The EC MUSA Project on Management and Uncertainty of Severe Accidents: Main Pillars and Status

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Abstract: In the current state of maturity of severe accident codes, the time has come to foster the systematic application of Best Estimate Plus Uncertainties (BEPU) in this domain. The overall objective of the HORIZON-2020 project on "Management and Uncertainties of Severe Accidents (MUSA)" is to quantify the uncertainties of severe accident codes (e.g., ASTEC, MAAP, MELCOR, and AC^2) when modeling reactor and spent fuel pools accident scenarios of Gen II and Gen III reactor designs for the prediction of the radiological source term. To do so, different Uncertainty Quantification (UQ) methodologies are to be used for the uncertainty and sensitivity analysis. Innovative AM measures will be considered in performing these UQ analyses, in addition to initial/boundary conditions and model parameters, to assess their impact on the source term prediction. This paper synthesizes the major pillars and the overall structure of the MUSA project, as well as the expectations and the progress made over the first year and a half of operation.

Keywords: nuclear fission; safety; severe accidents; BEPU; accident management; uncertainty quantification; source term

1. Introduction

Numerical simulation tools are widely used in the nuclear community to assess the behavior of Nuclear Power Plants (NPP) during postulated accidents, including severe accidents. Hence, they are a central element of the safety demonstration, where the compliance of the main safety features of an NPP is checked against the actual safety requirements reflecting the state of the art. In addition, the development and optimization of Accident Management (AM) measures, aiming at preventing and mitigating the consequences of a severe accident, heavily rely on numerical simulations, with codes such as ASTEC [1], AC^2 [2], MAAP [3], MELCOR [4], and so on. Since these tools predict important parameters such as the time of failure of the plant safety barriers, on one hand, and the potential radiological source term released into the environment if the safety barriers fail, on the other hand, it is of paramount importance to assure their highest accuracy.

Considering the complexity of the physical-chemical and thermal-hydraulic processes taking place during the different phases of a severe accident and the inherent nature of numerical codes (numerics, spatial and time discretization, initial and boundary conditions, etc.), it is mandatory to quantify their embedded uncertainties, taking into account the latest developments in methods and algorithms as well as the availability and power of

computational resources [5]. At present, many severe accident codes have reached a high enough level of maturity with regards to their modelling scope and accuracy, simulation capability of safety-relevant phenomena, and validation for a large number of reactor types and numerical stability, and extensive applications in industrial, regulatory, and research areas can be found [6]. Furthermore, they are extensively employed for the development and optimization of AM measures and to provide the source term to estimate the radiological impact of an accident on and around the NPP site.

For many years, mathematical tools for the quantification of code uncertainties and sensitivities have been under development worldwide, for example, DAKOTA [7], RAVEN [8], SUNSET [9], SUSA [10], URANIE [11], and so on. There is a huge accumulated experience already in the nuclear community in performing UQ with Best Estimate (BE) thermal-hydraulic system codes [12,13], and this is being extended to other fields, like fuel performance, neutronics, and sub-channel thermal hydraulics. So far, this has not been the case for severe accident codes, and few investigations have been focused on severe accidents and UQ in Europe [14] and elsewhere [15].

MUSA (Management and Uncertainties of Severe Accidents) is a 4-year HORIZON-2020 project, coordinated by CIEMAT (Spain) that moves beyond the state of the art regarding the predictive capability of severe accident analysis codes by combining them with the best available UQ tools. By doing so, not only will the prediction of the timing for the failure of safety barriers and of the radiological source term in case of a severe accident be possible, but also, the quantification of the uncertainty bands of selected analysis results, considering any relevant source of uncertainty, will be provided. It should be highlighted that MUSA is not restricted to reactor accidents; Spent Fuel Pool (SFP) accidents are also addressed and, in addition, the inclusion of AM in the uncertainty analyses. It is a particular goal of MUSA to develop innovative AM strategies for these SFP accidents.

2. Objectives and Structure

The overall objective of MUSA is to quantify the uncertainty in severe accident codes when modelling reactor and SFP accident scenarios of Gen II and Gen III reactor designs for the prediction of the radiological source term. Hence, UQ methodologies are applied where not only initial and boundary conditions and model parameters, but also AM measures are considered, to assess their impact on the source term prediction. Therefore, Figures of Merit (FOM) related to the source term are to be used in the UQ application. Consequently, the MUSA project will contribute to the determination of the state of the art on the application of UQ methods to severe accident codes, regarding their prediction of the source term that potentially may be released to the external environment and to the quantification of the associated code's uncertainties, applied for the analysis of these severe scenarios in both NPPs and SFPs.

The achievement of the overall objective is assured by a consistent and coherent work program, reflected in the five technical Work Packages (WP) defined as follows (Figure 1):

1. Identification and Quantification of Uncertainty Sources (WP2, IQUS).
2. Review of Uncertainty Methodologies (WP3, RUQM).
3. Application of UQ Methods against Integral Experiments (WP4, AUQMIE).
4. Uncertainty Quantification in Analysis and Management of Reactor Accidents (WP5, UQAMRA).
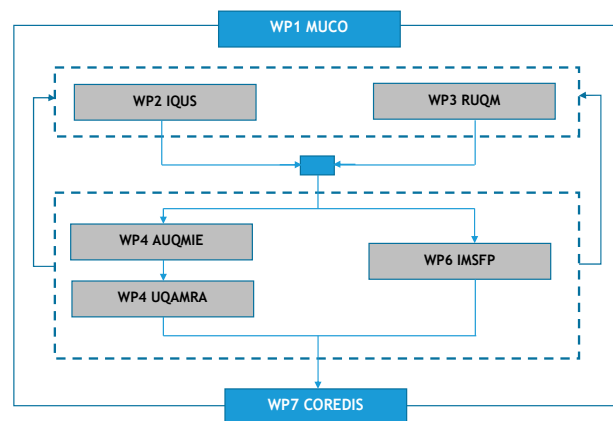5. Innovative Management of SFP Accidents (WP6, IMSFP).

Figure 1. MUSA Work Package interlink.

As noted in Figure 1, there is also a specific WP for managing the technical, financial, and legal aspects of the project (WP1, MUCO), and another one (WP7, COREDIS) for efficiently articulating the Communication and Dissemination (C&D) activities so that technical outcomes of MUSA reach as many stakeholders as possible, and the resulting enhancement of nuclear safety reaches the generic public.

These WPs aside, the technical WPs (WP2–WP6) are distributed in two blocks. The first one, including WP2 and WP3, is meant to prepare everything necessary to conduct the second block, which can be referred to as the "application WPs block" (WP4, WP5, and WP6). In the following, further technical details will be given on each of them. As shown in Figure 2, the "application block" represents roughly two-thirds of the total workforce in the project, whereas roughly one-fourth is to be spent in the "preparatory block". In terms of working load, MUSA is estimated to require 625 months (about 15 scientists/engineers working full-time for 4 years).
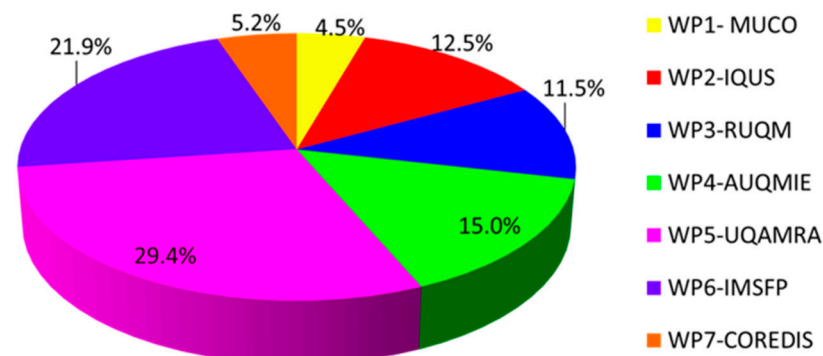

Figure 2. MUSA workforce distribution.

3. Major MUSA Features

Some MUSA specific features, reported in the following, strengthen the project significance in the field of nuclear safety:

- Twenty–eight organizations from three continents are MUSA partners (Figure 3). This ensures the involvement of a wide range of competencies and experience on severe accident phenomena and source term investigations all over the world with different perspectives (i.e., Technical Support Organizations (TSO), utilities, research centers, and academia). Moreover, and no less important, it guarantees a wide dissemination of the MUSA results. Table 1 gathers the organizations involved in each WP, where the organizations responsible for the WP are highlighted in bold.
- The focus on source term analysis stems naturally from the ultimate goal of severe accident codes, and it is consistent with the consequences experienced and the conclusions drawn after the Fukushima accident. The role played by source term in the emergency

measures implemented at the time of the accident and in the ongoing land recovery around the Fukushima Daiichi site underlines the relevance of its realistic evaluation. Furthermore, the wide participation in MUSA will contribute to the harmonization of the degree of confidence in source term estimates.

- The integrating nature of the project is outstanding. Despite the specific application on the source term area (i.e., release, transport, and chemistry), the project integrates all the aspects of both reactor and SFP severe accidents. In addition, it addresses a broad scope of reactor designs since the main outcomes would be generally applicable to all water-cooled reactor types.
- There is a strong link with the communities dealing with Probabilistic Safety Assessment (PSA) level 2, emergency response, environmental consequence analysis, and AM, all of whom are undertaking deep reviews since the Fukushima Daiichi accident. Note that the MUSA Advisory Board and the End-Users Group consist of scientists and engineers coming from those communities; their link to the project is shown in Figure 4.
- Key elements of the project are experimental data and knowledge about the severe accident phenomenology from earlier projects funded in the EURATOM framework, such as PHEBUS-FP [16] and SARNET [17].
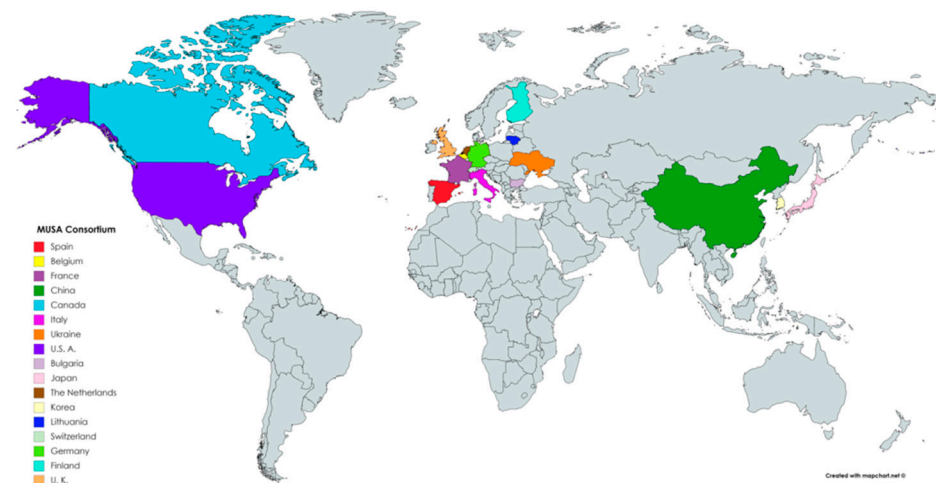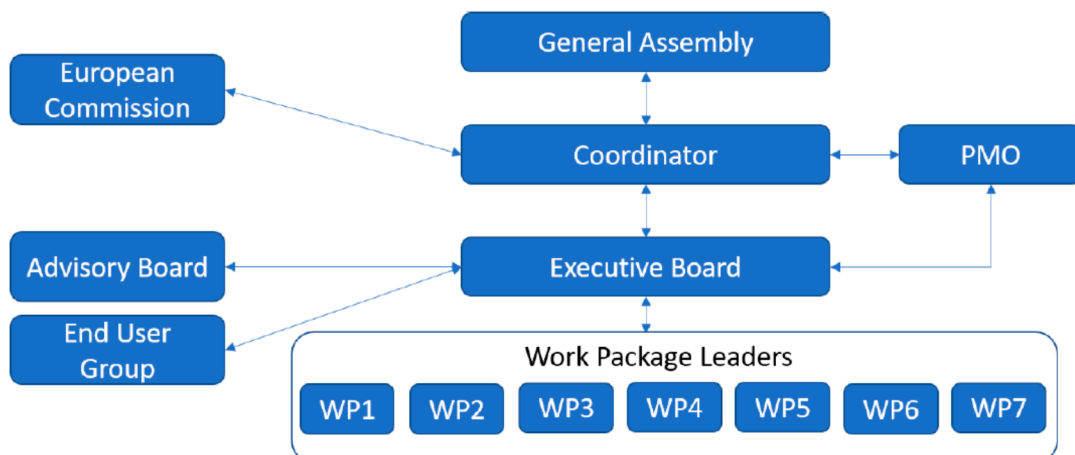

Figure 3. MUSA member countries.

Figure 4. Overall MUSA project structure.

Table 1. Partners distribution in MUSA WPs.

WP	Name	Partners
1	MUCO	CIEMAT, LGI
2	IQUS	CIEMAT, BELV, CEA, CNSC, ENEA, ENERGORISK, EPRI, GRS, INRNE, IRSN, KIT, LEI, PSI, SSTC, TRACTEBEL, TUS, VTT
3	RUQM	CIEMAT, BELV, CNSC, ENEA, ENERGORISK, EPRI, FRAMATOME GMBH, GRS, INRNE, IRSN, JAEA, KIT, LEI, NINE, SSTC, TRACTEBEL, TUS, UNIRM1, VMU
4	AUQMIE	CIEMAT, CEA, CNSC, ENEA, ENERGORISK, EPRI, GRS, INRNE, IRSN, KIT, LEI, PSI, SSTC, TUS, UNIPI, UNIRM1, VTT
5	UQAMRA	CIEMAT, BELV, CNPRI, CNSC, ENEA, ENERGORISK, EPRI, FRAMATOME GMBH, GRS, INRNE, IRSN, JAEA, JRC, KAERI, KIT, LEI, NINE, PSI, SSTC, TRACTEBEL, TUS, UNIRM1, VTT
6	IMSFP	CIEMAT, CEA, CNPRI, CNSC, ENEA, ENERGORISK, EPRI, INRNE, IRSN, KAERI, LEI, PSI, SSTC, TUS, UNIRM1
7	COREDIS	CIEMAT, ENEA, GRS, IRSN, JRC, KIT, LGI, NINE, UNIPI

Selected key milestones of the MUSA project are listed as follows:

- Identification of key processes/phenomena in a severe accident affecting the source term and quantification of their associated uncertainties.
- Identification and quantification of key parameters of AM measures implemented in an SA affecting the source term and their associated uncertainties.
- Evaluation of applicable methods of UQ (sensitivity analyses included) to the severe accident field and definition of best UQ application practices in the related analyses.
- Trial of Uncertainty and Sensitivity Analysis (UaSA) methodologies against simplified but representative experimental scenarios with strong emphasis on source term.
- Application of UaSA methodologies to risk-dominant severe accident sequences for reactors and SFPs.
- Recommendations for an effective reduction of remaining code uncertainties associated with the source term and their impact on AM measures, and for improvement and/or new innovative AM measures for reactor and SFP scenarios.

4. Brief Work Package Description

The technical content of MUSA is split into five technical WPs, as introduced in paragraph 2. The WP "preparatory block" WP2–WP3 has begun with a project for a first working period of about one year, and features a last working period to harvest insights from the WP "application block" in the last year of MUSA. The WP "application block" is roughly shifted half a year from the project launch, and the most conclusive part of WP5 and WP6 occurs during the second half of MUSA, once the maximum benefit of experience gained from WP4 can be put to work. Next, a brief description of each technical WP is given.

4.1. Identification and Quantification of Uncertainty Sources (WP2-IQUS)

WP2 identifies and partially quantifies the major sources of uncertainties of any types of processes and phenomena during severe accidents affecting the source term. This would entail both uncertainties in the existing models and uncertainties due to the lack of specific models in the codes. IQUS extends its domain to the entire accident history with a focus on source term, and also includes application to AM measure—both in the water-moderated reactors of various types (Gen II and Gen III) and their SFPs. The main expected outcome is a "knowledge-based matrix" containing the selected variables, parameters, and models, as well as its uncertainty ranges, which shall be applied by the code users within

the uncertainty and sensitivity studies in the successive "application" WPs (AUQMIE, UQAMRA, and IMSFP).

The first important step in this WP was the identification of source-term-related FOMs, which are needed to assess the capability of SA codes when modelling a reactor or SFP severe accident scenarios, and both UQ and UaSA will be focused on the use of these FOMs. Additional key variables will be stored in case they are needed to explain FOMs' behavior. The FOMs selection has been based on a set of criteria including, for example, focus on source term and, particularly, on high-radiological radionuclides; priority to be given to in-vessel FP release; in SFP, only releases corresponding to a limited fuel degradation will be addressed, with gas and liquid leak paths considered; timing of release to the environment is of outmost relevance with, when available, the gas and particulate nature of FPs (I) distinguished. Table 2 gathers the source-term-related FOMs chosen. For these FOMs, a thorough statistical characterization (i.e., minimum and maximum values, mean, median, standard deviation, etc.) is foreseen along the entire time domain and/or, if considered significant, an instantaneous characterization at a specific time of an FOM might be reported, such as the maximum aerosol mass suspended into the containment's atmosphere for FOM 1.6.

Table 2. Source-term-related Figures of Merit for reactor cases and SFP cases.

No	Source-Term-Related FOM (Time Dependent or at One Point in Time)
1.1	Total FP[1] & NG[2] release (mass fraction (% ii)) into the environment: - from containment or in bypass scenarios from RCS for reactor scenarios - *from SFP building for SFP scenarios*
1.2	Total Iodine release (mass fraction (% ii)) in gaseous form to the environment - *relevant for SFP scenarios*
1.3	Onset time of FP release from fuel/core (in-vessel), from debris in cavity/MCCI (ex-vessel) and into the environment - *begin of release is relevant for SFP scenarios*
1.4	Total FP and NG released (mass fraction (% ii)) from fuel/core - *relevant for SFP scenarios*
1.5	Total FP and NG released (mass fraction (% ii)) from debris in cavity/MCCI - *not relevant for SFP scenarios*
1.6	Total FP and NG airborne in the containment (mass fraction (% ii) and amount (kg) or concentration (kg/m^3)) of: - containment for reactor scenarios - *SFP building for SFP scenarios*
1.7	Total FP solved (mass fraction (% ii) and amount (kg) or concentration (kg/m^3)) in water pools of: - containment sump/wet well/other pools for reactor scenarios - *SFP water pool for SFP scenarios*
1.8	Total FP (mass fraction (% ii) and amount (kg) or concentration (kg/m^2)) deposited on structures: - containment walls and structures for reactor scenarios - *SFP building walls for SFP scenarios*
1.9	Total FP and NG (mass fraction (% ii)) into RCS or into SG secondary in case of a bypass scenario - *not relevant for SFP scenarios* *Evolution of the cumulated activity of a list of isotopes (to be defined) for SFP scenarios*

[1] FP = cesium and iodine for reactor cases. FP = cesium, iodine, and ruthenium for SFP cases. [2] NG = Noble Gases.

A directory with the important uncertain phenomena affecting the source term is being built as a guide to identify uncertain parameters, which will be characterized by their uncertainty range (lower and upper bound) and Probability Density Function (PDF), and this material is to be integrated in a database. The consolidation phase of the directory has already been started, but it will be considered a live reference throughout the course of the project, in order to also integrate all users' experiences and outcomes of WP4, WP5, and WP6.

4.2. Review of Uncertainty Quantification Methodologies (WP3-RUQM)

The objective of this WP3 is to review and assess promising methodologies and codes used for UQ and sensitivity analyses and their applicability for the analysis of severe accident scenarios with/without AM for NPPs and SFPs. In particular, the strengths and weaknesses of each UaSA methodology/code to be applied are to be identified and evaluated, and whenever possible, enhancements for such an application will be proposed. In fact, guidelines for the correct use of UaSA codes/methods in the severe accident domain are planned to be written. In short, the outcome of the activity would be a set of different UQ methods to be applied for SA analysis and a guide to do it. The most suitable methodologies to achieve the project goals will be used by partners in the following "application" WPs, which should provide feedback to RUQM to optimize methodologies and guidelines.

A review of the various practices and tools to be used by the partners for the quantification of the uncertainties embedded in the different severe accident codes (e.g., ASTEC, AC^2, MELCOR, MAAP, etc.) has been recently conducted. Besides, the main features of the UQ tools (e.g., SUSA, DAKOTA, URANIE, RAVEN) and data assimilation tools such as MOCABA [18] have been compiled and illustrated. The study has concluded that all the tools provide the basic necessary capabilities for the UQ of severe accident codes applied to predict the radiological source term. Some issues were identified that should be given attention in any UQ application: how to properly select the range of variation of the uncertain parameters, criteria for selection of appropriate PDFs, applicability of the Wilks formula [19] in case of multiple FOMs, and so on.

4.3. Application of UQ Methods against Integral Experiments (WP4-AUQMIE)

Aimed at getting some experience and insights into the application of the methodologies from the previous WP3 against internationally recognized integral experiments related to the source term evaluation, this WP4 is the first chance to test both the IQUS and RUQM outcomes on a simplified, but still representative, severe accident scenario. AUQMIE is, hence, a drill for other application WPs and an opportunity to provide some early feedback to RUQM. The experimental test PHEBUS FPT-1 [20] was selected for this purpose. By no means is this intended as a data vs. code benchmark, and the only reason why reliable and representative data have been proposed is to have full and credited details of the scenario and experimental data that might help to calibrate the final model to be used. This permits one to focus the WP4 exercise on the uncertainty application and to investigate how to address the issues that can arise in the UQ methodologies application to simplified, but still representative, severe accident scenarios.

Descriptions of the PHEBUS facility and FPT-1 test, with the related initial and boundary conditions, have been made available to WP4 partners by IRSN, together with selected FPT-1 experimental data chosen as FOMs and made available as well through ad hoc spreadsheets. The input decks were developed for the different codes and preliminary results have been already obtained; presently, the application and testing of the UQ methodologies is underway. The main outcome expected is the partners training with the UQ methodologies before facing a full-scope severe accident analysis and, no less important, to get feedback for WP2 (input deck uncertainty characterization) and WP3 (on the use of UQ methodologies).

4.4. Uncertainty Quantification in Analysis and Management of Reactor Accidents (WP5-UQAMRA)

This WP5 aims at demonstrating the applicability and the level of readiness of uncertainty assessment in the broad range of set-ups presented by different NPPs and of different tools investigated by the partners. The results achieved by propagating uncertainties through different integral severe accident codes will be assessed using UaSA codes, and governing uncertainties will be determined.

In addition to outlining the uncertainty bands affecting the source term estimates, two other major outputs are to be produced: a best practice protocol for applying UaSA methods to severe accident codes and an identification of areas where further research is needed to effectively reduce uncertainties affecting the source term estimates. AM measures are planned to be considered in both timing and efficiency.

So far, participants have reviewed their plant models and have performed BE transient calculations, leading to a fission products release into the containment. These applications have highlighted the high computational cost of simulating the in-vessel and the ex-vessel phase of the transient. Potential solutions under discussion are the use of high-performance computing clusters and the reduction of the input-deck complexity. Currently under way is the setting up of uncertainty cases that requires the implementation of the uncertainty sources defined in WP2, and the coupling of SA codes with UQ tools as covered in WP3. This step also draws on experiences made in WP4 and in earlier works such as [21].

4.5. Innovative Management of SFP Accidents (WP6-IMSFP)

WP6 is, to a good extent, similar to the previous WP5 with regards to the RUQM methodologies' application, but here, a significant emphasis is placed on reviewing existing or contemplated AM mitigation measures and systems and proposing innovative ones, the benefits of which should be assessed in terms of reduction of the radiological consequences.

The same design and scenario will be studied by all partners: a loss-of-cooling accident that leads to fission product releases that are not too important and an SFP design similar to that of Unit 4 of the Fukushima Daichi NPP, set in the AIR-SFP NUGENIA+ project [22]. The utilized FOMs have been adapted to the scenarios, as in the case of the FPT1 exercise, and it was agreed that the transient scope will be limited to a moderate damage of spent fuel rods. The build-up of the reference case, which is an important starting point before the application of the UQ, is progressing. Discussions of the results have enabled participants to consolidate their input data decks, to share files to post-process the results, and to get a better understanding of the accident progression. As in WP5, the high computational cost has been highlighted during this first stage. The implementation of uncertainty sources is currently under way.

In the meantime, traditional AM actions have been reviewed and the first part of a report entitled "Review and critical assessment of existing and contemplated SAM measures and systems in SFP" has been written. A brainstorming about innovative AM actions has been carried out, and it was envisaged that prevention measures (such as spray systems) will be considered when conducting the analyses.

5. Current Status

As mentioned above, most of the activity during the first 18 months of the project has been focused on WP2 IQUS and WP3 RUQM, together with the consolidation of the WP4 AQUMIE activities and the WP7 COREDIS ones.

WP2 IQUS has already determined the specific source term FOMs, and a second group of additional variables have already been highlighted as necessary for being able to discuss any potential trend and/or divergence that might be observed in these FOMs. The work is presently focused on the selection of relevant phenomena during severe accidents affecting the source term and the definition of uncertainties in input variables (i.e., ranges and PDFs). A directory with the important uncertain phenomena affecting the source term is being built as a guide to identify uncertain parameters, which will be characterized by

the uncertainty range (lower and upper bound) and PDFs. The consolidation phase of the directory was started in a tabular form, and it will be a living document throughout the course of the project, in order to also integrate all users' experiences and outcome of WP4, WP5, and WP6.

As for methodologies, the main features, capabilities, and interfaces with regards to severe accident codes of the different UQ tools to be used in MUSA are under review in WP3 RUQM, and the result of this will be part of a deliverable where recommendations for their use will be compiled. In addition, guidelines will be written for the use of UQ in connection with severe accident codes, considering the experience gained applying these tools in MUSA.

WP4 aims at applying and testing UQ methodologies against the PHEBUS FPT-1 test. This exercise represents the first MUSA UaSA application, and its main targets are to identify issues throughout the uncertainty application and to develop a critical analysis of the partners' uncertainty applications, giving feedback to WP3, WP5, and WP6. The PHEBUS FPT-1 test has been selected because it has been the subject of the OECD/CSNI ISP-46 [23], which provides a sound basis for WP4 uncertainty analysis. A list of FOMs has been chosen for discussion and the related experimental data, in spreadsheet form, have been distributed. In relation to the input uncertainty parameters and related characterization, a spreadsheet form table, with suggested input uncertain parameters, has been disclosed to the partners by the WP2. Currently, partners are involved in the calculation phase and are applying the UQ methodologies.

The COREDIS WP7 has been also very active during the first months of the project in the definition of a plan for dissemination and communication activities, as well as the rules that will frame the planned mobility initiatives. In addition, a series of C&D tools and actions have been implemented, including the following:

- The MUSA public website (http://musa-h2020.eu/, accessed on 23 July 2021) as the main communication channel for the project's stakeholders and the target audience, where the key information on the project and its progress are included, together with contents, such as news, articles, and announcements produced, which are also intended to engage with and build the MUSA community.
- A social network account (LinkedIn®) to communicate on MUSA, promote its results, and advertise workshops and learning modules, as well as the mobility opportunities, while also permitting a two-way dialogue with the target groups.
- The first issue of the external newsletter released in February 2021.

Special attention has been given to start the education and training initiatives to facilitate the transfer of the project's outcomes to young researchers in the severe accidents field and the Masters/PhD students at European universities. These initiatives include an ad hoc mobility program, and other actions planned for the last MUSA period, such as the three e-learning modules, compiling the major outcomes from the project. However, the sanitary context has forced a stop to this mobility program, with a provision for a possible restart only in the second half of 2021, based on the European sanitary situation and the different countries' rules. The related Mobility Manual, explaining the procedure and the eligibility criteria, is available on the MUSA public website.

6. Final Remarks

The MUSA project is a well-structured project, aimed at bringing the BEPU approach into severe accident analysis, including AM for reactor and SFP scenarios, by building an uncertainty matrix for code input variables and by adapting methodologies used in other nuclear safety domains. The advantages of the BEPU approach with respect to deterministic analyses are multiple; among others, it would avoid overly conservative assumptions in models and better assessment of safety margins, and no less important, the distribution variance of FOMs would provide insights into dominating uncertain parameters, on which coming research should focus. Source term is to be the focus of UQ and has already inspired the definition and agreement of FOMs.

In addition to awareness of the severe accident estimates' precision of system codes, the project is expected to give good insights into two other major areas: the issue of which investigation would be more effective in reducing uncertainties in the source term estimates, and AM optimization by either better implementing already foreseen actions or even proposing innovative ones.

By conducting MUSA, the European Union will take a step forward with regards to severe accident analyses by proposing systematic methodologies for a thorough application of BEPU in SA analyses. Such methods will have been vastly tested and will be spread all over Europe and beyond (as Asian and American organizations also participate in the project). In addition, the leadership of the European Union in ST will be even further consolidated by assessing the accuracy of the current ST predictions with SA codes and by identifying which variables are worth further investigation in terms of achieving a significant reduction of uncertainty bands. A key outcome from MUSA is the methodological guide planned to be released that, regardless of the specific SA and/or statistical tool used, would help any newcomer have a fast and sound start in the application of BEPU methods in the SA analysis domain. This will stem from the fact that a number of reactor technologies and analytical tools are being addressed/used in MUSA.

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