FIRST OUTCOMES FROM THE PHEBUS FPT1 UNCERTAINTY APPLICATION DONE IN THE EU-MUSA PROJECT

F. Mascari[a], A. Bersano[a], M. Massone[a], G.Agnello[a,b]
[a]ENEA-BOLOGNA
Via Martiri di Monte Sole 4, 40129, Bologna, Italy.
fulvio.mascari@enea.it, andrea.bersano@enea.it, mattia.massone@enea.it
[b]Università degli Studi di Palermo
Viale delle Scienze, Edificio 6, 90128, Palermo, Italy

O. Coindreau
IRSN
Centre de Cadarache, B.P. 3 – 13115 Saint-Paul-lez-Durance Cedex, France
olivia.coindreau@irsn.fr

S. Beck, L. Tiborcz
GRS
Germany
sara.beck@grs.de, Livia.Tiborcz@grs.de

S. Paci, M. Angelucci
UNIPI
Department of Civil and Industrial Engineering (DICI), University of Pisa, Italy
sandro.paci@unipi.it, michela.angelucci@phd.unipi.it

L.E. Herranz, R. Bocanegra
Nuclear Safety Research Unit, Department of Energy, CIEMAT
Avda. Complutense 40 Edificio 12-P0-13) 28040 Madrid, Spain
luisen.herranz@ciemat.es, Rafael.Bocanegra@ciemat.es

Y. Pontillon
CEA
CEA, DES, IRESNE, DEC, Cadarache F-13108 Saint-Paul-Lez-Durance, France
yves.pontillon@cea.fr

Wang Hui
CNPE
China
wanghuia@cnpe.cc

OU Pingwen, GE Zhenzhen
CNPRI
21/F, Science and Technology Building, Shangbuzhong Road, Futian District, Shenzhen, China
oupingwen@cgnpc.com.cn, gezhenzhen@cgnpc.com.cn

M. Berdai
CNSC
Canada
mounia.berdai@cnsc-ccsn.gc.ca

O. Cherednichenko, A. Iskra
Energorisk
Ukraine
e.risk@ukr.net, andriy.iskra@ukr.net

M. Nudi
EPRI
USA
mnudi@epri.com;

P. Groudev, P. Petrova
Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, (INRNE-BAS)
Tzarigradsko Chaussee 72, 1784 Sofia, Bulgaria
pavlinpg@inrne.bas.bg, petia@inrne.bas.bg

F. Kretzschmar, F. Gabrielli, Z. Kanglong
Karlsruhe Institute of Technology, Institute for Neutron Physics and Reactor Technology
Hermann-von-Helmholtzplatz, 1 D - 76344 Eggenstein-Leopoldshafen
Karlsruhe, Germany
frank.kretzschmar@kit.edu, fabrizio.gabrielli@kit.edu, kanglong.zhang@kit.edu

V. Vileiniškis, T. Kaliatka
Lithuanian Energy Institute (LEI)
Breslaujos g. 3, Kaunas 44403– Lithuania
Virginijus.Vileiniskis@lei.lt, Tadas.Kaliatka@lei.lt

Deng Lilin
NPIC
China
3165024168@qq.com

J. Kalilainen, M. Malicki
Paul Scherrer Institute
Forschungsstrasse 111, 5232 Villigen PSI, Switzerland
jarmo.kalilainen@psi.ch, mateusz.malicki@psi.ch

Gao Shengqin
SNERDI
China
gaoshengqin@snerdi.com.cn

D. Gumenyuk, Y. Vorobyov, O. Kotsuba
SSTC NRS
Ukraine
dv_gumenyuk@sstc.com.ua, yy_vorobyov@sstc.com.ua, ol_kotsuba@sstc.com.ua

P. Dejardin, M. Di Giuli, R. Thomas
TRACTEBEL
Tractebel ENGIE, Severe Accident Department, Avenue S. Bolivar 34-36, Brussels, BELGIUM
philippe.dejardin@tractebel.engie.com, mirco.digiuli@tractebel.engie.com, robin.thomas1@tractebel.engie.com

I.V. Ivanov
TUS
8 Kl. Ohridski Blvd., Block 12, 1000 Sofia, Bulgaria
ivec@tu-sofia.bg

F. Giannetti, M. D'Onorio, G. Caruso
Sapienza University of Rome, Department of Astronautical, Electrical and Energy Engineering (DIAEE), Corso Vittorio Emanuele II, 244 – 00186, Roma, Italy.
fabio.giannetti@uniroma1.it, matteo.donorio@uniroma1.it, gianfranco.caruso@uniroma1.it

M. Salay
USNRC
USA
Michael.Salay@nrc.gov

T. Sevon
VTT Technical Research Centre of Finland, Kivimiehentie 3, Espoo, Finland.
tuomo.sevon@vtt.fi

ABSTRACT

The Management and Uncertainties of Severe Accidents (MUSA) project, founded in HORIZON 2020 and coordinated by CIEMAT (Spain), aims to consolidate a harmonized approach for the analysis of uncertainties and sensitivities associated with Severe Accidents (SAs) by focusing on Source Term (ST) Figure of Merits (FOM). In this framework, among the 7 MUSA WPs the Application of Uncertainty Quantification (UQ) Methods against Integral Experiments (AUQMIE – Work Package 4 (WP4)), led by ENEA (Italy), looked at applying and testing UQ methodologies, against the internationally recognized PHEBUS FPT1 test. Considering that FPT1 is a simplified but representative SA scenario, the main target of the WP4 is to train project partners to perform UQ for 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, and in MUSA for SA analyses. As a consequence, WP4 application creates the technical background useful for the full plant and spent fuel pool applications planned along the MUSA project, and it also gives a first contribution for MUSA best practices and lessons learned. 16 partners from different world regions are involved in the WP4 activities. The purpose of this paper is to describe the

MUSA PHEBUS FPT1 uncertainty application exercise, the methodologies used by the partners to perform the UQ exercise, and the first insights coming out from the calculation phase.

KEYWORDS
MUSA, PHEBUS, UNCERTAINTY

1. INTRODUCTION

The Management and Uncertainties Of Severe Accidents (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". It is coordinated by CIEMAT (Spain) and started on the 1st June 2019 with a planned duration of 48 months. 28 Organizations from 16 Countries are involved [1,2].

The project aims to establish a harmonized approach for the Uncertainties and Sensitivities Analyses (UaSA) associated with Severe Accident (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 GEN II and III reactor designs. The main pillars of the project are:

- Identification of key SA processes/phenomena affecting the Source Term (ST) and quantification of their associated uncertainties;
- Identification and quantification of key parameters of Accident Management (AM) measures implemented in the SA affecting the ST, and their associated uncertainties;
- Evaluation of applicable methods of Uncertainty Quantification (UQ) (sensitivity analyses included) to the SA field and definition of best UQ application practices in SA analyses;
- Trial of UaSA methodologies against simplified but representative experimental scenarios with strong emphasis on ST;
- Application of UaSA methodologies to risk-dominant reactor and SFP SA sequences;
- Recommendations for an effective reduction of remaining code uncertainties associated with the ST and their impact on AM measures;
- Recommendations for improvement and/or new innovative AM measures for both reactor and SFP scenarios.

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 Work Packages structure (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).

In this framework, the WP4, led by ENEA (Italy), is aimed at applying and testing UQ methodologies, against the internationally recognized PHEBUS FPT1 test [3,4], used also for the OECD/NEA International Standard Problem 46 [3,6]. The purpose of this paper is to describe the MUSA PHEBUS FPT1 uncertainty application exercise [5], the methodologies used by the partners to perform the UQ exercise, the first insights coming out from the calculation phase. Section 2 describes the Phebus FPT1 exercise and WP4 objectives; Section 3 presents the exercise results and lessons learned and Section 4 the conclusions.

2. PHEBUS FPT1 EXERCISE AND WP4 OBJECTIVES

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 severe accident in a light water reactor [7]. The second test of the program (FPT1), carried out on 26 July 1996 in the Phébus facility at Cadarache (France) [8] 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 comprises a fuel degradation phase, an aerosol phase, a washing phase and a chemistry phase.

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. Consequently, WP4 application creates the technical background useful for the full plant and spent fuel pool applications planned along the MUSA project (WP4 and WP5). In addition, it provides a first contribution for MUSA best practices and lessons learned (WP3). 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. 16 partners from three different world regions are involved in the WP4 activities. Table I summarizes the involved partners, SA code and UT used.

The sub-WP4.1 has been focused on the development of the benchmark exercise specifications: description of the PHEBUS facility, of the FPT1 test, selection of the Figure Of Merits (FOM) and distribution of experimental data. All the efforts developed along the ISP 46 [3] have been considered as a common sound background to develop the WP4 exercise. As agreed in the specification phase, 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. Table II shows the FOMs, source term focused, that have been identified in the WP2 for the reactor case application and that have been considered relevant for the WP4. Similarly, a database for the input uncertain parameters has been elaborated in WP2 and partners have been encouraged to use that database. However, partners were free to use their own input uncertain parameters and the related characterization, with the requirement that they are defendable with respect to the ones proposed in WP2, and eventually give a feedback to WP2.

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. Since it has been agreed from the partner that the main WP4 purpose is to be a hands-on training with UaSA methods, no benchmark of the results has been planned and no task on accuracy evaluation of the reference calculation, against experimental data, has been requested. Therefore, considering the several activities done in the last 2 decades (e.g. ISP 46 [3,6]) and the limited resources available in the WP4, MUSA project benefits of these previous activities in term of code accuracy evaluation and benchmarking (code VS exp data and code-to-code) and this is considered the base sound background to build the WP4 exercise focused only on the uncertainty application.

Table I. WP4 partners, with the adopted SA codes and uncertainty tools.

PARTNER	SEVERE ACCIDENT CODE	UNCERTAINTY TOOL
CIEMAT	MELCOR 2.2	DAKOTA 6.12
CNPRI, SNERDI, CNPE, NPIC	There are four companies in China participating in the MUSA project, and CNPRI is the representative.	
CNSC	MELCOR	Python scripts
ENEA	MELCOR 2.2	DAKOTA
Energorisk	MELCOR 1.8.5	DAKOTA
EPRI	MAAPv5.05	Python w/associated packages, DAKOTA 6.10
GRS	AC^2	SUSA 4.2
INRNE	ASTEC 2.2	SUNSET
KIT	ASTEC v2.2	URANIE 4.1
LEI	ASTEC V2.1.1.6	SUNSET V2.1
	RELAP/SCDAPSIM mod3.4	SUSA 4.1
PSI	MELCOR 2.2	DAKOTA 6.12.0
SSTC	MELCOR 1.8.6, 2.1/2.2	SUSA 4.0
Tractebel	MELCOR 2.2	Python script
TUS	ASTEC 2.1.1.	SUNSET
UNIPI	MELCOR 2.2	DAKOTA 6.13.0
UNIRM1	MELCOR 2.2	RAVEN v2.1
USNRC	MELCOR 2.2	DAKOTA
VTT	MELCOR 2.2	DAKOTA with SNAP 3.1.3

The critical analysis of the results (WP 4.3) will start in July 2021 and will be based on the analysis of lessons learned and best practices for each SA and UT. This includes critical analysis of issues that arose during WP4.2 and eventually their resolution, as well as any recommendation for future UaSA tool development. This will provide a feedback to WP3, WP5 and WP6.

3. FIRST CRITICAL ANALYSIS OF THE RESULTS

This section gives the first insights coming out from the calculation phase, and the main issues and lesson learned so far. Therefore, the main discussion will be based on: analyses of SA and UT coupling, uncertainty analysis applications methodology, uncertainty analysis visualization of the results and lesson learned.

3.1. Analysis of SA and UT coupling

The application of a deterministic code, as SA code, together with an UT requires, as shown in Figure 1, two main phases: pre-processing and post processing phase.
The pre-processing phase includes:

- Identification of the FOMs to be investigated;
- Identification and characterization of the input uncertain parameters in term of Probability Density Function (PDF) and range;
- Sampling of the input uncertain parameters;
- Generation of the set of input decks;

The post-processing phase includes:

- Running the input decks by the selected SA code;
- Data extraction;

- Post processing (statistical and correlation analysis, plotting, automatic reporting generation if available).

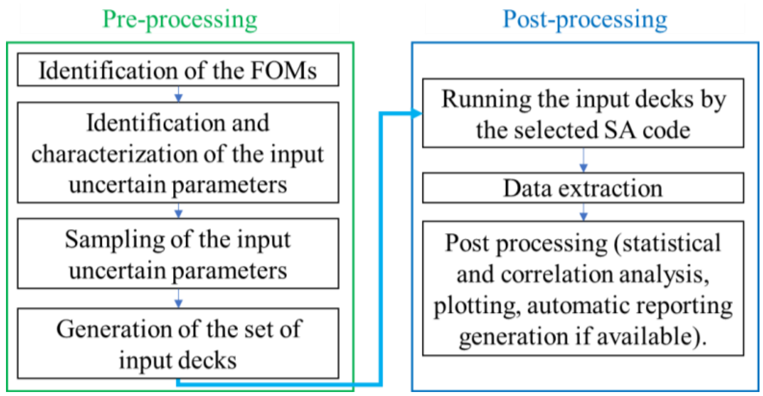

Figure 1. Example of main tasks to be performed to do an uncertainty analysis.

From the analysis of the first results, it can be underlined that four major challenges have been identified by the partner: 1) SA code and UT coupling (e.g., scripts); 2) Managing of the failed calculations and debugging; 3) Extraction of the data for the post processing; 4) Eventual implementation in the cluster of the SA code and UT.

First outcomes from the coupling of SA code and UT reveal that in some cases where Graphical User Interface (GUI) is not already available, the use of scripting to couple SA code and UT (e.g. Python, Pearl, Fortran, MATLAB, Visual Basic, etc.) was needed. This is a high time demanding process and in general it requires a teamwork. Along the discussion it has been observed that, in general, scripting is powerful but is not user friendly as a GUI, it is UT and SA code dependent and could be characterized by a limited portability by 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, one partner preferred to develop its own UT to have a 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 and UT coupling to perform the various steps.

In relation to the GUI, along the WP4 discussion it has been underlined that the main advantage is to be user-friendly and to require less time to be used. As example, Figure 2 (left) shows the Symbolic Nuclear Analyses Package (SNAP) [9] GUI to enter the properties to be set for the UA. Figure 2 (right) shows how all the UA steps have been implemented in the uncertainty quantification plug-in of the MAAP GUI. The major issue with the GUI is its 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. Same situations happen 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.

Calculations' failure is another issue that has been shared by many partners. Managing the calculation failures added supplementary effort to the code users to debug the errors, in addition to the need for handling the missing code runs from a solid statistical point of view. With this respect, it should be underlined that for one of the involved codes, changing one parameter related to the aerosol constants reduced the failures from 80% to 0%. This clearly shows the importance of the user effect in the selection of the reference value for the UQ and the PDF characterization.

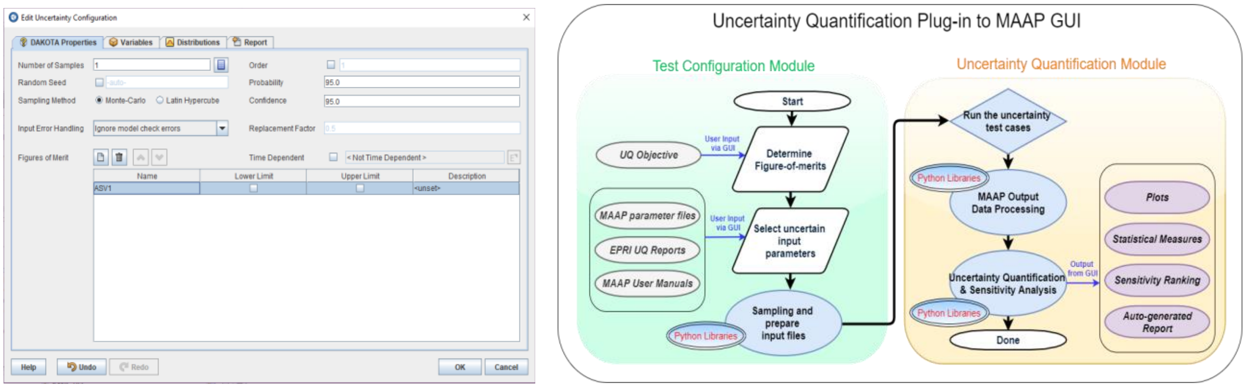

Figure 2. Examples of SA and UT coupling through GUI: SNAP DAKOTA properties view (left) and Uncertainty Quantification Plug-in to MAAP GUI (right).

Regarding the post data processing, different approaches have been adopted to extract the required data from each specific SA code. From the analysis of the UQ, it can be concluded that in general each partner could have different ways 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.

It has been showed that implementation 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 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 the cluster (e.g. 64 bit). This however has been handled adding libraries in the cluster (using root access rights). The use of GUI in the cluster should still be verified.

3.2. Uncertainty analysis applications methodology

All the partners adopted the probabilistic method to propagate input uncertainties [10], 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 [11,12] was adopted by all the partners considering the 1st or 2nd order. A still open point is the dependence among FOMs selected and how this fact will affect the uncertainty assessment.

Simple random sampling was adopted by all the partners with a Monte Carlo or Latin Hypercube method and the probability and confidence level have been set to 95% and 95% by all the partners except for two partners which adopted higher values. In relation to the statistical analysis in general the following parameters have been considered: minimum and maximum value (or lower and upper bound), mean, standard deviation, median, PDF, 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; in addition, one partner adopted also the Analysis of Variance (ANOVA). The possibility of exploring other correlation coefficients is also considered by some partners.
Concerning code calculation crashes, different approaches have been adopted. Among which it might be mentioned: starting with a higher number of runs, slight input adjustments, running separate calculations, modifying the time settings for the calculation. All of them to be discussed along MUSA.

3.3. Uncertainty analysis visualization of the results

Along the UA, all the partners did a statistical and a correlation analysis, as requested from the exercise specifications. The MUSA WP4 FOMs independently investigated by the partners and presented at the 3rd intermediate meeting are reported Table II. In addition, other FOMs independently selected and investigated by partners are: xenon in the containment and caesium retention in the containment by CNSC; mass of caesium in the containment by Energorisk; mass of hydrogen generated in the core by EPRI and KIT; caesium relative release from the PL by KIT; 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.

Table II. MUSA WP4 FOMs investigated by the partners.

Partners \ FOM	Release of iodine from the test fuel bundle	Release of caesium from the test fuel bundle	Caesium retention in the circuit	Aerosol mass in suspension in the containment's atmosphere	Amount of gaseous iodine in the containment's atmosphere	Amount of suspended iodine in the containment's atmosphere	Total deposited iodine in the containment
CIEMAT	X	X		X			X
CNPRI							
CNSC			X				
ENEA				X			
ENERGORISK							
EPRI	X	X		X	X	X	
GRS							
INRNE	X	X	X	X	X	X	X
KIT		X					
LEI-ASTEC	X	X	X	X	X	X	X
LEI-RELAPSCDAPSIM	X	X					
PSI			X	X			
SSTC					X		
TUS	X			X	X	X	X
UNIPI				X			
UNIRM1				X			
USNRC	X	X	X	X	X	X	X
VTT	X	X	X			X	X
TRACTEBEL		X	X	X			

Considering that the first step of the UA is the sampling of the uncertain input parameters, one of post processing approach presented by the partners is to characterize the variate and the response data. For example, in Figure 3 (left) is shown 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 Figure 3 (right) the FOM, integrated biological weighted airborne fraction in the containment, is plotted versus the molten clad drainage rate input uncertain parameters. From this kind of plot, it is easy to visualize eventual correlation between the FOM and the input uncertain parameters and to visualize possible outlier values.

Another post processing approach presented by the partners is the use the dispersion plots to have a visualization of the spread of the results. In Figure 4, are shown two examples of dispersion plot presented along the intermediate review meeting; in the first case has been visualized the Iodine release from fuel (% of the initial inventory), which in the presented calculation is in general inside the uncertainty band; in the second case is presented the amount of suspended iodine in the containment atmosphere that in the presented calculation in general is outside from the uncertainty band. Figure 5 (left) shows a time dependent statistical analysis (of the Cs relative release from core) where, considering the minimum and maximum values, it can be characterized the dimension of the uncertainty band; in addition, also in this case with the availability of experimental data, it can be evaluated if they are enveloped in the set of calculation results. Figure 5 (right), representing the aerosol amount in the containment atmosphere, includes the mean and median value. In this case it is possible to make evaluations about the mean curve with the reference calculation.

If the FOM considered is not time dependent and a single value FOM is considered, as reported in Table III, the tabular form is another way very useful to have clear visualization of the results. Also in this case statistical analysis was adopted to characterize the selected FOMs in term of minimum, maximum, mean, median, standard deviation. Mean and median values of the FOMs can be compared to the experimental results. Another post-processing approach proposed by the partners is to visualize the PDF of the FOMs. This can be done at a particular instant, as reported in Figure 6 (left) for the aerosol in containment, or along the transient (dynamic PDF) as reported in Figure 6 (right) for Cs and Xe in containment.

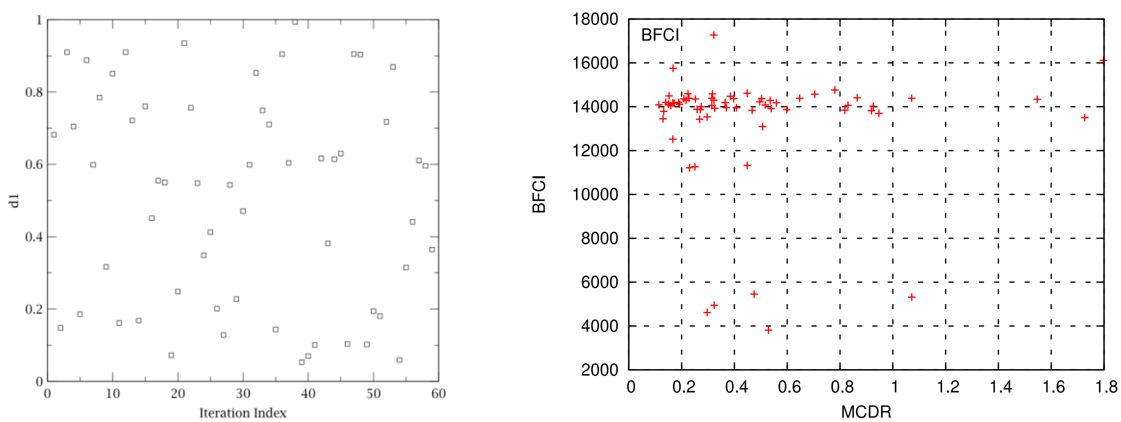

Figure 3. Examples of input uncertain parameter vs iteration index (left) and of FOM vs uncertain input parameter (right).

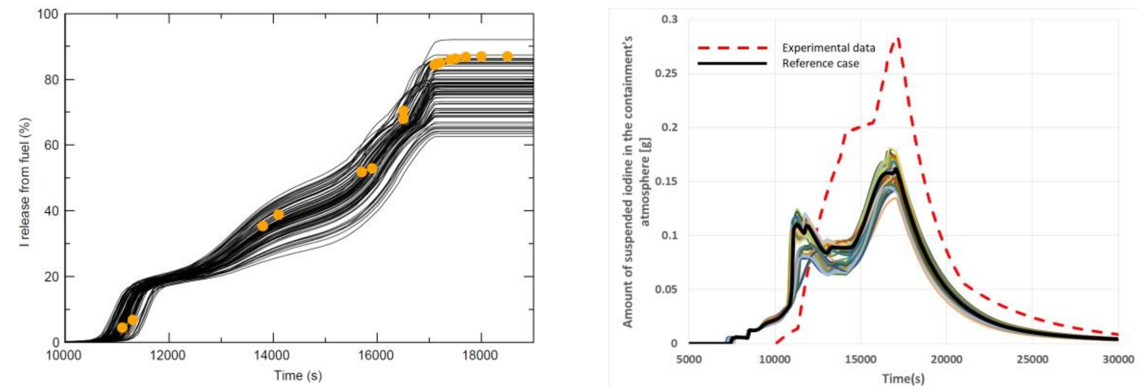

Figure 4. Examples of time dependent FOM dispersion.

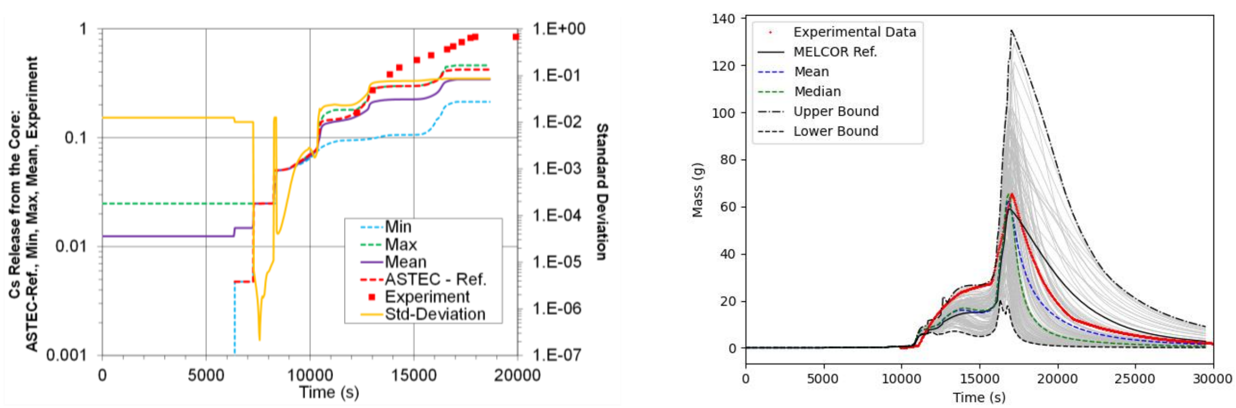

Figure 5. Examples of statistical analysis on time dependent FOM.

One of the post-processing approaches presented by the partners is to characterize the statistical correlation between the uncertain input parameters and the FOMs (e.g. through Pearson and Spearman coefficients). Depending on the parameter (e.g. maximum value of aerosol mass in the containment, or the aerosol mass time dependent behavior) the statistical and correlation analysis has been done on a single selected time value (e.g. Figure 7) or time dependent (Figure 8). In Figure 7 (left), the bar plot show in an easily way 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 analyses (total aerosol mass suspended in the containment end value). Same consideration for the Figure 7 (right), where the input uncertainty Spearman correlation is visualized against the FOM (Cs class mass in the containment).

Table III. 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

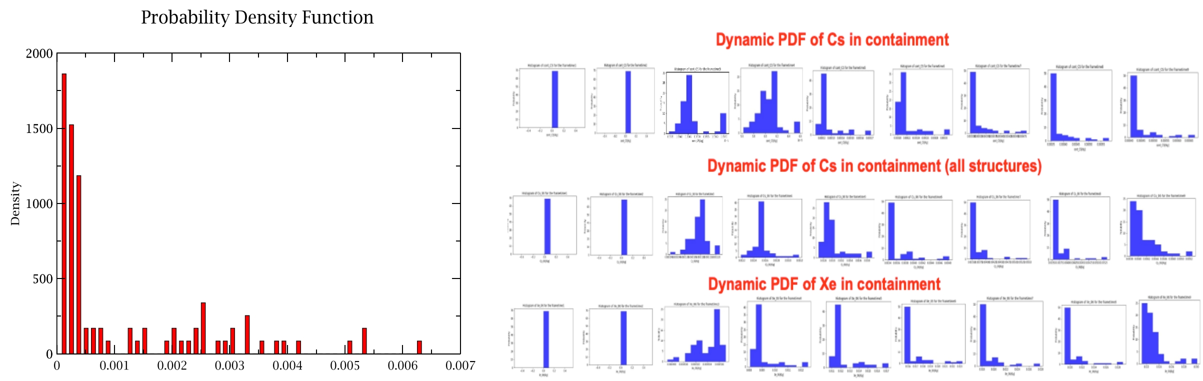

Figure 6. Examples of FOM PDF on a single value (left) and along the transient (right).

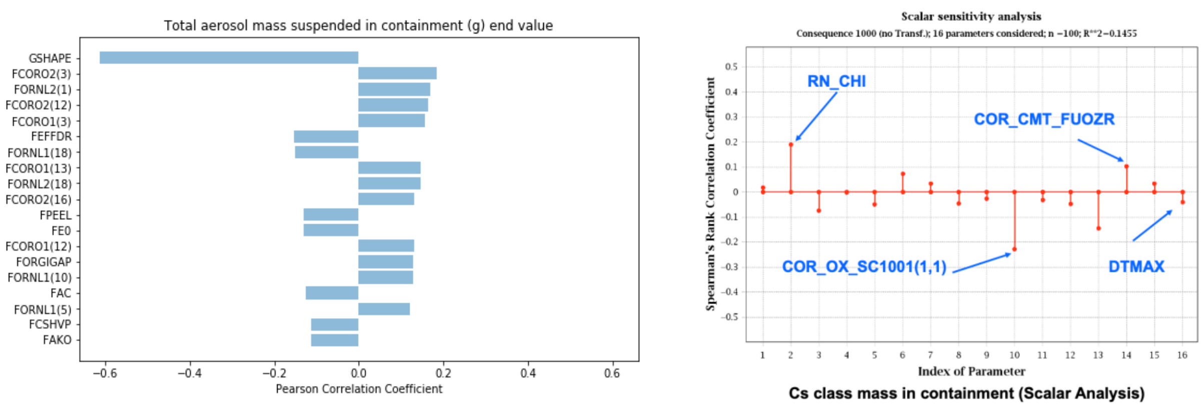

Figure 7. Examples of correlation analysis for a single value FOM.

It is also possible to have a time dependent visualization of the correlation coefficients; this allows to characterize the input uncertainty correlation along the transient progression. In Figure 8 the miscellaneous aerosol dynamic constant has been used has input uncertain parameter to characterize the aerosol mass suspended in the containment. Considering Figure 8 (right) it can be noted that in this case Pearson and Spearman coefficients results are close; moreover, comparing Figure 8 left and right it can be seen that the results are similar adopting different UTs with the same SA code. In addition, it can be also 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 20000 s.

3.4. Lessons learned

During the intermediate meetings, the following points have been extensively discussed to extract the first lessons learned in WP4: the identification and characterization of the input uncertain parameters, the management of the failed calculations, the coupling of the UT with the SA code, the post processing of the data and the SA code.

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. In fact, as example, certain combinations of input uncertain parameters can affect more the FOMs behavior, as shown for instance in Figure 10 (left) for the CsI in containment. In general, the 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. An approach for the identification and classification of the input uncertainty parameters has been proposed by one partner and it is summarized in Figure 9; 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. It is to underline that, in order to assess the impact on the final PDF for each FOM, partners underline the need to perform a number of runs larger than the minimum required number according to Wilks' formula for the selected probability and confidence level.

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 Figure 10 (right) for the Cesium deposited in RCS. Partners, in general, selected different approaches and it has been underlined the need for the management of the failed runs from a statistically solid point of view. This will be a point of discussion in the development of the MUSA project.

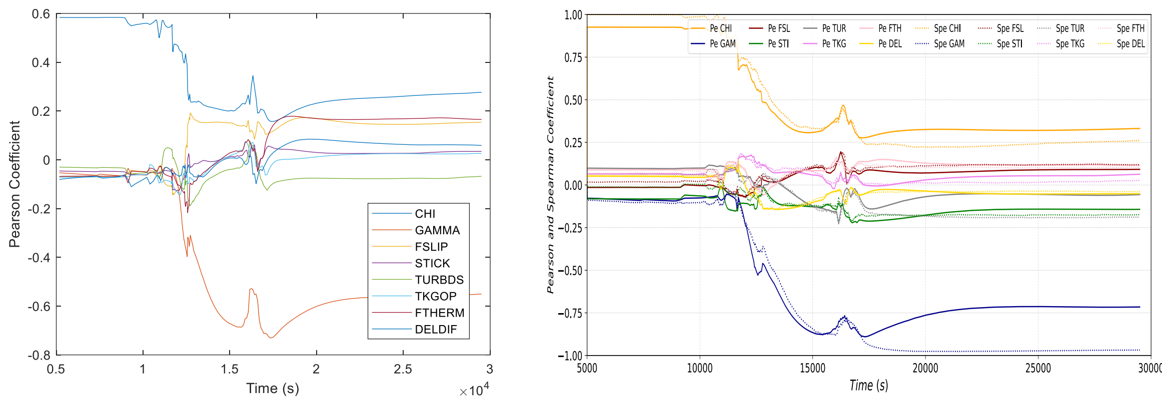

Figure 8. Examples of correlation analysis for time dependent FOM.

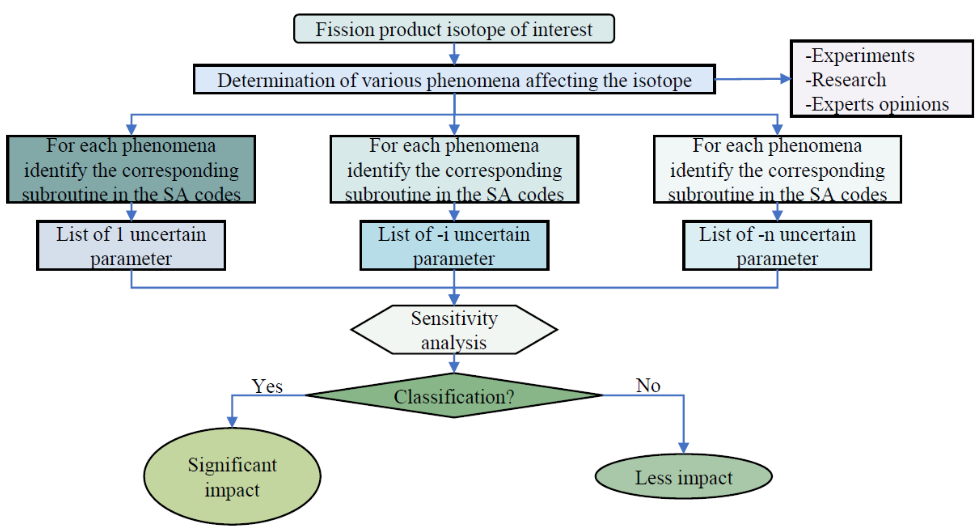

Figure 9. Example of a proposed approach for the selection of the input uncertain parameters.

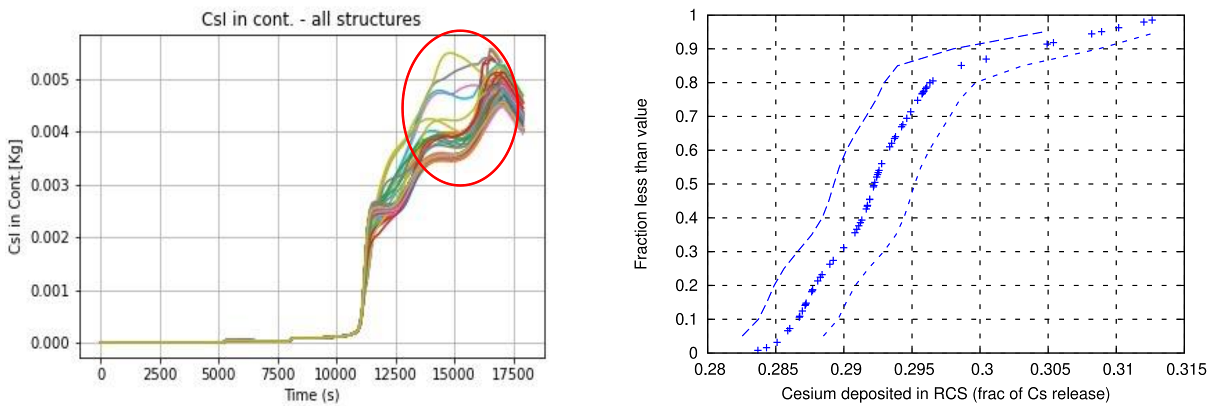

Figure 10. Examples of possible FOM outlier (left) and distortion due to failed calculations (right).

The coupling of the UT with the SA code is a necessary step to automate the process and 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. In this sense, 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 (e.g. in post-processing capability, management of failed calculations).

The post processing of the data is a key element of the uncertainty application. The analyses can be done in a particular point of the FOM (e.g. the maximum value of the aerosol in the containment) or time dependent. This last option 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; in this regard, dynamic PDF is considered very useful and the explanation of the PDF variation with time can be an added value of the analyses. 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.

Along the UA, the SA code showed to be sensible to the choice of the input uncertain parameters and their range. In fact, 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 user should be aware of that and should use consolidated values as a reference for the analyses. If more modules or packages are used in one SA code, the consistency between parameters should be carefully considered and there can be some limitations in the coupling between the modules. Also, it is to underline that the computational time required could be an issue for plant applications. There is the general agreement that more user guidelines for using SA and UT are needed; this will be one of the outcomes of MUSA project.

Finally, considering the enveloping of the experimental data by the uncertainty band, some partners underlined that the UA 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 UA. The role of accuracy evaluation before doing UA can be a feedback to WP3.

4. CONCLUSIONS

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 WP4 is aimed at applying and testing UQ methodologies, against the internationally recognized PHEBUS FPT1 test, and 16 partners are involved. The purpose of this paper is to describe the MUSA PHEBUS FPT1 uncertainty application exercise, as well as the methodologies used by the partners to perform the UA and the first insights resulting from the calculation phase.

In the process of evaluation of applicable methods of UQ (sensitivity analyses included) to the SA field and definition of best UQ application practices in SA analyses, the WP4 exercise contributed to solve some of the issues encountered in these first applications. The probabilistic method has been adopted by partners to propagate input uncertainties with different SA codes. Scripting requires major efforts for its development and this was needed to couple SA and UT in most applications. Furthermore, scripting provided more flexibility in term of post-processing capabilities, compared to UT that has the GUI and which, despite being user-friendly, present certain limitations.

It has been recognized that the proper choice of the input uncertain parameters and their characterization is a crucial task, based in general on a sound background (e.g. experimental and analytical data, references, engineering judgment, etc.). Certain combinations of input uncertain parameters can affect more the FOMs behavior, generating possible outliers that should be investigated by the analyst. In relation to the SA codes, results showed that they could be sensitive to the choice of the input uncertain parameter and the related range. Moreover, the choice of values not varied (i.e. not sampled) in the UQ can influence the stability of the calculations. In addition, it has been recognized that computational time is a key element to perform UA and for plant applications the use of clusters may be necessary. Several post-processing approaches have been tested.

This exercise has been a good opportunity for all partners to identify and to share the issues encountered during the application of UQ that require further discussions. For instance, the need for a statistically solid handling of failed calculations, the improvement of post-processing capabilities of some UTs, the adoption of clusters to perform UQ and the implementation of the GUI in clusters. The current status of the activity does not allow to draw a comprehensive conclusion on the main sources of uncertainty for the various FOMs; however, for example, the miscellaneous aerosol constants and heating power showed a major correlation on the aerosol mass in the containment.

NOMENCLATURE

AM	Accident Management
ANOVA	Analysis of Variance
CDF	Cumulative Density Function
FOM	Figure Of Merit
FP	Fission Product
GUI	Graphical User Interface
MUSA	Management and Uncertainties Of Severe Accidents
NPP	Nuclear Power Plant
PDF	Probability Density Function
SA	Severe Accident
SFP	Spent Fuel Pool
ST	Source Term
UaSA	Uncertainties and Sensitivities Analyses
UQ	Uncertainty Quantification
UT	Uncertainty Tool
WP	Work Package

ACKNOWLEDGMENTS

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

REFERENCES

1. L.E. Herranz, S. Beck, V.H. Sanchez-Espinoza, F. Mascari, S. Brumm, O. Coindreau, S. Paci, "The EC MUSA Project on Management and Uncertainty of Severe Accidents: Main Pillars and Status," *Energies*, **14** (2021)
2. F. Mascari, L.E. Herranz, S. Beck, V. Sánchez-Espinoza, S. Brumm, O. Coindreau, S. Paci, "The MUSA project: Management and Uncertainties of Severe Accidents," *EUROSAFE2021,* Paris (France), November 22-23, 2021
3. B. Clément, T. Haste, E. Krausmann, S. Dickinson, G. Gyenes, J. Duspiva, F. de Rosa, S. Paci, F. Martin-Fuertes, W. Scholytssek, H.-J. Allelein, S. Güntay, B. Arien, S. Marguet, M. Leskovar, A. Sartmadjiev, "Thematic network for a Phebus FPT1 international standard problem (THENPHEBISP)," *Nuclear Engineering and Design*, **235** (2–4), pp. 347-357 (2005)
4. D. Jacquemain, S. Bourdon, A. de Braemaeker, M. Barrachin, "FPT1 Final Report (Final version)", IPSN/DRS/SEA/PEPF report SEA1/00, IP/00/479 (2000)
5. O. Coindreau, F. Mascari, WP4 – Specifications to apply UQ Methods against the PHEBUS-FPT1 experiment, Version 1 – 30/07/2020
6. OECD/NEA/CSNI, "ISP-46 - PHEBUS FPT-1 Integral Experiment on Reactor Severe Accidents," NEA/CSNI/R(2004)18 (2004)
7. B. Clément, R. Zeyen, "The objectives of the Phébus FP experimental programme and main findings," *Annals of Nuclear Energy*, **61**, pp. 4-10 (2013)
8. R. Dubourg, H. Faure-Geors, G. Nicaise, M. Barrachin, "Fission product release in the first two PHEBUS tests FPT0 and FPT1," *Nuclear Engineering and Design*, **235**, pp. 2183–2208 (2005)
9. Applied Programming Technology, Inc. Symbolic Nuclear Analysis Package (SNAP) User's Manual (2012)
10. H. Glaeser, "GRS Method for Uncertainty and Sensitivity Evaluation of Code Results and Applications," *Science and Technology of Nuclear Installations* (2008)
11. S.S. Wilks, Determination of sample sizes for setting tolerance limits," *Annals of Mathematical Statistics*, **12**(1), pp. 91–96 (1941)
12. S.S. Wilks, "Statistical prediction with special reference to the problem of tolerance limits," *Annals of Mathematical Statistics*, **13**(4), pp. 400–409 (1942)