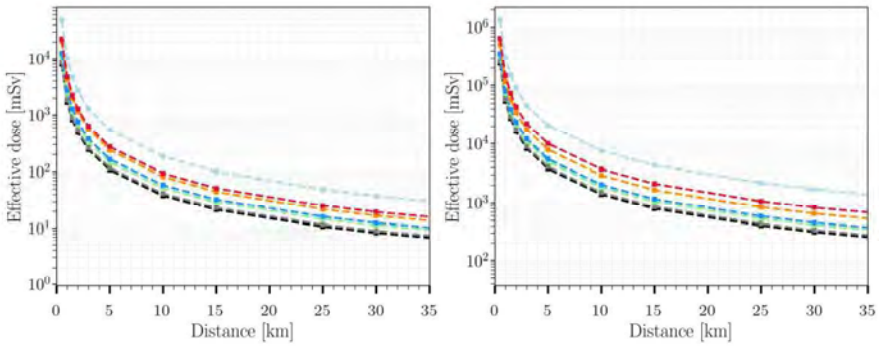
ENEA	ASTEC RAVEN RASCAL 4.3 JRODOS
IRSN	ASTEC R SYMBIOSE
LEI	ASTEC SUNSET RELAP/SCDAPSIM SUSA HOTSPOT
UNIRM1	MELCOR 2.2 RAVEN MACCS

RC

Input parameters	
Radionuclides	Sr90, Cs137, Cs134, Ru106, Ce144, Sr89, Ba137m, Ru103 (Coindreau, 2020 b). Release kinetics computed by the SA code
Ecosytems	Not specified
Population	Adult
Exposure scenario	Not specified
Meteorological conditions	Not specified
Distance	1 - 5 - 25 km
Period	10 d - (1 y)
Output parameters	
Dose	Total Effective Dose Equivalent (TEDE)

RC

IRSN Selection of 7 ASTEC runs corresponding to the percentiles 0,05 0,25 0,5 0,75 0,95 of the metric



Major Insights from MUSA

Luis E. Herranz (CIEMAT)

MUSA Final Open Workshop - Hybrid meeting; May, 10-11. 2023

MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

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General Statements

- **"We made it to the end",** across a hostile environment.
- **UaSA in SA** is, by nature, **a "joint work".**
- **Further exchange** would have brought MUSA to a different level.
  - Discussion of issues and challenges to overcome
  - Sharing expertise
- **MUSA is an "imperfect success"!** Much has been achieved!

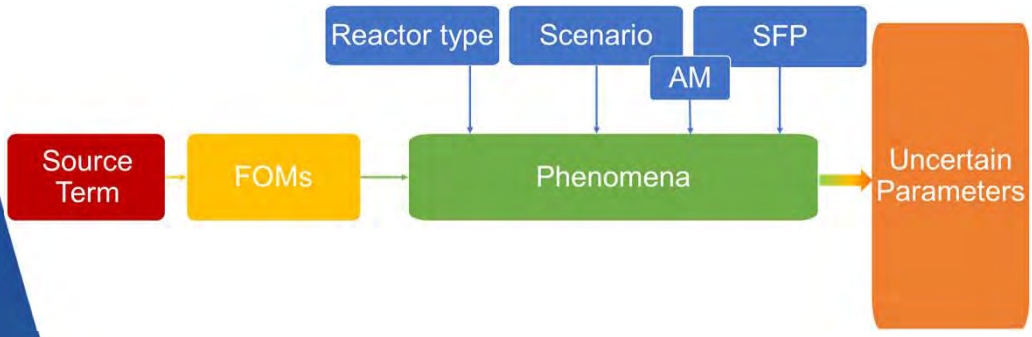
Major «Intangible» Achievements

- **A journey from an uneven to an "even" community:**
  "Diffusion driven by expertise & knowledge gradients".
- **A "grown" community in an "unexplored world"**
  "Team work" proved to be incredibly resourceful when working out of the comfort zone. (BaU)
- **An "empowered community" ready to give the best**
  Self-criticism, stamina to keep fighting, and an open mind to look ahead.

Major «tangible» Achievements

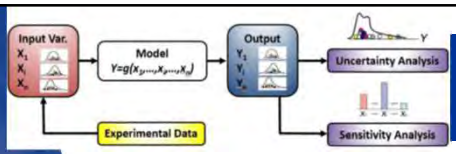
- **An extensive UP database!**
- **A vastly diverse tested range of methods & tools!**
- **A large variety of reactor & scenarios UQ database!**
- **A "first-of-a-kind" UQ SFP application!**
- **A "still growing" dossier of open references!**

The UP Database



- **400 (+150) UP identified & characterized.**
- **Substantiated "expert judgement".**

Methods & Tools



UQ Tool	SA Code
DAKOTA/Python scripts	MELCOR2.2
DAKOTA	MELCOR2.2
DAKOTA /SNAP	MELCOR2.2
DAKOTA/SNAP, MATLAB script	MELCOR2.2
DAKOTA/SNAP	MELCOR2.2
DAKOTA	MELCOR1.8.6
DAKOTA, Python, ass. packages	MAAP5.05

UQ Tool	SA Code
SUNSET	ASTEC2.2b
SUNSET	ASTEC2.2b
SUNSET	ASTEC2.2b

UQ Tool	SA Code
SUSA4.2	AC^2
SUSA4.0	MELCOR2.2
SUSA4.2	RELAP/SCDAP

UQ Tool	SA Code
Python Tools	MELCOR 2.2
Python in-house Tool	MELCOR 2.2
Scripts	MELCOR2.2

UQ Tool	SA Code
RAVEN	MELCOR2.2
URANIE	ASTEC2.1

- **Diversity in codes and tools** (strength/weakness).
- **Convergence in key choices … to come!**

In-Reactor Applications

#	Partner	NPP	Scenario(s)	SAM
1	BelV	PWR-1000	LBLOCA	
2	CIEMAT/UNIPI	PWR (Surry)	SBO	
3	CNPRI	HPR-1000	LBLOCA	
4	ENEA	PWR-900	SBO	
5	ENSO	PWR 4-Loops	LT-SBO at Low P	
6	EPRI	PWR (Surry)	ELAP w/o SAM ELAP+SAM	AC restored at RPV failure
7	GRS	KONVOI	MBLOCA+SBO	
8	IRSN	PWR-900	SBO+Loss of aux. FW	Sump flooding, CFVS
9	KAERI	APR-1400	C-SGTR by SBO	
10	KIT/Framatome	KONVOI	MBLOCA w/o SAM MBLOCA+SBO MBLOCA+SAM	CFVS
11	PSI	PWR-1100	SBO+SGTR	SG re-flooding
12	SNERDI	CAP-1400	LOCA+SBO	
13	TRACTEBEL	PWR-1000	SBO	Cavity flooding+CFVS

In-Reactor Applications

#	Partner	NP
1	BelV	PWR-
2	CIEMAT/UNIPI	PWR (
3	CNPRI	HPR-
4	ENEA	PWR
5	ENSO	PWR 4-
6	EPRI	PWR (
7	GRS	KON
8	IRSN	PWR
9	KAERI	APR-
10	KIT/Framatome	KON
11	PSI	PWR-
12	SNERDI	CAP-1400
13	TRACTEBEL	PWR-1000

#	SA Code	U&S Tool	#UPs	#FoM	#Calcs. for UQ
1	MELCOR	URANIE			
2	MELCOR	DAKOTA	24	3	93
3	ASTEC	SUNSET	5	8	100
4	MELCOR	DAKOTA	8	1	130
5	RELAP/SCDAP	IUA2.0	19	26	124
6	MAAP	Python	232	12	500
7	AC2	SUSA	81	10	100
8	ASTEC	SUNSET, Python	43	12	100
9	MELCOR	DAKOTA	6	4	300
10	ASTEC	KATUSA	18	6	900 (300*3)
11	MELCOR	DAKOTA, Python	17	2	100
12	MAAP	DAKOTA			
13	MELCOR	Python	15	6	111

LOCA+SBO		
SBO		Cavity flooding+CFVS

In-Reactor Applications

#	Partner	NP
1	BelV	PWR-
2	CIEMAT/UNIPI	PWR (
3	CNPRI	HPR-
4	ENEA	PWR
5	ENSO	PWR 4
10	KIT/Framatome	KON
11	PSI	PWR-
12	SNERDI	CAP-1400
13	TRACTEBEL	PWR-1000

#	SA Code	U&S Tool	#UPs	#FoM	#Calcs. for UQ
1	MELCOR	URANIE			
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4	MELCOR	DAKOTA	8	1	130
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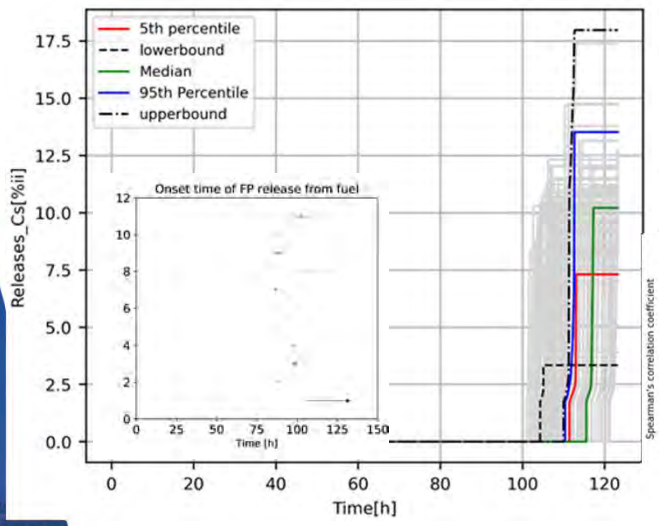
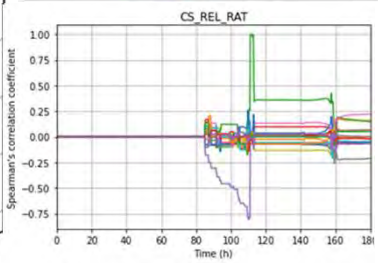
6	MAAP	Python	232	12	500
7	AC2	SUSA	81	10	100
11	MELCOR	Python	17	2	100
12	MAAP	DAKOTA			
13	MELCOR	Python	15	6	111
	LOCA+SBO				
	SBO		Cavity flooding+CFVS		

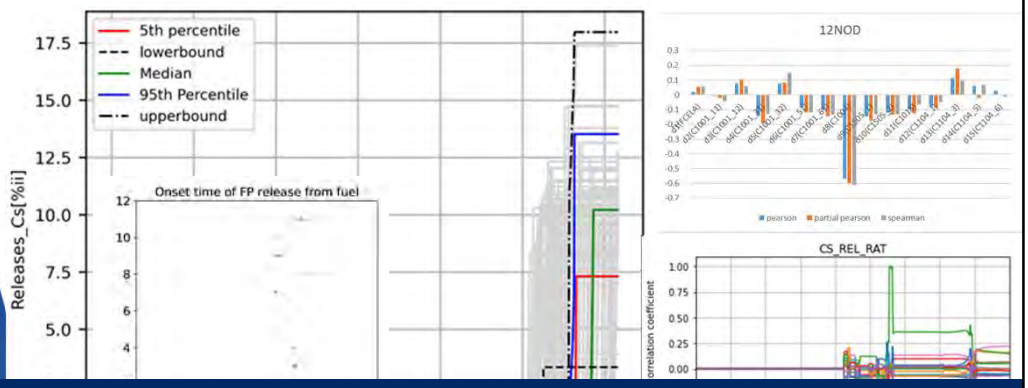
- **DB in technology/scenarios/UQ approaches/ … (strength/weakness).**
- **Preliminary insights into Ammgmt.**
- **Cross-comparison might "substantiate" some options!**

In-SFP Applications





In-SFP Applications



- **Onset of fuel melting (1%)**
- **Specific, highly conditioned** (FOMs; termination; phenomena; BCs; codes; …) scenario.

NUGENIA 2019 Forum
FISA 2019
EUROSAFE 2021 Forum
SNETP 2021 Forum
NESTet Conference 2021
FISA 2022
SNETP Coordinators Hub Day
SNETP 2023 Forum

MUSA C&D Numbers

General presentations at Conferences and meetings	20
Main Communication Events	8
Technical Presentations at Conferences	17
joint	7
planned	+3 + **ERMSAR**
Articles on scientific journals	8 (+)
joint	4
planned	+2

Education & Training Activities

- **3 learning modules** (MSc students & to generic audience:

1. **Analysis of SA from the Early Days to the Next Future** (CIEMAT) – on web
2. **Methodologies for uncertainty assessment in SA** (UNIPI) – on web
3. **ST Uncertainties in Fukushima-like scenarios** (CIEMAT) - ongoing

Module 1

Module 2

Module 3

- **A Specific lecture in the SAP Course Technical Programme**

Major Challenges Ahead

- **The UP database optimization** (filling; extension; restrc.).
- **A systematic consolidation of UaSA application in SA.** (#UP; nodding; FOMs; …) – **Innovation.**
- **A "balanced" use of expert judgement.**
- **Further attention to accident management** (forward/reverse effect).
- **Show-cases for innovative technologies** (ST-ATFs; LW-SMRs)

Thank you for your trust!
Thank you for your work!
Thank you for your patience!

Let’s believe and do it!

MUSA

MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

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Final uncertainties database: Reflections

10. May 2023

Sara Beck (GRS), Olivia Coindreau (IRSN), L.E. Herranz (CIEMAT)

MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

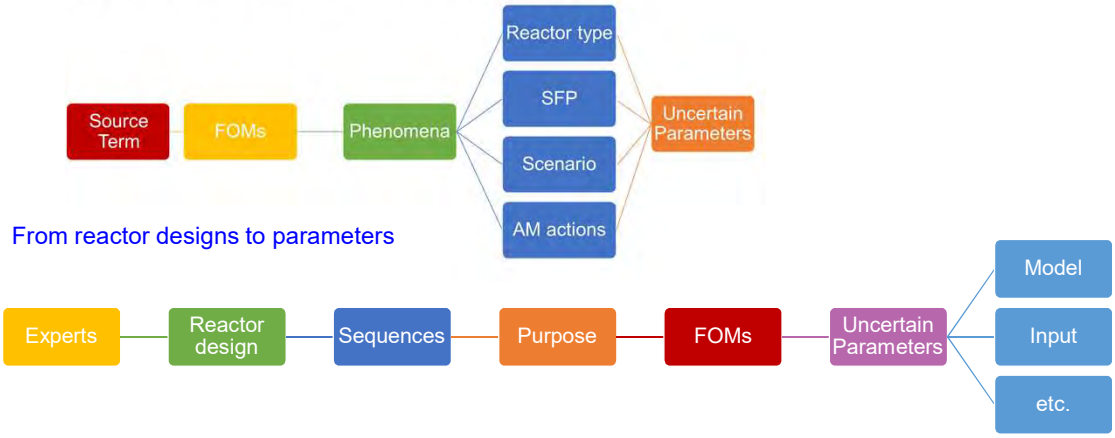
Reflections

- Over 400 UPs included in the database
- Questions raised:
  - What is the user feedback from WP 4 – 6?
  - Would we chance the methodology?
  - How complete is the database?

Reflections

- What is the user feedback from WP 4 – 6?
  - Partners feedback:
    - some UPs, uncertainty distributions provided by the partners are different from table → under consolidation
    - some uncertainty sources can not be accounted with the probabilistic propagation
    - Reduction of FOMs
    - Concentration
      - on sequence oriented uncertainties
      - UPs strictly linked with FOMs
    - Phenomena missing not modelled in the code is missing
    - Uncertain parameters in models could not be available for partners
    - FOMs uncertainties dominated by availability of SAM systems, included plant features
  - Recommendation:
    - Identify main phenomena

- Would we chance the methodology?



Reflections

- How complete is the database?
  - Comprehensive
  - Critical review
  - Split database in sequences
  - Structure database

- Different platform to make it user friendly
- Extension of database for important phenomena
- Take into account missing phenomena and on purpose left out issues (noise, system availability, etc.)

WP3 Review of Uncertainty Quantification Methodologies

Recommendations on methods

V. H. Sanchez-Espinoza, F. Gabrelli, K. Chevalier-Jabet, A. Höffer, E-M. Pauli, A. Bersano, F. Mascari

MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

Content

- Recommendations based on review of UQ/SA tools
- Recommendations based on Phebus analysis (WP4)
- Recommendations based on Plant analysis (WP5/WP6)

General recommendations based on Review on UQ/SA-Tools

- Quality of U&S quantification of SA-codes depends on
  - Kind of UPs considered
    - Input parameters, initial conditions, model parameters
    - Correlated /uncorrelated
  - Characterization of PDF for each UP
    - Range, type of PDFs
    - Good approach needed
- Need understanding of Wilks approach by analyst
  - Number of runs, FOMs
- Analyst has to check consistency of results!
  - Physical meaning of correlation between UPs and FOM
  - Reference solution shoul be within uncertainty band
- Open issues regarding methods for UA:
  - Part of it the same as for DBA-domain (PREMIUM, SAPIUM)
- A robust „reference solution“ with any SA-code will reduce the code failures
- Extension of EU-expertise using UQ for SA-codes is eequired

UQ-Tools:
- DAKOTA
- URANIE
- RAVEN
- SUSA
- IUA2

SA-Codes:
- AC2
- ASTEC
- MELCOR
- MAAP
- R5/SCDAPSIM

Recommendations based on UQ of SA-Codes applied to Phébus FPT1

(D3.2)

Phebus FPT1: UQ/SA-codes used for U&S-quantification

UQ Tool	SA Code
DAKOTA/Python scripts	MELCOR2.2
DAKOTA	MELCOR2.2
DAKOTA /SNAP	MELCOR2.2
DAKOTA/SNAP, MATLAB script	MELCOR2.2
DAKOTA/SNAP	MELCOR2.2
DAKOTA	MELCOR1.8.6
DAKOTA, Python, associated packages	MAAP5.05

UQ Tool	SA Code
SUSA4.2	AC^2
SUSA4.0	MELCOR2.2
SUSA4.2	RELAP/SCDAPSIM mod3.4

UQ Tool	SA Code
SUNSET	ASTEC2.2b
SUNSET	ASTEC2.2b
SUNSET	ASTEC2.2b

UQ Tool	SA Code
Python Tools	MELCOR 2.2
Python in-house Tool	MELCOR 2.2
Scripts	MELCOR2.2

UQ Tool	SA Code
RAVEN	MELCOR2.2
URANIE	ASTEC2.1

Recommendations based on Phebus UQ (1/4)

- The UQ tools are characterized by different post-and pre-processing capabilities
  - most partners have developed their own scripts for pre-processing and post-processing to improve GUIs
- The coupling of UQ-tools with SA-codes is also very heterogeneous
  - SUSA and AC2, ASTEC/SUNSET are closely coupled
  - MELCOR/DAKOTA or MELCOR/RAVEN, are not closely coupled
    - GUI SNAP works fine for DBA
  - ASTEC and URANIE: no coupling at all was available. Python-based interface was developed for WP4 to perform UQ in Linux/Windows
- CPU of SA-codes differs largely from each other for reference case: small /large.
  - Analyst needs expertise about the code to develop “proper” nodalisation and avoid numerical instabilities, too small time steps
    - Follow recommendations of code developers is a MUST
  - Training of analyst is highly recommended: Expertise on following areas is needed: NPP, code features, model capabilities & numerics, understanding of SA-phenomena
  - Validated SA-codes should be used for UQ

Phébus FPT1: CPU time for Reference Case with SA-Codes

Partner	Severe accident code	Duration
CIEMAT	MELCOR 2.2	5.6 h
CNSC	MELCOR 2.2	5 h
ENEA	MELCOR 2.2	8 h
Energorisk	MELCOR 1.8.6	1.5
EPRI	MAAPv5.05	13 min
GRS	AC²	4.5 h
INRNE	ASTEC 2.2	39 min
KIT	ASTEC 2.2	130 min
LEI	ASTEC V2.2.b	39 min
	RELAP/SCDAPSIM mod3.4	0.2 h
PSI	MELCOR 2.2	5.87 h
SSTC	MELCOR 2.2	15 min
Tractebel	MELCOR 2.2	1 h
TUS	ASTEC 2.2b	60 min
UNIPI	MELCOR 2.2	3-5 h
UNIRM1	MELCOR 2.2	**8 h**
USNRC	MELCOR 2.2	6 h
VTT	MELCOR 2.2	**28 min**

- MELCOR
- MAAP
- ASTEC
- AC2
- R5/SCDAPSIM

Recommendations based on Phebus UQ (2/4)

- The analyst must undertake actions when failed runs exist e.g.
  - Check the reasons for a code failure
  - Search for possible solutions e.g. reduce time step, identify in which volume is the problem
  - Repeat simulations with modified input deck e.g. smaller time steps, redonalize etc.
  - Make sure to have sufficient number of runs depending on the analyst's choice for the UQ regarding confidence and probability content (Wilk's minimum number of runs)

Recommendations based on Phebus UQ (3/4)

- Performing UQ….
  - First select the FOM based on the goal of your analysis
  - Then, select UPs (input/model parameters) relevant for the FOM for a specific SA-sequence
  - In addition:
    - Check if correlation of UPs and FOMs are physical sound
    - Find out which UPs are important
  - If needed, repeat analysis with different set of UPs (PDF, range)

Recommendations based on Phebus UQ (4/4)

- When experimental results are available, assure that it is inside the uncertainty bands
  - if not, the UQ must be repeated
  - Characterizing the UPs, look at available experimental data to select type of PDF, max./min. values
- Parametric studies may be useful to distinguish noise from physical effects in simulation's results

Recommendations based on UQ of SA-Codes applied to SA in NPPs and SFPs

(D3.3)

Type of NPPs and UQ/SA Combinations used in WP5

- WP5 UQ
  - Subgroup 5.1:
    - VVER 1000: 5
    - French PWR 900: 2
    - French PWR 1000: 2
    - PWR Surry: 2
    - PWR konvoi: 2
    - PWR-1100: 1
    - PWR 4 Loop: 1
    - APR1400: 1
    - HPR1000: 1
    - CAP1400: 1
    - CANDU-6: 1
  - Subgroup 5.2:
    - BWR4 Mark1: 3
    - BWR 5: 1
    - ABWR: 1

WP subgroup	Uncertainty tool	
PWR Gen III	SUNSET	ASTEC
	DAKOTA	MELCOR
	DAKOTA	MAAP 4.0.7
	DAKOTA	MELCOR 2.2
	DAKOTA	MELCOR
PWR Gen II	Python-based KATUSA	ASTEC
	URANIE	MELCOR
	DAKOTA	MELCOR
	DAKOTA	MELCOR
	DAKOTA, Python	MELCOR
	SUSA	AC2
	SUNSET, Python	ASTEC
	Python scripts	MAAP 5.05
	Python scripts	MELCOR
	Genpara, MOCABA	See KIT
	IUA2.0	RELAP/SCDAPSIM
VVER/CANDU	SUNSET	ASTEC
	Python scripts	MAAP
	NEMM method	MELCOR
	SUNSET	ASTEC
	SUSA	MELCOR
	DAKOTA	MELCOR
BWR	SUSA	RELAP/SCDAPSIM
	RAVEN	MELCOR
	DAKOTA	MELCOR
	RAVEN	MELCOR
	DAKOTA, Python	MELCOR

UQ Tools used:
- DAKOTA: 10
- SUNSET: 4
- SUSA: 3
- Python Scripts: 3
- RAVEN: 2
- URANIE: 1
- Python KATUSA: 1
- **IUA2: 1**

Data assimilation:
- NEMM: 1
- MOCABA: 1

Combination of UQ/SA-Codes applied to the SFP (FUK) in WP6

SA code	Uncertainty tool	SFP design	Building model	Number of UPs
DAKOTA	MELCOR	BWR FU-4	No	15
DAKOTA	MELCOR	BWR FU-4	Yes	8
DAKOTA	MELCOR	BWR FU-4	No	15
SUNSET	ASTEC	BWR FU-4	Yes	7
SUNSET	ASTEC	BWR FU-4	Yes	12
SUNSET	ASTEC	BWR FU-4	Yes	7
SUNSET	ASTEC	BWR FU-4	Yes	n.a.
SUSA	RELAP/SCDAP	BWR FU-4	No	25
SUSA	MELCOR	BWR FU-4	Yes	24
RAVEN	MELCOR	BWR FU-4	Yes	25
R + Python script	ASTEC	BWR FU-4	Yes	18
RAVEN + Python script	ASTEC	BWR FU-4	Yes	21

Recommendations from WP5/WP6 (1/2)

In addition to the recoomendations based on Phebus analysis …

- The assessment of **reference calculation** before the UA is important
  - Optimized input deck improve robustness, reduce CPU and increase stability
- The proper selection of the UP is a challenging task
  - Select the UP relevant for the FOM
  - Take profit of your knowledge about the reactor design,
  - Look for experimental data, consider previous work
- Uncertainty tools are in general adequate to perform the UA
  - GUI are less flexible compared to scripting
  - Flexible tools for pre- and post processing and to automatize large number of runs needed
  - Replaced by Python scripting in some cases
- Use of different indicators in post-processing phase strongly recommended
  - e.g. to evaluate the sensitivity, correlation of the FOMs with UPs

Recommendations from WP5 / WP6 (2/2)

- Check the appropriateness of the sampling methods i.e. Monte Carlo or LHS for your specific application
- Both scalar and index-dependent (time dependent) evaluations of the correlation of UPs and the FOM must be considered

Needs for consolidation / harmonisation

Needs for consolidation /harmonisation (1/4)

- Selection of UP
  - Use PIRT, previous work
- Definition of range of UPs
  - Investigations needed for cases: no exp. Data available, model parameter without physical meaning
- Selection of PDF for UPs
  - If no references, check for availability of measured data
  - Derive PDF from data
- Dealing with failed runs
  - Consitent approach needed

Needs for consolidation /harmonisation (2/4)

- Selection of numbers of FOMs
  - Wald‘s approach
  - Alternative solution?
- Selection of UPs relevant for selected FOMs
  - Dependent of reactor design
  - Dependent of accidental sequence
  - Dependent of SAMs
- Remarks:
  - Not same physical phenomena is important in ALL sequence for a specific FOM!

Needs for consolidation /harmonisation (3/4)

- Reference solution
  - Should relfect recommendations of code developers for the activation of models, nodalisation, time step control, etc.
    - Stable, large time step, numerical robust
  - In case of long SA-sequences with complex phenomena going on, „inputdeck“ simplifications are mandatory for UA
  - Remember: SA-codes are optimized to run fast and stable!

Needs for consolidation /harmonisation (4/4)

- Methods to consider correlation between UPs in a UQ are needed
- Some models are implemented in tools:
  - SUSA
  - KATUSA
  - EPRI Python tool
- Consolidated models needed

INNOMUSA:

INNOvation in Managing Uncertainties in Severe Accident analysis

Luis E. Herranz (CIEMAT)

MUSA Open Workshop, Madrid 10-11 May, 2023 (Hybrid meeting)

MUSA

MUSA has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441.

LGi sustainable innovation

Background: The MUSA Venture

Severe Accidents are the major contributors to NPP risk!
The "safety case" heavily relies on simulations!

How accurate are SA simulations?

Can uncertainties affect Accident Management?
Can Accident Management affect uncertainties?

Priorities for further research?

Background: Thermal-hydraulics

BEPU was born within the domain of Thermal-hydraulics!

Application of BE to **ECCS licencing** (USNRC: 1974-1986)

OECD/CSNI

(NEA/CSNI/R(1994)20; NEA/CSNI/R(97)35; NEA/CSNI R(97)4; …)

BEMUSE(2004-2010);
PREMIUM(2012-2015);
SAPIUM (2017-2019);
ATRIUM (2021-2024)

Background: Severe Accidents

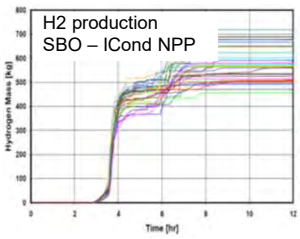
- **A pioneer work based on STCP** (Khatib-Rahbar et al., 1989)

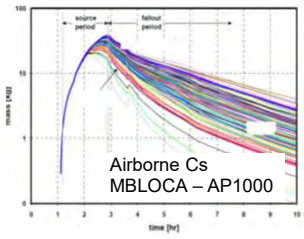
  - Identification of input param.
  - Determination of pdf's
  - Random combination samp.
  - Calculation running

  → **Source Term uncertainties**

  - Meltdown parameters
  - FP release coefficients
  - Chemical activities (MCCI)
  - Containment performance

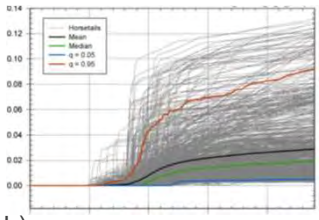
- **Similar methodology based on MELCOR 1.8.5** (Gauntt R.O., 2005)



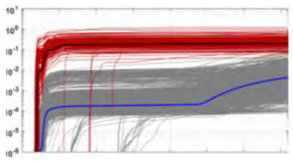


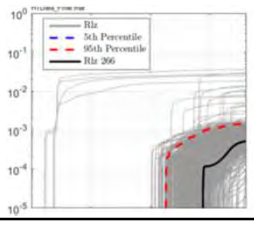
Contemporary: Severe Accidents

"Summary of the Uncertainty Analyses for the State-of-the-Art Reactor Consequence Analyses Project"
(NUREG-2254; 2022)



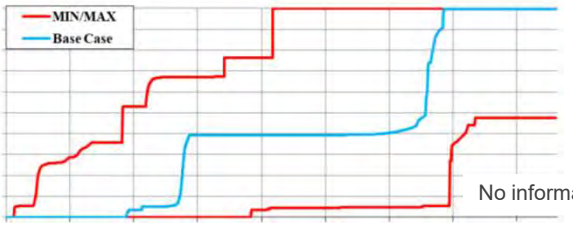
- 2010-2019.
- 3 "full-scope" UaSAs: PBottom; Sry; Sqyah.
- Unmitigated LTSBO (PB), STSBOs (S&S).
- MELCOR-MAACS; MC (865, 567, 1147); LHS.
- Assumptions on SVs, breach (SGTR), time (48 h; 72 h), ...
- **Expert judgement!!!** (input parameters, 15-20).





Contemporary: IAEA CRP

" Advancing the State-of-Practice in Uncertainty and Sensitivity Methodologies for Severe Accident Analysis in Water Cooled Reactors"
(IAEA CRP I31033)



No information published yet

- MUSA closely connected from the start.

InnoMusa Bases

- **Major achievements of MUSA already visible:**
  - An “entire” community deeply involved in UaSA in SA analysis!
  - Huge progress made in “methodology essentials”.
  - Major challenges identified when bringing UaSA in SA analysis.
- **Sizeable issues still stand for a “systematic” method** (need of “more & better”, more work and a better approach).
- **A “systematic” method is indispensable**
  - To consolidate UaSA application in SA analysis
  - To gain confidence in risk estimates
  - To optimize SA research

General Objectives

- **To exploit the achievements made in MUSA.**
- **To consolidate a systematic methodology to bring UaSA in the severe accident simulation.**
- **To focus on AM*:** Effect of U on AM & Effect of AM on U.
- **To address innovation Ntech.:** NT-ATFs; LW-SMR

*** Decision making efficiency and effectiveness**

Major Pillars

- **MUSA outcomes, a sound basis**
  - Input deck uncertainties DB
  - Deep insights into methodologies: strengths & drawbacks
  - Put-in-place tools & associated expertise
  - Open issues out of MUSA reach
  - Most important … "an uncertainty community"
- **Innovation to be brought on-board in every regard**
  - Open issues resolution in methodologies
  - Consortium composition
  - Applications
  - …

Conceptual Structure

WP1	COORDINATION & MANAGEMENT
WP2	METHODOLOGY
WP3	APPLICATIONS
WP4	EDUCATION & TRAINING
WP5	DISSEMINATION & COMMUNICATION

Conceptual Structure

METHODOLOGIES

- Uncertainties DB
- MC, Wilks, others, …
- Noding
- Engineering judgement
- Data analysis (SA)
- FOMs
- Bifurcation, outliers, fails, bias, …
- Phasing
- Noise
- …

APPLICATIONS

- Water-cooled reactors (Gen-II & Gen-III)
- LW-SMRs
- AMgmt*
- Short-term ATFs
- Spent fuel pools
- …

Initial Organizational Ideas

& (ZZZ)

Dissemination

METHOD
(XXX; YYY)

- Uncertainty DB
  (approach; qualification; extensión; …)
- UA Approach
  (MC, Wilks, others, …;
  FOMs; parameters;
  bifurcations; outliers; bias; crashes; …)
- Data analysis (SA)
  ("Best suite"; physical consistency; …)
- Noding/ Phasing / Noise

EDUCATION & TRAINING (RRR)

APPLON
(PPP; QQQ)

- Water-cooled reactors
  (Gen-II & Gen-III; AMgmt)
- LW-SMRs
  (Av. Designs; SASPAM)
- Amgmt*
- Short-term ATFs (shc)
- Spent fuel pools (shc)

Communication

Initial Organizational Ideas

- **AMgmt*!!!**
- **Fully open products.**
- **Strong axis on E&T for a broad implementation.**
- **Small Task groups focused on specific challenges (METHOD).**
- **Grouping applications, as fit best (APPLON).**
- **Three calculation campaigns anticipated:**
  - Reference (MUSA; onset of the project; 0-12 months);
  - Prelim. METHOD progress (18-24 month);
  - Method proposed (38-44 m)
- **Continuous communication between WPs**

Expressions of Interests

Organization	Country	Contact Person
Bangor U.	UK	W. Villanueva
BELV	Belgium	A. Malkhasyan
CIEMAT	Spain	L.E. Herranz
ENEA	Italy	F. Mascari
Energorisk	Ukrania	S. Sholomitsky
ENSO	Spain	V. Martínez
Framatome	France	M. Sagan
GRS	Germany	S. Beck
INRNE	Bulgary	P. Groudev
IRSN	France	O. Coindreau
JRC-Petten	JRC	S. Brumm
JSI	Slovenia	M. Leskovar
KIT	Germany	F. Gabrielli

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RUHR-UB	Germany	M.K. Koch
SSTC	Ukraine	D. Gumenyuk
TRACTEBEL	Belgium	S. Yu
TUS	Bulgary	I. Ivanov
UNIPI	Italy	S. Paci
VDU	Lithuania	R. Krikstolaitis
VTT	Finland	T. Karkela

Expressions of Interests: Beyond EU Borders

Organization	Country	Contact Person
KAERI.	Korea	B. Lee
	USA	
	Canada	
	Japan	
	…	

Thank you for your attention!

MUSA

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LGi sustainable innovation

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