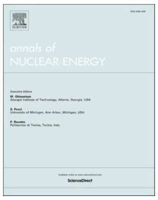
Annals of Nuclear Energy 196 (2024) 110205

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Main outcomes of the Phebus FPT1 uncertainty and sensitivity analysis in the EU-MUSA project

F. Mascari [a,*], A. Bersano [a], M. Massone [a], G. Agnello [a,b], O. Coindreau [c], S. Beck [d], L. Tiborcz [d], S. Paci [e], M. Angelucci [e,*], L.E. Herranz [f], R. Bocanegra [f], Y. Pontillon [g], M. Berdai [h], O. Cherednichenko [i], A. Iskra [i], M. Nudi [j], P. Groudev [k], P. Petrova [k], F. Kretzschmar [l], F. Gabrielli [l], Z. Kanglong [l], V. Vileiniškis [m], T. Kaliatka [m], J. Kalilainen [n], M. Malicki [n], D. Gumenyuk [o], Y. Vorobyov [o], O. Kotsuba [o], P. Dejardin [p], M. Di Giuli [p], R. Thomas [p], I.V. Ivanov [q], F. Giannetti [r], M. D'Onorio [r], G. Caruso [r], M. Salay [s], T. Sevon [t]

[a] *ENEA-BOLOGNA, Via Martiri di Monte Sole 4, 40129 Bologna, Italy*
[b] *Università degli Studi di Palermo, Italy*
[c] *IRSN, Centre de Cadarache, B.P. 3 – 13115 Saint-Paul-lez-Durance Cedex, France*
[d] *GRS, Germany*
[e] *UNIPI, Department of Civil and Industrial Engineering (DICI), University of Pisa, Italy*
[f] *CIEMAT, Nuclear Safety Research Unit, Department of Energy, Avda. Complutense 40, 28040 Madrid, Spain*
[g] *CEA, DES, IRESNE, DEC, Cadarache F-13108 Saint-Paul-Lez-Durance, France*
[h] *CNSC, Canada*
[i] *Energorisk, Ukraine*
[j] *EPRI, USA*
[k] *Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, (INRNE-BAS) Tzarigradsko Chaussee 72, 1784 Sofia, Bulgaria*
[l] *Karlsruhe Institute of Technology, Institute for Neutron Physics and Reactor Technology, Hermann-von-Helmholtzplatz, 1 D - 76344 Eggenstein-Leopoldshafen, Karlsruhe, Germany*
[m] *Lithuanian Energy Institute (LEI) Breslaujos g. 3, Kaunas 44403, Lithuania*
[n] *Paul Scherrer Institute, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland*
[o] *SSTC NRS, Ukraine*
[p] *TRACTEBEL, Tractebel ENGIE, Severe Accident Department, Avenue S. Bolivar 34-36, Brussels, Belgium*
[q] *TUS, 8 Kl. Ohridski Blvd., Block 12, 1000 Sofia, Bulgaria*
[r] *Sapienza University of Rome, Department of Astronautical, Electrical and Energy Engineering (DIAEE), Corso Vittorio Emanuele II, 244 – 00186, Roma, Italy*
[s] *USNRC, USA*
[t] *VTT Technical Research Centre of Finland, Kivimiehentie 3, Espoo, Finland*

ARTICLE INFO

Keywords:
MUSA
Severe accident
Phebus
Uncertainty

ABSTRACT

The Management and Uncertainties of Severe Accidents (MUSA) project was funded in HORIZON 2020 and is coordinated by CIEMAT (Spain). The project aims at consolidating a harmonized approach for the analysis of uncertainties and sensitivities associated with Severe Accidents (SAs) analysis, focusing on source term figures of merit. The Application of Uncertainty Quantification (UQ) Methods against Integral Experiments (AUQMIE – Work Package 4 (WP4)), led by ENEA (Italy), was devoted to apply and test UQ methodologies adopting the internationally recognized PHEBUS FPT1 test. FPT1 was chosen to test UQ methodologies because, even though it is a simplified SA scenario, it was representative of the in-vessel phase of a severe accident initiated by a break in the cold leg of a PWR primary circuit.

WP4 served as a platform to identify and discuss the issues encountered in the application of UQ methodologies to SA analyses (e.g. discuss the UQ methodology, perform the coupling between the SA codes and the UQ tools, define the results post-processing methods, etc.). The purpose of this paper is to describe the MUSA PHEBUS FPT1 uncertainty application exercise with the related specifications and the methodologies used by the partners to perform the UQ exercise. The main outcomes and lessons learned of the analysis are: scripting was in general needed for the SA code and uncertainty tool coupling and to have more flexibility; particular attention

---

* Corresponding authors.
E-mail addresses: fulvio.mascari@enea.it (F. Mascari), michela.angelucci@ing.unipi.it (M. Angelucci).

https://doi.org/10.1016/j.anucene.2023.110205
Received 26 June 2023; Received in revised form 5 October 2023; Accepted 26 October 2023

should be devoted to the proper choice of the input uncertain parameters; outlier values of figures of merit should be carefully analyzed; the computational time is a key element to perform UQ in SA; the large number of uncertain input parameters may complicate the interpretation of correlation or sensitivity analysis; there is the need for a statistically solid handling of failed calculations.

Nomenclature

AC^2	ATHLET, ATHLET-CD, COCOSYS
ASTEC	Accident Source Term Evaluation Code
AUQMIE	Application of Uncertainty Quantification (UQ) Methods against Integral Experiments
BEPU	Best Estimate Plus Uncertainty
CDF	Cumulative Density Function
DAKOTA	Design Analysis Kit for Optimization and Terascale Application
FOM	Figure Of Merit
FP	Fission Product
GUI	Graphical User Interface
ISP	International Standard Problem
MAAP	Modular Accident Analysis Program
MELCOR	Methods for Estimation of Leakages and Consequences of Releases
MUSA	Management and Uncertainties Of Severe Accidents
NPP	Nuclear Power Plant
PDF	Probability Density Function
RAVEN	Risk Analysis Virtual ENvironment
SA	Severe Accident
SFP	Spent Fuel Pool
SNAP	Symbolic Nuclear Analysis Package
ST	Source Term
SUNSET	Sensitivity and UNcertainty Statistical Evaluation Tool
SUSA	Software for Uncertainty and Sensitivity Analyses
UaSA	Uncertainties and Sensitivities Analyses
UQ	Uncertainty Quantification
UT	Uncertainty Tool
WP	Work Package

1. Introduction

1.1. Uncertainty and sensitivity analysis in severe accidents

Considering the complexity and the various interacting/interrelated phenomena/processes that occur during a Severe Accident (SA) evolution, state-of-the-art SA integral codes (Mascari et al., 2019a; Mascari et al., 2019b, Van Dorsselaere et al., 2018, De la Rosa Blul et al., 2018) play an important role in characterizing plant behavior along the postulated transient. These codes are adopted to evaluate the accident progression up to the characterization of radiological releases to the environment; in particular they characterize the phenomena/processes taking place in the reactor pressure vessel, reactor cavity, containment and the confinement building of LWR. The analytical capabilities allow the calculation of the main safety relevant Figures Of Merit (FOMs) selected in the development of deterministic safety analyses for regulatory decision-making applications. These capabilities are also used to develop accident management strategies.

Several models/correlations have been implemented in state-of-the-art SA codes and must be set by a code user during the input-deck development. Models/correlations that are implemented in a SA code reflect the state-of-the-art knowledge of SA phenomena/processes. However, even though several experimental campaigns in the field of SA phenomena (OECD/NEA/CSNI, 1992, OECD/NEA/CSNI, 1996, OECD/NEA/CSNI, 2001, OECD/NEA/CSNI, 2009, OECD/NEA/CSNI, 2014) have been performed and provided a valuable “assessment database” (Mascari et al., 2015) for SA simulation tools, there is the need for reducing some uncertainties still present (Mascari et al., 2019a; Mascari et al., 2019b, Van Dorsselaere et al., 2016). Therefore, an investigation of phenomena/processes, to date not researched in geometric prototypical experimental facilities with prototypical material, should be addressed. For this reason, discrepancies in the prediction of some core degradation phenomena can be still observed when comparing the results of different SA codes, considering the different core degradation models implemented (Mascari et al., 2019a; Mascari et al., 2019b, Humphries, 2018).

Considering the need to reduce and/or quantify some uncertainties still present, and the level of development and maturity reached by SA codes, analyses of SA progression with uncertainty estimation is currently a key topic in the Best Estimate Plus Uncertainty (BEPU) framework. In fact, the use of a BEPU approach to quantify the uncertainty of selected FOMs is of great interest for the international scientific community. In the field of nuclear thermal-hydraulics, the BEPU approach is being applied since several years and some relevant international projects have been conducted, such as the OECD/NEA/CSNI BEMUSE (OECD/NEA/CSNI, 2007, OECD, NEA, CSNI, 2011) and PREMIUM (OECD/NEA/CSNI, 2016) projects.

Considering the key role of SA codes for deterministic safety analyses and Source Term (ST) evaluations, several research activities in national and international frameworks are in progress to reduce and/or estimate the uncertainty in SA phenomena prediction. Moreover, it is expected that the direct application of BEPU methodologies developed for example in nuclear thermal-hydraulics could be more challenging in the SA field. In fact, it should be considered the possible larger number of uncertain input parameters (e.g. due to some limitations of geometric prototypical experimental facilities with prototypical material), the possible higher failure rate of SA code runs, the possible presence of cliff-edge effects, etc. In this framework, a relevant activity is the Management and Uncertainties of Severe Accidents (MUSA) project (Herranz et al., 2021).

1.2. Description of the EU MUSA project

The MUSA project was funded in HORIZON 2020 EURATOM NFRP-2018 call on “Safety assessments to improve accident management strategies for generation II and III reactor”. The project started in 2019 involving 28 organizations from 16 countries, with a planned duration of 48 months, and is coordinated by CIEMAT (Spain) (Herranz et al., 2021, Mascari et al., 2021). MUSA aims at establishing a harmonized approach for the Uncertainties and Sensitivities Analyses (UaSA) associated with SA, among EU and non-EU entities. The main objective of the project is to assess the capability of SA codes when modelling Nuclear Power Plant (NPP) and Spent Fuel Pool (SFP) accident scenarios of generation II and III reactor designs.

One of the main targets of MUSA is to move beyond the state-of-the-art regarding the predictive capability of SA codes by combining them with the best available Uncertainty Quantification (UQ) tools. The achievement of the overall objective is assured by a consistent and coherent work program, reflected by the Work Packages (WP) structure, 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) (Herranz et al., 2021).

In this framework, the WP4, led by ENEA (Italy), is aimed at applying and testing UQ methodologies, against the internationally recognized PHEBUS FPT1 test (Clément et al., 2005, Jacquemain et al., 2000), used also for the OECD/NEA International Standard Problem (ISP) 46 (Clément et al., 2005, OECD/NEA/CSNI, 2004). FPT1 was chosen to test UQ methodologies because, even though it is a simplified SA scenario, it was representative of the in-vessel phase of a severe accident initiated by a break in the cold leg of a PWR primary circuit. WP4 is also a collaborative platform to highlight and discuss results and issues arising from the application of UQ methodologies already used for Design Basis Accidents and now employed for SA analyses in MUSA.

Considering the resources available for the WP4, and the previous ISP 46 activity (Clément et al., 2005, OECD/NEA/CSNI, 2004), a code benchmark against the experimental data is not in the scope of the exercise. However, representative experimental data have been used to 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 to investigate how to address the issues that can arise in the UaSA methodologies application to simplified, but still representative, SA scenarios. Therefore, the main objectives of WP4 are:

1. To apply and test the proposed UQ methods and UaSA tools against the FPT1 experiment, which is relevant for SA progression and ST prediction;
2. To identify issues (if existing) along the UQ methodology application and propose solutions;
3. To develop a critical analysis of the UQ results from the partners in view of the employment of such uncertainty methodologies for NPP and SFP applications.

The WP4 is divided in three main sub-WPs: the specification phase (WP4.1) led by IRSN, the calculation phase (WP4.2) led by GRS, and the analyses of the results (WP4.3) led by UNIPI.

A preliminary summary of the MUSA PHEBUS FPT1 uncertainty application exercise together with the methodologies used by the partners to perform the UQ exercise and the first insights from the calculation phase was presented in (Mascari et al., 2022). The aim of the present paper is to provide a more comprehensive analysis of the exercise and the main outcomes and lessons learned of the WP4 application. Section 2 describes the Phebus FPT1 experiment and the exercise specifications; Section 3 describes the calculation phase; Section 4 presents the UQ methodologies, the coupling of the SA code with the UQ tools and the uncertainty application; finally, Section 5 reports the main outcomes and lessons learned and the conclusions are drawn in Section 6.

2. PHEBUS FPT1 experiment and WP4 specification

2.1. Summary of PHEBUS FPT1 experiment

The sub-WP4.1 has been focused on the development of the exercise specifications: description of the PHEBUS facility, of the FPT1 test, selection of the FOM and distribution of experimental data. All the efforts developed along the ISP 46 (Clément et al., 2005) have been considered as a common sound background to develop the WP4 exercise.

The PHEBUS Fission Product (FP) program was initiated in 1988 with the main objective of studying the release, transport and retention of fission products in an in-pile facility under conditions representative of a SA in a light water reactor (Clément and Zeyen, 2013). The second test of the program (FPT1), carried out on July 26th, 1996, in the Phébus facility at Cadarache (France) (Dubourg et al., 2005) involved the 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 fuel bundle was re-irradiated in situ in order to “(re)build” short-life fission products inventory inside the fuels rod in order, in particular, to allow their quantification by gamma spectrometry measurements. 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 comprised a fuel degradation phase, an aerosol phase, a washing phase and a chemistry phase. 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.

2.2. WP4 specifications

2.2.1. Figures of merit

The FOMs of the WP4 exercise have been derived from those identified in MUSA WP2 for the reactor case. They have been chosen for their relevance with respect to MUSA objectives and for the availability of experimental data in open literature. They correspond to a selection of key targets, and they are ST focused. The FOMs for WP4 are (Coindreau and Mascari, 2020):

Release of iodine from top of the bundle [% of i.i.] (Clément et al., 2005);
Release of caesium from top of the bundle [% of i.i.] (Dubourg et al., 2005, Darnowski et al., 2020);
Caesium retention in the circuit [% of Cs released from the core]: final value = 0.476 ± 0.107 (Clément et al., 2005);
Aerosol amount in the containment’s atmosphere [g] (Clément et al., 2005);
Total gaseous iodine amount in the containment’s atmosphere [g] (Clément et al., 2005);
Total iodine aerosols amount in the containment’s atmosphere [g] (Bosland et al., 2012);
Total deposited/adsorbed iodine amount in the containment [g] (Bosland et al., 2012).

2.2.2. Uncertain input parameters

A database of uncertain input parameters with their range and the corresponding Probability Distribution Functions (PDF) is the output of MUSA WP2. WP4 partners were free to select the uncertain input parameters for the UQ with the following recommendations:

- WP4 partners can select the input uncertain parameters form the database assessed in the WP2;
- In case WP4 partners may want to use their own uncertainty characterization, they should make it defendable with respect to the ones proposed in WP2;
- WP4 partners can use parameters not included in the WP2 database, but their characterization (PDF and range) should be supported by reference or engineering judgement;
- Partners are invited to select input uncertain parameters that have the most influence and then rank them within the uncertainty application.

3. WP4 calculation phase: Description of nodalization and computing environment

In relation to the calculation phase (sub-WP 4.2), the main technical goals are: the assessment of SA code capabilities to predict ST-related phenomena including uncertainty analyses estimation, the training of the partners to UaSA, the discussion and proposal of solutions if some issues arise during the UaSA applications.

Seventeen partners from different world regions are involved in the WP4 activities. Table 1 summarizes the involved partners, SA code and UT used. Considering the SA codes, 1 partner adopted AC^2 code (Lerchl et al., 2019, Austregesilo et al., 2019, Arndt et al., 2019), 4 partners adopted ASTEC code (Chatelard et al., 2014), 1 partner adopted MAAP code (EPRI, 2019), 11 partners adopted MELCOR code (Sandia National Laboratories, 2017), 1 partner adopted RELAP/SCDAPSIM code (Allison et al., 1997, Allison et al., 1998). Considering the UT, 8 partners adopted DAKOTA (Adams et al., 2020, Dalbey et al., 2020) 1 partner adopted RAVEN (Rabiti et al., 2017), 3 partners adopted SUNSET (Chojnacki and Baccou), 3 partners adopted SUSA (Kloos, 2020), 1 partner adopted URANIE (Blacard et al., 2019), 2 partners performed the UaSA only through Python (Python, 2023) scripts.

The nodalizations developed for the calculations of MUSA WP4 depend on the choices made by each partner and on the code used. In fact, in some codes a reference geometry can be integrated directly into the input-deck and in this case, this reference geometry has been used directly without any modification, or else slightly modified by the partner. Otherwise, a complete nodalization is developed. The following list summarizes the main features of the partners nodalizations:

- **CIEMAT**: The PHEBUS-FPT1 MELCOR input deck developed by CIEMAT incorporates data mainly from the PHEBUS-FPT1 final report (Jacquemain et al., 2000). Overall, there are 30 Control Volumes (CVs), 29 Flow Paths (FPs), and 68 Heat Structures (HSs), describing the test-section and down-stream circuit.
- **CNSC**: The used FPT1 input deck has been provided by Sandia National Laboratories (SNL) and was developed using MELCOR. CNSC got access to the MELCOR input deck, through the Cooperative Severe Accident Research Program (CSARP).
- **ENEA**: The MELCOR model is based on a FPT1 input deck provided by the US Nuclear Regulatory Commission (USNRC) to ENEA as part of the Cooperative Severe Accident Research Program (CSARP). USNRC disclosed it and granted permission to ENEA to use it as a part of international collaboration on the MUSA project. Main data derives from FPT-1 Data Book, ISP-46 specifications and FPT-1 Final Report.
- **Energorisk**: Data provided by the IRSN related to PHEBUS facility and public available information PHEBUS FPT1 have been used for model development. The model and input deck for MELCOR 1.8.6 code developed for post-test analysis of FPT1 experiment was used.
- **EPRI**: MAAP has traditionally included the FPT1 experiment as a code benchmark, but the scope of the benchmark was limited to the bundle degradation phase and did not evaluate later phases of the FPT1 experiment. The scope of the uncertainty analysis application in this section include the aerosol release and transport phase of the experiment in addition to the bundle degradation phase, but did not include the washing or chemistry phases.
- **GRS**: The input data set for the Phébus FPT1 Test is based on previous studies carried out in GRS [ISP46 participation- (Clément and Haste, 2003)] and on the data provided by IRSN in the framework of the MUSA Project. The model of the Phébus FPT1 Test facility for AC^2 includes two input data sets: one for ATHLET-CD, responsible for the calculation of phenomena within the RCS, and one for COCOSYS, simulating the processes within the containment.
- **INRNE**: The input deck for the Phébus FPT1 was developed by the INRNE based on the generic input case (input deck) from ASTECv2.1.1.4 and also some data from older ASTEC code versions.
- **KIT**: The ASTEC model contains Hot Leg, primary side of t the Steam Generator and Cold Leg of Phébus. The Lower and Upper Plenum are parts of the vessel, but must be defined in ASTEC as volumes of the primary circuit. Volumes must have connections to make a material flow possible. The containment is modeled by three zones, but one of them is the environment. This zone has no influence on the calculation, because there is no leak in the containment wall.
- **LEI – ASTEC**: As basis for the ASTEC model development FPT1 model available in ASTEC V2.1.1.4 code validation library was taken. Standard model allows to investigate only bundle phase, so model was updated including the containment part.
- **LEI- RELAP/SCDAPSIM**: Starting point of the RELAP/SCDAPSIM model was the standard model of PHEBUS FPT1 problem, which was given together of with RELAP/SCDAPSIM code for the demonstration of code compatibility. This input deck was updated and modified according to the experimental data given by IRSN.
- **PSI**: PSI as a base of the FPT1 input deck is using delivered by Sandia National Laboratories (SNL) FPT1 MELCOR 2.1 input deck. It was converted to MELCOR 2.2, visualized, and updated by PSI in the Symbolic Nuclear Analysis Package (SNAP) environment.
- **SSTC**: The TH nodalization approach for FPT1 experiment facility for the purpose of WP4 MUSA task is chosen to be compromising between calculations run time and covering all the specifics of the task. So, the core region is chosen to be one TH volume.
- **Tractebel:** The core model is subdivided into 2 radial rings and 13 axial levels. The experimental circuit and containment tank models are developed through CVH package.
- **TUS**: The Basic Input Deck (BID) of the PHEBUS FPT1 for ASTEC' application (the circuit part) is represented into 12 volumes consist of: upper part, hot leg, steam generator, cold leg. There is used also one additional volume – VOLBOT representing the bottom. The nodalization scheme of the containment consist of five volumes.
- **UNIPI:** The MELCOR model is based on a FPT1 input deck provided by USNRC to UNIPI as part of Cooperative Severe Accident Research Program (CSARP). Main data derives from FPT-1 Data Book, ISP-46 specifications and FPT-1 Final Report.
- **UNIRM1:** The MELCOR nodalization of the Phébus FPT1 used has been provided by USNRC Sapienza University of Rome as part of Cooperative Severe Accident Research Program (CSARP). Main data derives from ISP-46 specifications, FPT1 Data Book and FPT1 Final Report.
- **VTT:** The MELCOR model was developed by VTT from scratch. The Core package nodalization has two radial rings and 14 axial levels.

Table 1
WP4 partners, with the adopted SA codes and UT.

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	AC^2	SUSA 4.2
INRNE	ASTEC 2.2	SUNSET
KIT	ASTEC 2.2	URANIE 4.1
LEI	ASTEC V2.2.b. RELAP/SCDAPSIM mod3.4	SUNSET V2.1 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

The thermal–hydraulic nodalization has 15 control volumes and 35 heat structures.

Table 2 reports the computing environment adopted by the various partners to perform the WP4 calculation. Most of the partners used a workstation based on Windows operative system. Few partners implemented the SA code/UT coupling on a cluster to perform the calculation. Table 3 reports the computational time needed by the various partners to perform the reference calculation and the UaSA. In general, it can be observed that an UaSA requires a significant time to be executed. This should be considered in particular for plant analysis.

4. Uncertainty analysis methodology and SA code/UT coupling

4.1. *Description of the uncertainty methodology*

All the partners adopted the probabilistic method to propagate input uncertainties (IAEA, International Atomic Energy Agency, 2008, Glaeser, 2008), varying simultaneously the input uncertain parameters. In order to evaluate the minimum number of code runs for the selected probability and confidence level, the Wilks formula (Wilks, 1941, Wilks, 1942) was adopted by all the partners considering the 1st or 2nd order. A still open point is the dependence among the FOMs and how this will affect the UQ. A partner underlined that in SA codes, it can be complicated to justify the total independence of one output from another, so the application of the Wilks method where more than one FOM is being investigated should be carefully considered and, eventually in case the FOMs are dependent, the method developed by (Wald, 1943) must be adopted. Some partners decided to start the calculation with a number of runs higher than the minimum requested to account for possible code failures. A partner underlined that bifurcations and edge cases can result in the number of cases derived from Wilks not being sufficient to capture the behavior near these bifurcations. In addition, it should be underlined that the FOM time dependent analysis within the adopted methodology is still an open point and needs further discussion (e.g. number of calculations required).

Table 2
Computing environment adopted by WP4 partners.

Partner	Operative systems	RAM	CPU Characteristics
CIEMAT	Windows 10	32 GB	I7 11700 k (8 cores at 5.0 GHz)
CNSC	Win10-1803 5.06	8 GB	Intel R core i7 CPU1.90 GHz 2.11 GHz
ENEA	Windows 10	32 GB	Intel® Xeon® Silver 4108 CPU @ 1.80 GHz, 1796 MHz, 8 Core (s), 16 Logical Processor(s)
Energorisk	Windows 10	16 GB	IntelI CITM) i9-9900 K CPU
EPRI	Windows 10	16 GB	Xeon 3.6 GHz
GRS	PC-Windows 10/Unix server – Linux, x86_64		
INRNE	64-bit operating systems working under windows 10 Pro	8,00 GB	Intel® Core™ i5-9600 K 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 @ 2.20 GHz
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™ i5-3210 M CPU @ 2,50 GHz 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)

Table 3
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	24–30 h
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

Sampling of the uncertain input parameters was performed by all the partners with Monte Carlo or Latin Hypercube methods. A partner pointed out that simple random sampling (i.e., Monte Carlo) is recommended in association with the Wilks Method (Wilks, 1941, Wilks, 1942). Still Latin Hypercube sampling could be more appropriate (McKay et al., 1979) when other methods are employed. This may be also connected to the management of failed calculations (see Section 5.3). In fact, if the failed calculations are removed from the UQ, the type of sampling may influence the coverage of the uncertain input parameters range.

The probability and confidence level have been set by most of the partners to 95 %, which is in general accepted for UQ; two partners decided to adopt higher values and one partner decided to adopt lower values. Furthermore, it has been underlined that the tolerance limits can be selected in view of the considered FOMs. Some variables may require stricter limits with respect to others to account of their relevance for the safety of the system (i.e., their influence on ST).

In relation to the statistical analysis in general the following parameters have been considered: minimum and maximum values (or lower and upper bounds), mean, standard deviation, median, PDF, Cumulative Distribution Function (CDF), 5 %/95 % band. In addition, one partner adopted the CDF- area difference (Minkowsky L1 metric) and PDF- area difference for a quantitative comparison with the experimental data. In relation to the correlation analysis in general the Pearson and Spearman coefficients have been considered.

4.2. *Analysis of SA code and UT coupling*

The application of a deterministic code, as SA code, together with an UT requires in general two main phases, pre-processing and post-processing, before and after the code running phase, as shown in Fig. 1.

The pre-processing phase includes:

- The identification of the FOMs to be investigated;
- The identification and characterization of the input uncertain parameters PDF and range;
- The sampling of the input uncertain parameters;
- The generation of the set of input-decks.

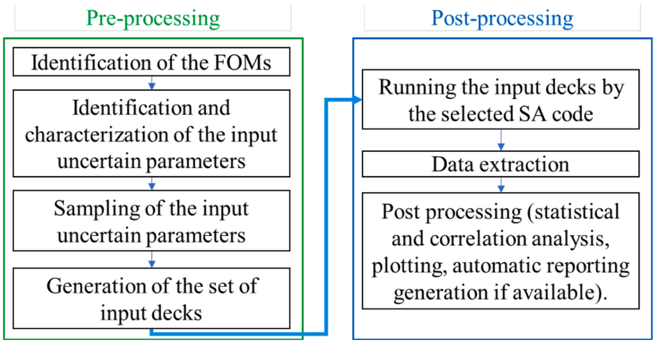


Fig. 1. Example of main tasks to be performed for an UaSA.

The post-processing phase includes:

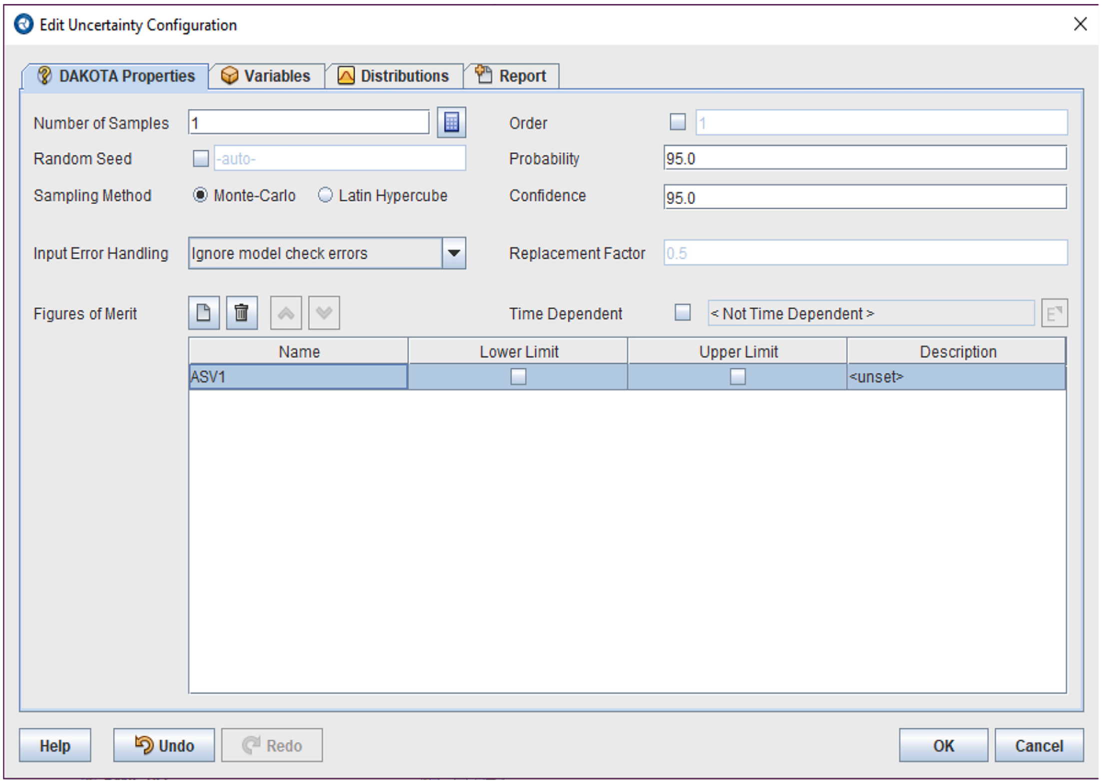
- Running the input-decks by means of the selected SA code;
- The data extraction;
- Statistical and correlation analysis.

The SA code and UT coupling may be performed though a Graphical User Interfaces (GUI). Their main advantage is to be in general user-friendly and to require less time to be used. As example, Fig. 2 shows the Symbolic Nuclear Analyses Package (SNAP) (Applied Programming Technology, 2012) GUI to enter the properties to be set for the UQ. Fig. 3 shows how all the UQ steps have been implemented in the UQ plug-in of the MAAP GUI. The major issue with the GUI is the limited flexibility compared to scripting. In fact, for the statistical analysis, the user can only use the options already available; if the users want to adopt other statistical parameters, this cannot be performed unless the GUI developers implement the needed features, or a mixed approach (e.g. GUI + scripting) is adopted. A similar situation happens if there are some bugs in the GUI that requires the developer intervention. In particular, the issue of managing the failed calculation has been identified in one of the GUI used and the solution required interactions with the GUI developer.

If a GUI is not available, the use of scripting to couple SA code and UT (e.g. Python (Python, 2023), MATLAB (MathWorks, 2023), Visual Basic (Microsoft, 2023) etc.) is needed. This is a high time demanding process and in general it requires a teamwork. Some partners observed that, scripting is powerful, but not user-friendly as a GUI. Moreover, it is UT and SA code dependent, and it could be characterized by a limited portability from one input-deck to another. In addition, compatibility issues between UT and SA code have been underlined by several partners. In general, these issues have been solved with further scripting, which is high time demanding. Along the WP4, for example, some partners preferred to develop their own UT to have major flexibility; another partner initially preferred to develop the pre-processing phase manually. Finally, several tools and programming languages may be adopted in the same SA code and UT coupling to perform the various steps, e.g. as shown in Fig. 4.

Regarding the data post processing, different approaches have been adopted to extract the required data from each specific SA code. In general, each partner has a different way to extract the data from a specific SA code and currently there are no common code user guidelines on it. Along the exercise it has been also observed some compatibility issues of UT (or base programming language) and code plot variable (syntax problem) and the fact that UT could have problem to access the SA code data file. This latter point is a major effort for the code users.

Concerning the possible implementation of the SA code/UT coupling on a cluster to speed up the UQ, some issues have been observed depending on the dimension and number of users of the cluster. In fact, for big clusters the root access right is fundamental to set the SA code and UT; this is coupled with the need for the management of the code license node (e.g. dynamic token, etc.). Therefore, small clusters are more easily manageable, while big clusters are less flexible. In fact, for the latter, it is necessary to contact the administrator of the cluster for route actions and more time is in general needed. In addition, it has been referred some compatibility issues between SA codes (e.g. 32 bit) and



Number of Samples: 1

Random Seed: ☐ -auto-

Sampling Method: ● Monte-Carlo ○ Latin Hypercube

Input Error Handling: Ignore model check errors

Figures of Merit

Name	Lower Limit	Upper Limit	Description
ASV1	☐	☐	<unset>

Order: ☐ 1

Probability: 95.0

Confidence: 95.0

Replacement Factor: 0.5

Time Dependent: ☐ < Not Time Dependent >

Fig. 2. Examples of SA code and UT coupling through GUI: SNAP DAKOTA properties view.

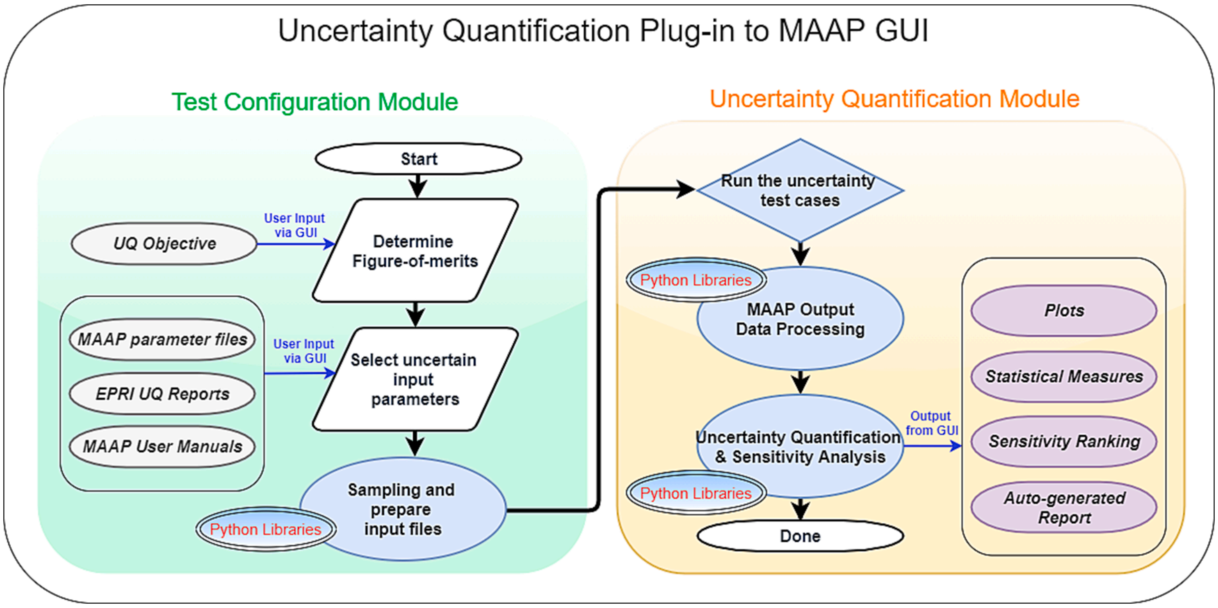


Fig. 3. Examples of SA code and UT coupling through GUI: UQ Plug-in to MAAP GUI.

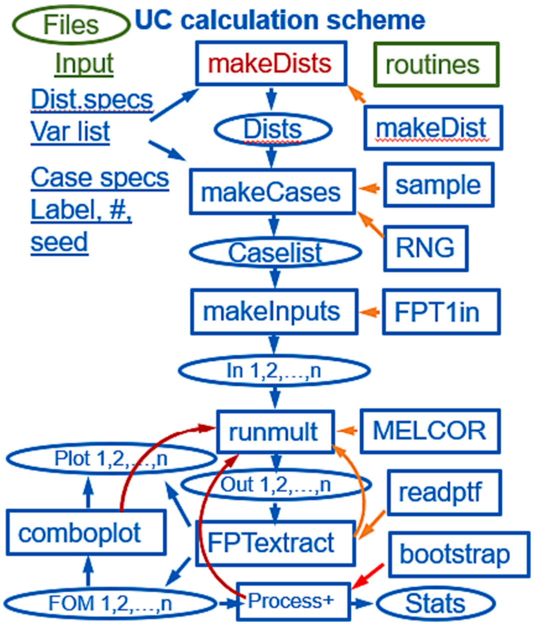


Fig. 4. Example of calculation architecture adopting several scripts.

the cluster (e.g. 64 bit). This however has been handled adding libraries in the cluster (using root access rights).

4.3. *Description of the uncertainty application*

As previously described, partners were free to select the FOMs for the WP4 exercise and the related uncertain input parameters. A list of possible FOMs was provided in the exercise specification (see Section 2.2.1). The MUSA WP4 FOMs independently investigated by the partners are reported in Table 4. In addition, other FOMs independently selected and investigated by partners are:

- Xenon in the containment, caesium iodine (CsI) deposited in containment and total amount of caesium iodine (CsI) in containment by CNSC;
- Amount of suspended element mass – Caesium and Amount of deposited element mass – Caesium by GRS;
- Mass of hydrogen generated by EPRI and KIT;
- Containment pressure by EPRI;
- Total caesium release to the containment, total caesium aerosols amount in the containment's atmosphere and total iodine aerosols (CsI) amount in the containment's atmosphere by SSTC;
- Integrated biologically-weighted airborne fraction in containment by USNRC.

Since a comparison of the reference calculations, and the related accuracy evaluation, was not performed being out of the scope of WP4, the goal of the UaSA application is not to compare the results of the partners in term of statistical values of the FOM but to highlight the encountered issues, the related solutions, and the approaches adopted to analyze the UaSA results (see Section 5).

For the analysis of the UaSA results several indicators were considered by the various partners as described in Section 4.1. However, most of the partners adopted Pearson and Spearman coefficients to characterize the correlation between the FOMs and the selected uncertain input parameters.

5. Main outcomes and lessons learned

In the development of the WP4, the following aspects have been extensively analyzed to collect the main outcomes and lessons learned resulting from the exercise on:

- 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 (including sensitivity analysis);
- SA code.

It should be underlined that some lessons learned and recommendations are general, while others may depend on the scenario that in this case consider only the in-vessel phase of the accident (without molten material in the containment). In addition, it should be recalled that the recommendations from WP4 mainly aim at supporting the plant and SFP analyses.

Table 4
MUSA WP4 FOMs investigated by the partners.

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

5.1. 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 UQ based on the probabilistic propagation of input uncertainties method, also considering that many input uncertain parameters may be code dependent. Sequence/plant assessment to identify the involved phenomena is mandatory prior to the uncertainty source identification and characterization. It should be underlined that in WP4 exercise, the number of input uncertain parameters selected by the partners was different and this may affect the results of the analysis.

Certain combinations of input uncertain parameters may affect the FOMs behavior generating outlier results, as shown for instance in Fig. 5 for the CsI in containment. In general, the combination of input uncertain parameter values close to the upper and lower limits of the corresponding PDF should be investigated separately to understand if they generate outliers and if the obtained FOM behavior is physically acceptable. A possible approach, in case the obtained results show some extreme behavior or one of the investigated parameters gives highly unexpected FOM values, could be to perform an additional set of calculations to see how different ranges of these parameters, or their discard, are impacting the final results. This should give some view on how credible results are and which are the most influencing parameters affecting the overall results. Moreover, on the combination of uncertain input parameters, dependencies between parameters can be applied at the sampling level to avoid unphysical combination of parameters.

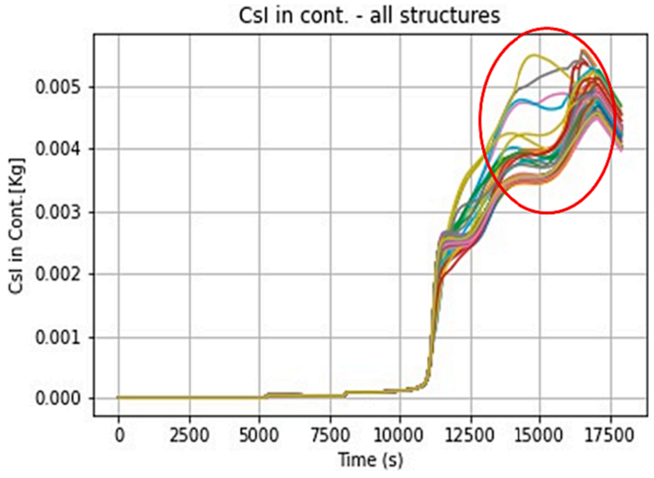


Fig. 5. Examples of possible FOM outlier: CsI in containment – all structures.

In addition, the range of the input uncertain parameters can affect the correlation (e.g. linear, monotonic, etc.) with the FOM. Therefore, the selection of the PDF and the range should be done with care and should be based on references or engineering judgment. In general, experimental data, analytical data and expert judgement are necessary. Existing Phenomena Identification and Ranking Table (PIRT) practices can support the identification of uncertain input parameters and help reducing their number. Different recommendations on this issue have been raised in the WP4. A method for the identification and classification of the input uncertain parameters has been proposed by one partner and it is summarized in Fig. 6; in particular, experiments, researches and expert opinions are considered to determine the phenomena affecting each isotope, then a sensitivity analysis is performed to classify the impact of the uncertain parameters. A partner underlined that when different data sources are found for a specific parameter, a combination of data sources can be applied by selecting the minimum, maximum and expected value from all the data available. With respect to the PDF, if all the data sources for a parameter show the same PDF (i.e., uniform), then this same distribution can be applied.

In case there is no evidence to choose a specific PDF type, several partners suggested the adoption of uniform distributions. It could also be useful to perform a sensitivity analysis starting from wide ranges and simple distributions to characterize the parameter influence on the FOM. However, it should be studied the impact of the uncertain input parameter range and PDF on the final FOM PDF.

Even if the scope of WP4 is not a direct comparison of the partner results some insights can be gained concerning the correlation of some parameters with the various FOMs:

- The FOM "Aerosol amount in the containment's atmosphere" shows a significant correlation with the parameters aerosol dynamic shape factor (CHI) and aerosol agglomeration factor (GAMMA), the correlation varying during the transient;
- The release of fission products from the fuel shows a significant correlation with the XGRAIN parameter (surface area for fission product release);

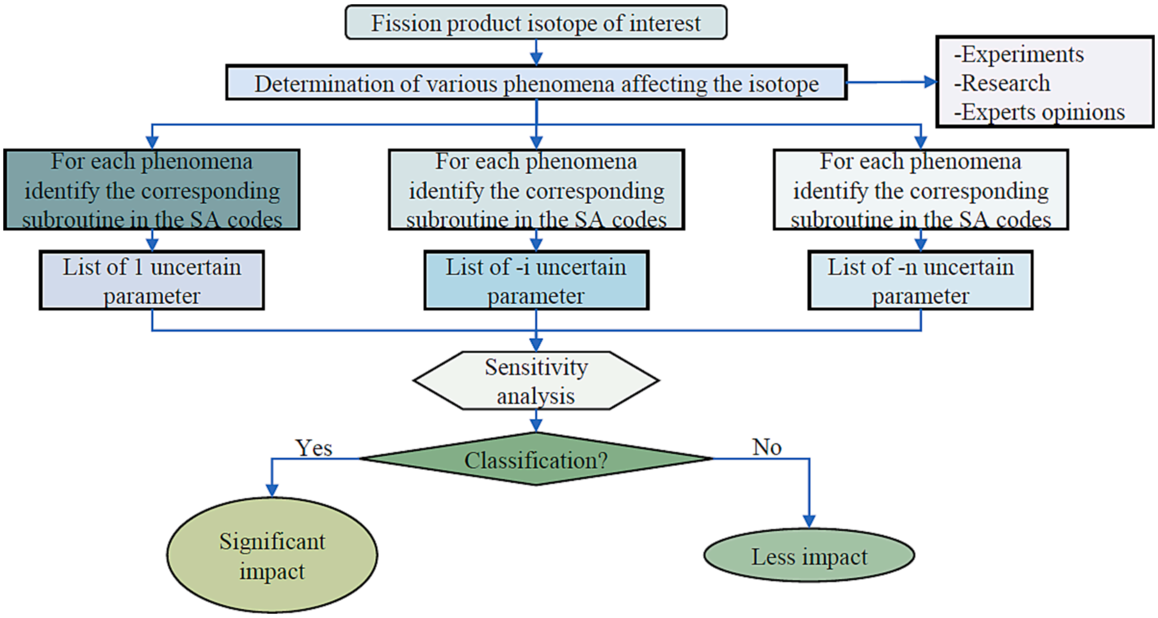


Fig. 6. Example of a proposed approach for the selection of the input uncertain parameters.

- The TCLMAX parameter (that captures the time-at-temperature behavior associated with creep rupture of overheated cladding) influences the in-vessel hydrogen production;
- Another influential parameter is the axial porosity profile, which shows a positive correlation with the amount of gaseous Iodine in the containment's atmosphere and with the total deposited Iodine in the containment, whilst a negative relationship is shown with the other FOMs suggested for WP4;
- The temperature of dislocation of the oxide layer of the cladding resulted to be an influential parameter for the FOMs Iodine and Cesium release from top of the bundle, Cesium retention in the circuit and, additionally, cumulative Hydrogen production;
- Almost all FOMs suggested for WP4, except for suspended and deposited Iodine in containment, show an influence from parameter Zirconia shroud thermal conductivity. The selection of the physical law of Zircaloy-4 cladding oxidation has an impact on all FOMs suggested for WP4, except for the amount of gaseous Iodine in the containment's atmosphere. The parameter UO_2 solidus temperature has an influence on the aerosol mass and in the suspended Iodine in the containment's atmosphere;
- The thermal conductivity of ZrO_2 has an influence on the release of Iodine and release of Cesium from top of the bundle;

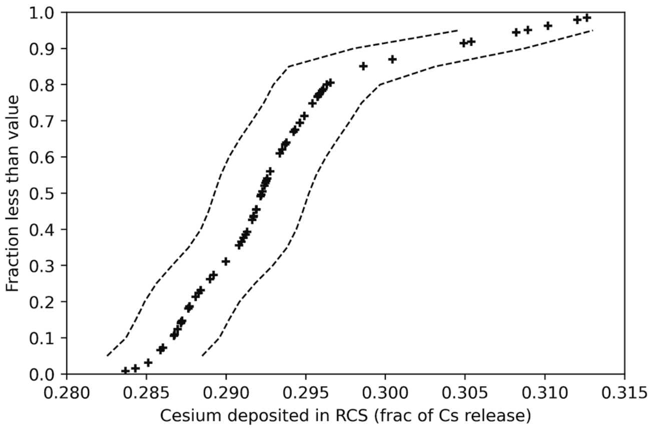


Fig. 7. Example of CDF distortion due to failed calculations.

- CORSOR-Booth model parameter (used to predict radionuclide release) has an influence on the aerosol in containment FOM, in particular a cliff-edge effect occurs when the CORSOR-Booth parameter has the value of 1.0;
- The uncertainty of the heating power has an influence on the releases from the fuel.

5.2. 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 and there is the need to balance user flexibility, user friendliness and tool robustness. Scripting and use of GUI are the two main ways to perform the coupling.

Scripting, even if less user-friendly and more time demanding, resulted extremely powerful and flexible to automate the UaSA process, also for selecting ad-hoc statistical and post-processing techniques maybe not available in some UTs. In the scripting development, 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 and ready to use, but some limitations have been observed in particular for the post-processing capability and in the management of failed calculations. Finally, it should be underlined that a partner that adopted two different approaches for the coupling (GUI and scripting) reported that the results for the scalar analysis (maximum value of the FOM) showed that, despite the different number of total runs and the different samples, mean values were similar and close to the experimental one. Similar results were obtained for the standard deviation.

5.3. Management of the failed calculations

In the adoption of computer codes to develop deterministic safety analysis, during the transient simulation, calculation failures may occur and the simulation is terminated before the time set by the user. The management of the failed calculations is important because, as example, the failed runs can affect the calculated FOM PDF, which may be distorted as shown for instance in Fig. 7 for the Cesium deposited in RCS. Partners, in general, selected different approaches such as:

- Starting the UQ with a number of runs higher than the minimum required number according to Wilks' formula for the selected probability and confidence level. In this way the minimum number of runs can be hopefully correctly executed. Attention should be paid on sampling techniques as Latin Hypercube because discarding the failed runs it can be lost the sampling subinterval value, so the analysis of such failed cases should show their even distribution over the sampling intervals. If failed cases are absent this increased sampling may improve the resulting statistics;
- Replacing the failed runs with new ones, with a different combination of input uncertain parameters;
- Restarting the failed runs to force their completion (adjusting the time step near the run termination time);
- Doing very small adjustment of the input value causing the failure (i^{n} th^{e} 3rd-4th decimal place);
- Removing from the analysis the input parameter that causes the problem, in case it is possible to identify it, and taking into account the bias in the final results;
- Increasing the Wilks' order to allow discarding higher FOM's values (assuming that the failed cases would give the higher FOM's magnitudes), as suggested in (OECD/NEA/CSNI, 2017).

The combinations of input parameters resulting from the sampling process could cause failures in the calculations. If one or more of these combinations can be tracked down, a sensitivity analysis should be performed to evaluate if extreme values are involved in the failures and eventually reduce parameters range of variation. Sometimes, the failures are not directly connected with a sampled uncertain input parameter value or their combination. In these circumstances, the cause of the calculation failure should be investigated and fixed. However, this approach is not practical in case of a large number of run failures.

In general, it has been underlined the need for the management of the failed runs from a statistically solid point of view.

5.4. *Post processing of the data*

The post processing of the data is a key element of the UaSA to properly analyze the results. The analysis can be done for a specific value of the FOM (e.g. the maximum or final value) or time dependent. The latter option allows to analyze the behavior of the FOM considered along the scenario evolution; in this regard, PDF at different timings can be very useful (e.g. Fig. 8). For time dependent analysis, the capabilities of some UTs may be improved for an easier automatic set-up and extraction of the results. However, it should be underlined that the FOM time dependent analysis within the adopted methodology still needs more discussion (e.g. number of calculations required).

In relation to UaSA, some partners considered different threshold values to characterize the relationship between the uncertain input parameters and the FOM (e.g. low, moderate, significant). Table 5 summarizes the coefficients adopted by the partners to characterize the input uncertain parameters with the related adopted threshold values.

Considering that the first step of the UQ is the sampling of the uncertain input parameters, one of post processing approach is the characterization of the variate and the response data. For example, Fig. 9 shows the input uncertain parameter debris velocity (d1) against the iteration index. This plot shows how the parameter range is sampled in various code runs and gives an idea of the coverage of the sampling space. Also, the FOMs can be visualized against the iteration index or against an input uncertain parameter. For example, in Fig. 10 the FOM, integrated biological weighted airborne fraction in the containment, is plotted versus the molten clad drainage rate input uncertain parameter. From this kind of plot, it can be visualized an eventual correlation between the FOM and the input uncertain parameters and possible outlier values.

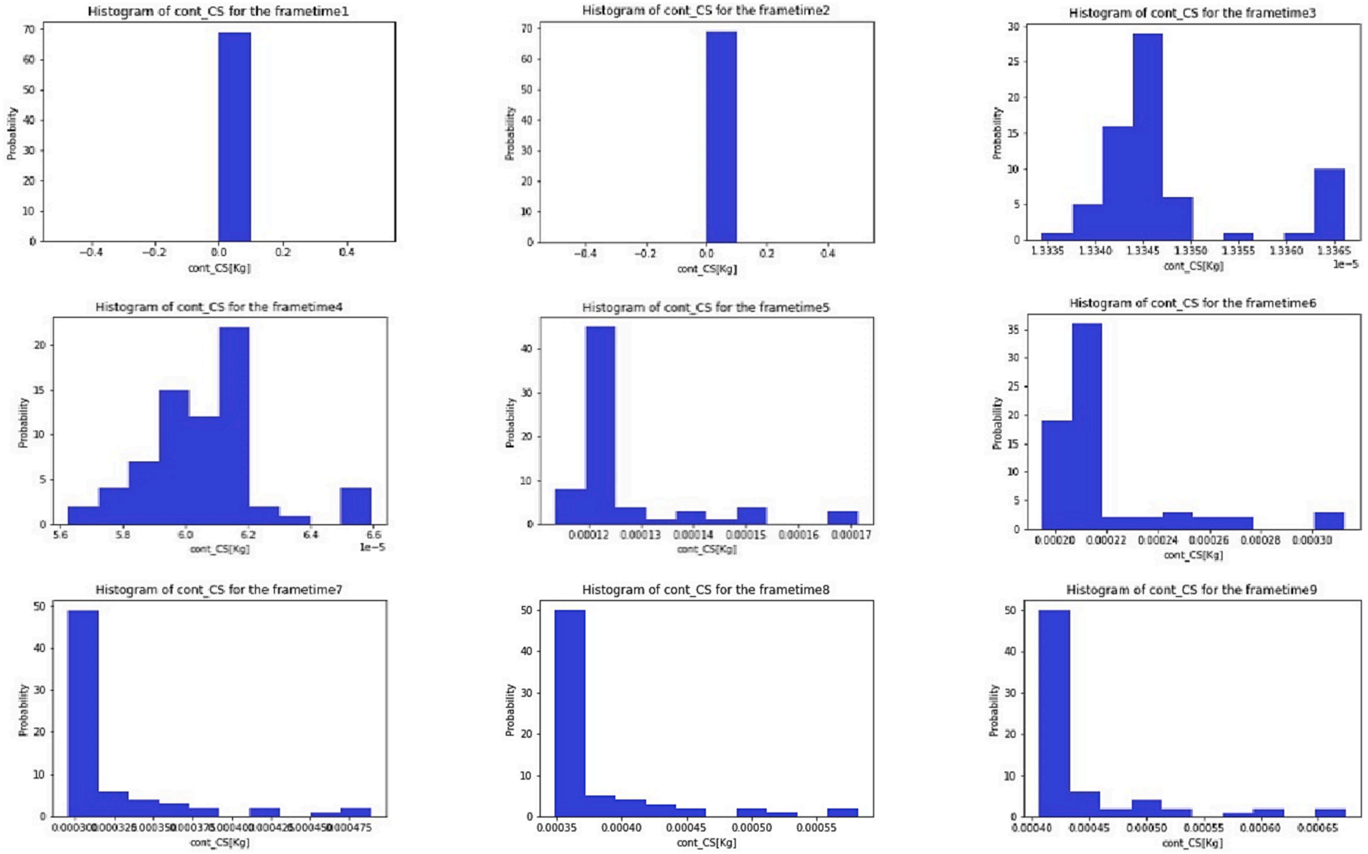


Fig. 8. Example of time dependent FOM PDF: Cs in containment.

Table 5
Coefficients adopted by the partners to characterize the input uncertain parameters relationship with the FOM.

Partner	Type of analysis	Coefficients used	Threshold used to consider the contribution of the uncertain parameters
CIEMAT	Linear	Pearson, Spearman	p-value < 0.05CC confidence interval (Fisher's Transformation)
CNSC	NA	NA	NA
ENEA	Correlation	Pearson, Spearman	Absolute value: <0.2: low ≥0.2 and < 0.5: moderate ≥0.5: significant (Bersano et al., 2020)
Energorisk	Correlation	Pearson, Spearman	Absolute value: >0.9 and < 1.0: very highly >0.7 and < 0.9: highly >0.5 and < 0.7: moderately >0.3 and < 0.5: low <0.3: little if any
GRS	Correlation	Spearman	Absolute value < 0.2: no statistical significanceNote: Coefficient 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	Absolute value: >0.1 and < 0.3: small; >0.3 and < 0.5: medium; >0.5 and < 1.0: large. (Cohen, 1988)
KIT	Correlation	Pearson	Absolute value: <0.2: small/negligible ≥0.2 and < 0.5: moderate ≥0.5: significant
LEI	Correlation	Spearman	Absolute value: <0.2: negligible impact; ≥0.2: influencing parameter. (Kaliatka et al., 2016)
	Correlation	Spearman	Absolute value > 0.2 (Kaliatka et al., 2016)
PSI	Correlation	Pearson, Spearman	Absolute value > 0.2 (Bersano et al., 2020)
SSTC	Correlation	Pearson, Spearman	
Tractebel	Correlation	Pearson	Absolute value: <0.30: Low degree >0.30 and < 0.50: Moderate degree >0.50: Significant degree
TUS	Correlation	Pearson	Absolute value: >0.1 and < 0.3: low >0.3 and < 0.5: middle >0.5: high
UNIPI	Correlation	Pearson, Spearman	Absolute 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)	Absolute 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
VTT	Correlation	Pearson	

Another post processing approach presented by the partners is the use the dispersion plots to have a visualization of the spread of the results. Fig. 11 and Fig. 12 show two examples of dispersion plot; in the first case it has been visualized the Iodine release from fuel (% of the initial inventory), which in the presented calculation is in general within the results dispersion band; in the second case it is presented the amount of suspended iodine in the containment atmosphere that in the presented calculation in general is outside from the results dispersion band. Fig. 13 shows a time dependent statistical analysis (of the Cs relative release from core); in this case with the availability of experimental data, it can be evaluated if they are enveloped in the set of calculation results. Fig. 14, representing the aerosol amount in the containment atmosphere, includes the mean and median value. In this case it is possible to do evaluations about the mean and median curves against the reference calculation.

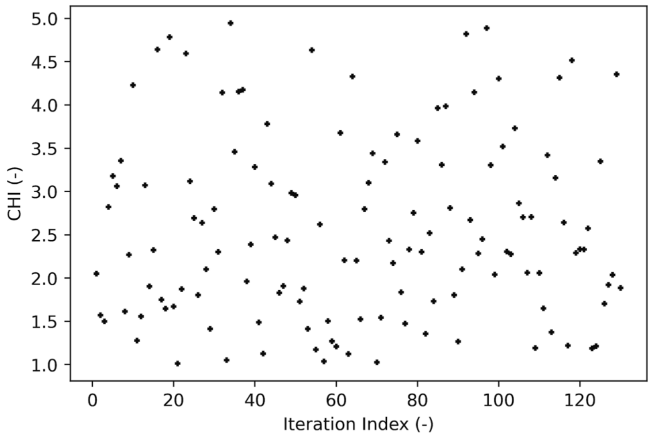


Fig. 9. Example of input uncertain parameter vs iteration index.

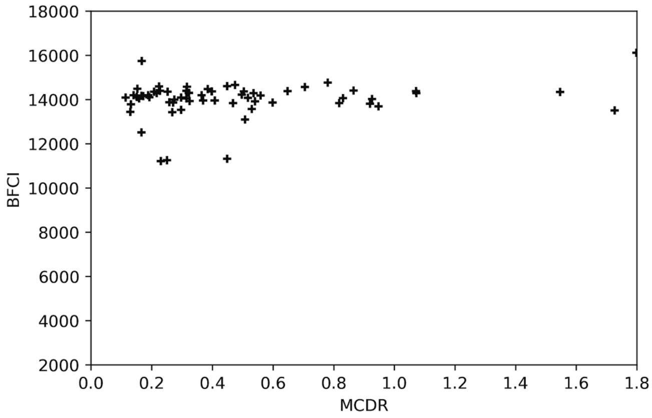


Fig. 10. Example of FOM vs uncertain input parameter.

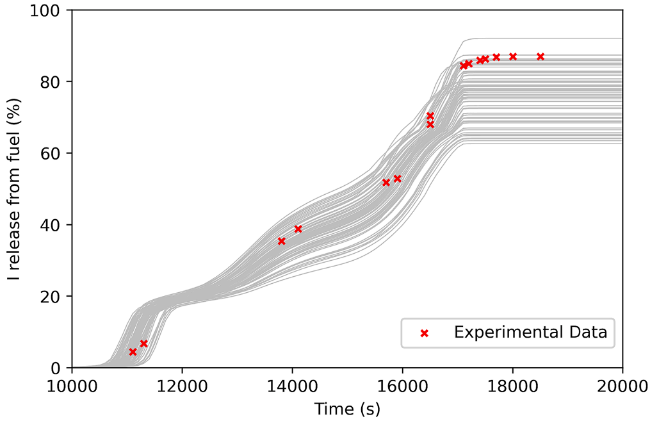


Fig. 11. Example of time dependent FOM dispersion: Iodine release from fuel.

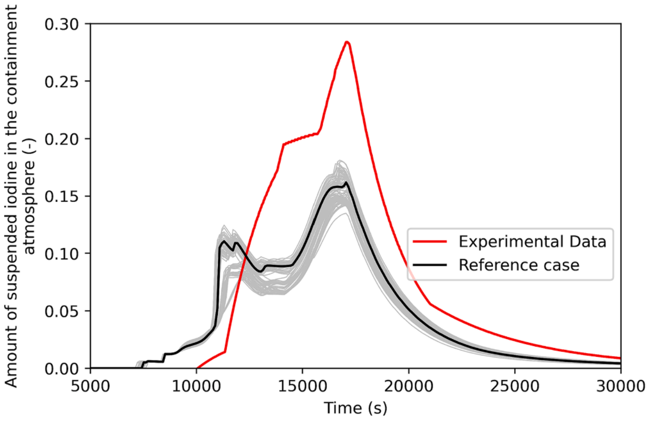


Fig. 12. Example of time dependent FOM dispersion: amount of suspended iodine in the containment atmosphere.

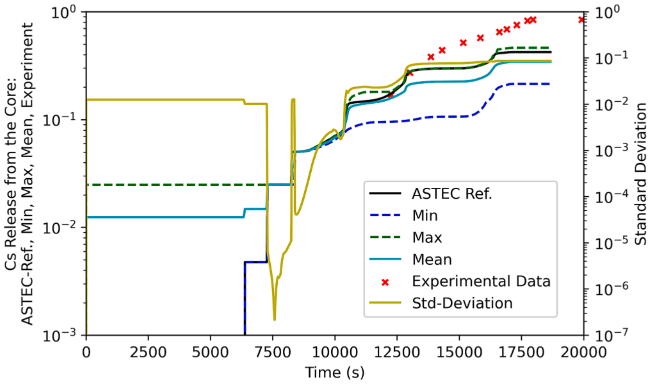


Fig. 13. Example of statistical analysis on time dependent FOM: Cs release from the core.

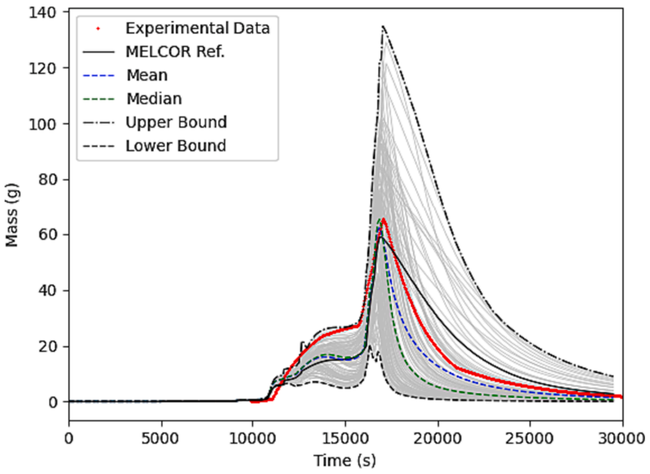


Fig. 14. Example of statistical analysis on time dependent FOM: Aerosol amount in the containment's atmosphere.

If a single value FOM is considered, the tabular form is another way to visualize the results (e.g. Table 6). Also in this case, the statistical analysis was adopted to characterize the selected FOMs in term of minimum, maximum, mean and standard deviation. Another post-processing approach proposed by the partners is to visualize the PDF of the FOMs. This can be done at a given instant, as reported in Fig. 15 for the aerosol in containment, or along the transient as reported in Fig. 8 for Cs and Xe in containment.

Table 6
Example of single value FOM statistical analysis in tabular form for different FOMs.

	Average	Standard deviation	Min	Max
'Outputs_variable#1' (FoM1)	74.95974	0.6271124	73.4806	75.4852
'Outputs_variable#2' (FoM2)	75.80036	0.6060636	74.3709	76.3082
'Outputs_variable#3' (FoM3)	46.74657	0.1430633	46.3545	46.9812
'Outputs_variable#4' (FoM4)	17.39123	0.620686	15.663	17.8552
'Outputs_variable#5' (FoM5)	14.82506	1.730274	10.9911	17.0791
'Outputs_variable#6' (FoM6)	695.6891	23.08408	637.114	712.928
'Outputs_variable#7' (FoM7)	323.1179	39.71518	233.434	364.333

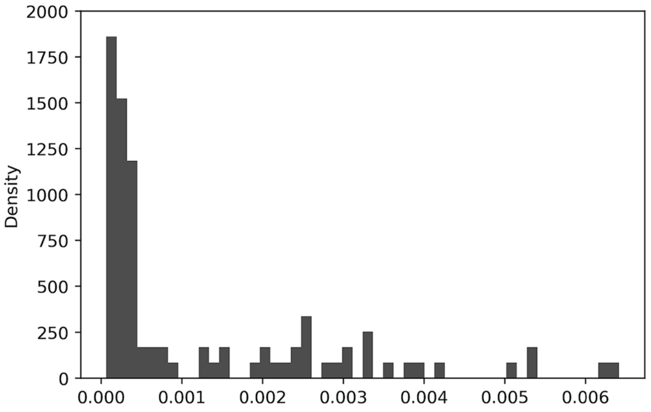


Fig. 15. Example of the frequency of a FOM.

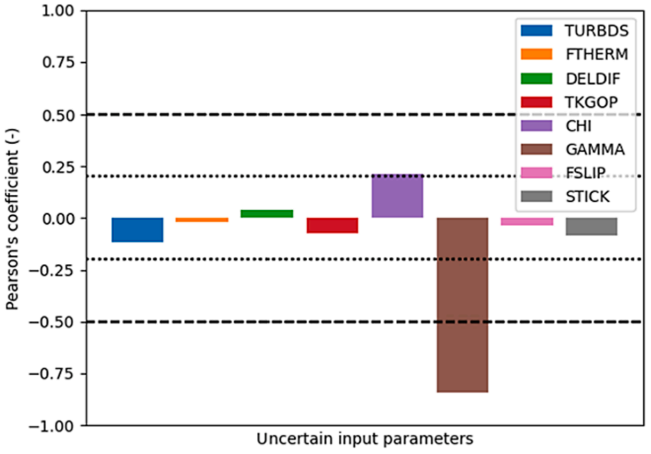


Fig. 16. Example of correlation analysis for a single value FOM.

Finally, another post-processing is the characterization of the statistical correlation between the uncertain input parameters and the FOMs (e.g. through Pearson and Spearman coefficients). Depending on the parameter (e.g. scalar value or time dependent behavior of aerosol amount in the containment's atmosphere) the statistical and correlation analysis has been done on a specific value (Fig. 16) or time dependent (Fig. 17). Fig. 16 shows that the shape factor (to account for non-spherical aerosols in the calculation of coagulation and setting phenomena) has a major linear correlation with the FOM considered in the

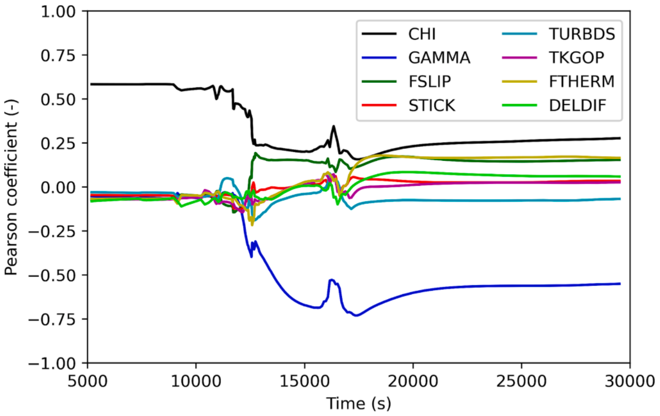


Fig. 17. Example of time dependent correlation analysis.

analyses. The time dependent visualization of the correlation coefficients allows to characterize the correlation between the uncertain input parameters and the FOM along the transient progression. In Fig. 17 the miscellaneous aerosol dynamic constants have been used has input uncertain parameters to characterize the aerosol amount in the containment's atmosphere. It can be observed that the correlation between the input uncertain parameters and the FOM may significantly vary along the transient and, in this case, it stabilizes after around 20000s.

5.5. *SA code*

A comprehensive UQ analysis would require a deep code assessment through which the uncertain input parameters can be identified and, if information available, characterized. Code validation documents might be useful. Eventual missing models should be also identified and considered somehow in the full-scope UQ. However, at the present time SA codes are supposed to address comprehensively most of the relevant phenomena in SA, although presumably modeling in some areas will develop further in the future.

Along the UaSA, the SA codes showed to be sensible to the choice of the input uncertain parameters and their range. Moreover, even the choice of the values of input parameters not varied in the calculation can influence the stability of the calculations (i.e. number of runs that failed); therefore, the user should be aware of that and it is suggested to use consolidated values as a reference for the analyses. In general, it would be a good practice to optimize the input-deck to be as robust as possible; this should help to avoid some failed UQ calculations.

If more modules or packages are used in one SA code, the consistency between input parameters should be carefully considered and there can be some limitations in the coupling between the modules. It means that a deep knowledge of the code models is needed by the code user to fully understand the links between the input parameter values and their physical interpretation to ensure their consistency among the different modules. Also, it is to underline that the computational time required could be an issue for plant applications.

5.6. *Additional remarks*

Considering the enveloping of the experimental data by the UQ calculations, some partners underlined that the UQ should be performed after the accuracy evaluation of the reference calculation. In fact, the reference calculation should be considered accurate enough (if experimental data are available) to be used as a base for the UQ.

6. Final remarks

The WP4 of the MUSA project was aimed at applying and testing UQ methodologies, against the internationally recognized PHEBUS FPT1 test. Despite the completeness of PHEBUS FPT1 test, WP4 exercise is a simplified scenario with respect to a NPP UQ. This allows to build simple, sound and reliable models to: reduce the number of calculation failures; ease the results understanding; and reduce the computational time.

The main outcomes of the WP4 are:

- In general, the direct application of UQ methodologies developed e.g. in nuclear thermal–hydraulic or thermo-mechanics could be more challenging for SA. In fact, some considerations are needed for example for the possible large number of uncertain input parameters (e.g. due to some limitations of geometric prototypical experimental facilities with prototypical material), for the possible higher failure rate of code runs, for the 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 but provided more flexibility, in terms of post-processing capabilities.
- 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.). In fact, the 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. Moreover, 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.
- 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.
- The differences in partners' nodalizations and UaSA applications do not allow to draw a comprehensive conclusion on the uncertainty of the various FOM. However, it has been collected a list of input parameters mostly correlated with various FOMs according to Pearson and Spearman coefficients.

Thanks to the knowledge gained and shared among WP4 partners it is recommended to proceed with NPP scale applications, which are being carried out, among others, in MUSA WP5 and WP6.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

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

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.

References

Adams, B.M., Bohnhoff, W.J., Dalbey, K.R., Ebeida, M.S., Eddy, J.P., Eldred, M.S., Hooper, R.W., Hough, P.D., Hu, K.T., Jakeman, J.D., Khalil, M., Maupin, K.A., Monschke, J.A., Ridgway, E.M., Rushdi, A.A., Seidl, D.T., Stephens, J.A., Swiler, L.P., Winokur, J.G., 2020. A multilevel parallel object-oriented framework for design optimization, parameter estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.13 User's Manual.

Allison, C.M., et al., 1997, SCDAP/RELAP5/MOD 3.2 code manual volume II: damage progression model theory, Tech. Rep. NUREG/CR-6150 INEL-96/0422, Idaho National Engineering and Environmental Laboratory, New York, NY, USA.

Allison, C.M. Berna, G.M., et al., 1998, SCDAP/RELAP5 Users Guide and Input Manual, NUREG/CR-6150 EGG-2720. USA, Idaho National Engineering Laboratory, Vol. 3.

Arndt, S., Band, S., Beck, S., Eschricht, D., Iliev, D., Klein-Heßling, W.,et al., 2019. COCOSYS 3.0.1 User Manual. Hg. v. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH (GRS). Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH (GRS) (GRS-P-3 / Vol. 1, Rev. 54).

Austregesilo, H., Bals, C., Hollands, T., Lovasz, L., Köllein, C., Luther, W., et al., 2019. ATHLET-CD 3.2-User's Manual. Hg. V. Gesellschaft Für Anlagen- Und Reaktorsicherheit (GRS) gGmbH GRS) GRS-P-4/Vol, 1.

Bersano, A., Mascari, F., Porfiri, M.T., Maccari, P., Bertani, C., 2020. Ingress of coolant Event simulation with TRACE code with accuracy evaluation and coupled DAKOTA uncertainty analysis. Fusion Eng. Des. 159.

Blacard, J.B., Damblin, G., Martinez, J.M., Arnaud, G., Gaudier, F., 2019. The URANIE platform; an open-source software for optimisation, meta-modelling and uncertainty analysis. EPJ Nuclear Sci. Tech. 5, 4.

Bosland, L., Weber, G., Klein-Hessling, W., Girault, N., Clement, B., 2012. Modeling and interpretation of iodine behavior in PHEBUS FPT-1 containment with ASTEC and COCOSYS codes. Nucl. Technol. 177 (1), 36–62.

Chatelard, P., Reinke, N., Arndt, S., Belon, S., Cantrel, L., Carenini, L., Chevalier-Jabet, K., Cousin, F., Eckel, J., Jacq, F., Marchetto, C., Mun, C., Piar, L., 2014. ASTEC V2 severe accident integral code main features, current 2.0 modelling status, perspectives. Nucl. Eng. Des. 272, 119–135.

Chojnacki, E., Baccou, J,. SUNSET V2.1: Theory Manual and User Guide, Report N^o PSN-ES/SEMIA/2013-00237.

Clément, B., Haste, T., 2003. Comparison Report on International Standard Problem ISP-46 (PHEBUS FPT1). IRSN. Cadarache, France (Note Technique Semar 03/021).

Clément, B., Zeyen, R., 2013. The objectives of the Phébus FP experimental programme and main findings. Ann. Nucl. Energy 61, 4–10.

Clément, B., Haste, T., Krausmann, E., Dickinson, S., Gyenes, G., Duspiva, J., de Rosa, F., Paci, S., Martin-Fuertes, F., Scholytssek, W., Allelein, H.-J., Güntay, S., Arien, B., Marguet, S., Leskovar, M., Sartmadjiev, A., 2005. Thematic network for a Phebus FPT1 international standard problem (THENPHEBISP). Nucl. Eng. Des. 235 (2–4), 347–357.

Cohen, J., 1988. Statistical power analysis for the behavioral sciences, (2nd ed.),. Erlbaum, Hillsdale, NJ.

Coindreau, O., Mascari, F., 2020. WP4 – Specifications to apply UQ Methods against the PHEBUS-FPT1 experiment, Version 1.

Dalbey, K.R., Eldred, M.S., Geraci, G., Jakeman, J.D., Maupin, K.A., Monschke, J.A., Seidl, D.T., Swiler, L.P., Tran, A., Menhorn, F., Zeng, X., 2020. A multilevel parallel object-oriented framework for design optimization, parameter estimation, uncertainty quantification, and sensitivity analysis: Version 6.13 Theory Manual.

Darnowski, P., Włostowski, M., Stępień, M., Niewiński, G., 2020. Study of the material release during PHÉBUS FPT-1 bundle phase with MELCOR 2.2. Ann. Nuclear Energ. 148.

De la Rosa Blul, J.C., Brumm, S., Mascari, F., Lee, S.J., Carenini, L.,2018. ASTEC–MAAP Comparison of a 2 Inch Cold Leg LOCA until RPV Failure, Science and Technology of Nuclear Installations, 2018.

Dubourg, R., Faure-Geors, H., Nicaise, G., Barrachin, M., 2005. Fission product release in the first two PHEBUS tests FPT0 and FPT1. Nucl. Eng. Des. 235, 2183–2208.

EPRI, 2019, Modular Accident Analysis Program (MAAP) Version 5.05, User's Manual, Palo Alto, CA. 3002015309.

Glaeser, H., 2008. GRS method for uncertainty and sensitivity evaluation of code results and applications. Science and Technology of Nuclear Installations.

Herranz, L.E., Beck, S., Sanchez-Espinoza, V.H., Mascari, F., Brumm, S., Coindreau, O., Paci, S., 2021. The EC MUSA project on management and uncertainty of severe accidents: main pillars and status. Energies 14.

Humphries, L., 2018. MELCOR Code Development Status EMUG 2018, 10th Meeting of the European MELCOR User Group, University of Zagreb, Zagreb, Croatia, April 25-27, https://www.psi.ch/emug/Emug2018EN/EMUG_2018_01.pdf.

IAEA, International Atomic Energy Agency, 2008. Best estimate safety analysis for nuclear power plants. Uncertainty Evaluation, Safety Reports Series.

Jacquemain, D., Bourdon, S., de Braemaeker, A., Barrachin, M., 2000. FPT1 final report (Final version). IPSN/DRS/SEA/PEPF Report SEA1/00, IP/00/479.

Kaliatka, T., Kaliatka, A., Vileiniškis, V., 2016. Application of best estimate approach for modelling of QUENCH-03 and QUENCH-06 experiments. Nucl. Eng. Technol. 48, 419–433.

Kloos, M., 2020. SUSA Version 4.2, Software for Uncertainty and Sensitivity Analyses, User's Guide and Tutorial, GRS-P-5, Vol. 1, Rev. 6, GRS gGmbH, Garching.

Sandia National Laboratories, 2017, MELCOR Computer Code Manuals, Vol. 1: Primer and Users' Guide, Version 2.2.9541," SAND 2017-0455 O, (ADAMS Accession No. ML17040A429). MELCOR Computer Code Manuals, Vol. 2: Reference Manual, Version 2.2.9541," SAND 2017-0876 O, Sandia National Laboratories, January 2017 (ADAMS Accession No. ML17040A420).

Lerchl, G., Austregesilo, H., Langenfeld, A., Schöffel, P.J., von der Cron, D., Weyermann, F., 2019. ATHLET 3.2 User's Manual. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH (GRS) (GRS-P-1/Vol. 1 Rev. 8).

Mascari, F., Nakamura, H., Umminger, K., De Rosa, F., D'Auria, F., 2015. Scaling issues for the experimental characterization of reactor coolant system in integral test facilities and role of system code as extrapolation tool, Proceedings Of International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH 2015), 6, 4921-4934.

Mascari, F., Rocchi, F., Carny, P., Liptak, L., Adorni, M., Fontanet, J., Herranz, L.E., 2019. FASTNET SCENARIOS DATABASE DEVELOPMENT AND STATUS, The 9th European Review Meeting on Severe Accident Research (ERMSAR2019), Prague, Czech Republic, March 18-20, 2019.

Mascari, F., De La Rosa Blul, J.C., Sangiorgi, M., Bandini, G., 2019. Analyses of an unmitigated station blackout transient in a generic PWR-900 with ASTEC, MAAP and MELCOR codes, NUREG/IA-0515.

Mascari, F., Herranz, L.E., Beck, S., Sánchez-Espinoza, V., Brumm, S., Coindreau, O., Paci, S., 2021. The MUSA project: management and uncertainties of severe accidents, EUROSAFE2021, Paris (France), November 22-23 2021.

F. Mascari, A. Bersano, M. Massone, G. Agnello, O. Coindreau, S. Beck, L. Tiborcz, S. Paci, M. Angelucci, L.E. Herranz, R. Bocanegra, Y. Pontillon, OU Pingwen, GE Zhenzhen, M. Berdai, O. Cherednichenko, A. Iskra, M. Nudi, P. Groudev, P. Petrova, F. Kretzschmar, F. Gabrielli, Z. Kanglong, V. Vileiniškis, T. Kaliatka, J. Kalilainen, M. Malicki, Gao Shengqin, D. Gumenyuk, Y. Vorobyov, O. Kotsuba, P. Dejardin, M. Di Giuli, R. Thomas, I.V. Ivanov, F. Giannetti, M. D'Onorio, G. Caruso, M. Salay, T. Sevon, 2022, First outcomes from the PHEBUS FPT1 uncertainty application done in the EU-MUSA project, The 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19) Brussels, Belgium, March 6 - 11, 2022.

MathWorks, 2023, https://www.mathworks.com/.

McKay, M.D., Conover, W.J., Beckman, R.J., 1979. A comparison of three methods for selecting values in the analysis of output from a computer code. Technometrics.

Microsoft, 2023, https://learn.microsoft.com/en-us/dotnet/visual-basic/.

OECD, NEA, CSNI,, 2011. BEMUSE Phase VI Report: Status Report on the Area, Classification of the Methods. Conclusions and Recommendations NEA/CSNI/R (2011), 4.

OECD/NEA/CSNI, 1992, Source term uncertainty, recent development in understanding fission product behaviour, NEA/CSNI/R(92)2.

OECD/NEA/CSNI, 1996, SOAR on Containment Thermalhydraulics and Hydrogen Distribution, NEA/CSNI/R(1999)16.

OECD/NEA/CSNI, 2001, In-Vessel Core Degradation Code Validation Matrix, Update 1996-1999, NEA/CSNI/R(2000)21.

OECD/NEA/CSNI, 2004, ISP-46 - PHEBUS FPT-1 Integral Experiment on Reactor Severe Accidents, NEA/CSNI/R(2004)18.

OECD/NEA/CSNI, 2007, BEMUSE Phase III Report: Uncertainty and Sensitivity Analysis of the LOFT L2-5 Test, NEA/CSNI/R(2007)4.

OECD/NEA/CSNI, 2009, State-Of-The-Art Report On Nuclear Aerosols, NEA/CSNI/R (2009).

OECD/NEA/CSNI, 2014, Containment code validation matrix, NEA/CSNI/R(2014)3.

OECD/NEA/CSNI, 2016, PREMIUM: A Benchmark on the Quantification of the Uncertainty of the Physical Models in the System Thermal-hydraulic Codes. Methodologies and Data Review, NEA/CSNI/R(2016)9.

OECD/NEA/CSNI, 2017, Post-BEMUSE Reflood Model Input Uncertainty Methods (PREMIUM) Benchmark – Final Report, NEA/CSNI/R(2016)18.

Python, 2023, https://www.python.org/.

Rabiti, C., Alfonsi, A., Cogliati, J., Mandelli, D., Kinoshita, R., Sen, S., Wang, C., Talbot, W.P., Maljovec, D. P., Chen, J., 2017. RAVEN User Manual, INL/EXT-15-34123.

Applied Programming Technology, 2012, Inc. Symbolic Nuclear Analysis Package (SNAP) User's Manual.

Van Dorsselaere, J.P., Mustoe, J., Power, S., Adorni, M., Schaffrath, A., Nieminen, A., 2016. ETSON views on R&D priorities for implementation of the 2014 Euratom Directive on safety of nuclear installations. Kerntechnik 81 (5), 527–534.

Van Dorsselaere, J.P., Barrachin, M., Power, S., Adorni, M., Hrehor, M., Mascari, F., Schaffrath, A., Tiselj, I., Uspuras, E., Yamamoto, Y., Gumenyuk, D., Fedotova, N., Cronvall, O., Liska, P., 2018. The summary of ETSON strategic orientations on research activities ETSON research group activity. ATW International Journal for Nuclear Power 63 (1).

Wald, A., 1943. An extension of Wilks' method for setting tolerance limits. Ann. Math. Stat. 14, 45–55.

Wilks, S.S., 1941. Determination of sample sizes for setting tolerance limits. Ann. Math. Stat. 12 (1), 91–96.

Wilks, S.S., 1942. Statistical prediction with special reference to the problem of tolerance limits. Ann. Math. Stat. 13 (4), 400–409.