Management and Uncertainties of Severe Accidents (MUSA): An H2020-Euratom Project

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***Abstract** – In the current state of maturity of severe accident codes, application of BEPU (Best Estimate Plus Uncertainties) methodology in severe accident analysis, including Accident Management (AM), might provide key insights in terms of predictability and research needs. The EC project on "Management and Uncertainties of Severe Accident (MUSA)", funded by Horizon 2020 Framework Programme, is aimed to assess the capability of severe accident codes when modeling reactor and SFP (Spent Fuel Pool) accident scenarios of Gen II and Gen III reactor designs, AM included. To do so, different UQ (Uncertainty Quantification) methodologies are to be used, with focus on Source Term (ST). With work force estimated in 630 person-months, MUSA gathers 28 international organizations (about 25% non-EU members) from research, regulatory bodies, industry, universities and TSOs (Technical Support Organizations). Structured in five technical Work Packages (WP), the project will: identify and quantify uncertainty sources in severe accident analyses; review and adapt UQ methodologies; test such methodologies against integral experiments (PHEBUS-FPT1); and apply to reactor and SFP accident scenarios, including AM. In addition, a whole WP has been planned to foster dissemination and communication of the major project outcomes (WP7) and the coordination and management is conducted through another (WP1).*

CIEMAT coordinates MUSA and organizations like CSN and ANAV are involved in the project through its Advisory Board (AB) and End User Group (EUG), respectively. This paper describes the main pillars of the MUSA project, the milestones foreseen and the major outcomes expected at the end of the project. Particular attention is paid to the progress made since its launch in June 2019.

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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 SA. Hence, they are a central element of the safety demonstration where the compliance of the main safety features of a NPP is checked against safety requirements reflecting the state-of-the-art. In addition, the development and optimization of AM measures aiming at preventing and mitigating the consequences of SA heavily rely on a large number of numerical simulations with SA codes such as ASTEC, AC2, MAAP, MELCOR, etc. Since the SA tools predict important parameters such as the time of failure of safety barriers, on one hand, and the potential radiological ST to be released to 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 different SA phases 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 [1]. At present, many SA codes have reached a considerable maturity regarding their modelling scope and accuracy, simulation capability of safety-relevant phenomena, validation for a large number of reactor types and numerical stability, and extensive applications in industrial, regulatory and research areas have been done. Furthermore, they are extensively employed for the development and optimization of AM measures and to provide the ST to estimate the radiological impact on the site and around it.

For many years, mathematical tools for the quantification of code uncertainties and sensitivities have been under development worldwide, e.g., DAKOTA, RAVEN, SUNSET, SUSA, URANIE etc. There is a huge accumulated experience already in the nuclear community in performing Uncertainty Quantifications (UQ) with Best Estimate (BE) thermal-hydraulic system codes and it is being extended to other fields, like fuel performance, neutronics, sub-channel thermal hydraulics and Computational Fluid Dynamics (CFD). So far, though, this has not been the case for SA codes. Only a few investigations have been focused on SA and UQ in Europe [2] and elsewhere [3].

MUSA (Management and Uncertainties of Severe Accidents) is a 4-year, HORIZON-2020 project that moves 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. By doing so, not only the prediction of the timing for the failure of safety barriers and of the radiological ST in case of a SA in a NPP will be possible, but also the quantification of the uncertainty bands of selected variables, considering any relevant source of uncertainty, will be provided. It should be highlighted that MUSA is not restricted to reactor accidents, but Spent Fuel Pool (SFP) accidents are also addressed. Therefore, as a result of MUSA, innovative AM strategies might be developed for both reactor and SFP accidents. In addition to describe the main pillars of the MUSA project, the milestones foreseen and the major outcomes expected at the end of the project, this paper pays particular attention to the progress made since its launch in June 2019.

2. OBJECTIVES & STRUCTURE

The overall objective of MUSA is to assess the capability of SA codes when modeling reactor and SFP accident scenarios of GEN II, GEN III and GEN III+ reactor designs. To do so, UQ methodologies are to be employed, with an emphasis on the effect of both existing and innovative AM measures on the accident progression, particularly those measures related to the ST mitigation. Therefore, ST-related FOMs (Figures of Merit) are to be used in the UQ application. Consequently, the MUSA project will contribute to the determination of the state-of-the-art prediction capability of SA codes regarding the ST that potentially may be released to the external environment in a SA, and to the quantification of the associated code's uncertainties applied to SA sequences in both NPPs and SFPs.

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

- Identification and Quantification of Uncertainty Sources (WP2, IQUS).
- Review of Uncertainty Methodologies (WP3, RUQM).
- Application of UQ Methods against Integral Experiments (WP4, AUQMIE).
- Uncertainty Quantification in Analysis & Management of Reactor Accidents (UQAMRA).

- Innovative Management of SFP Accidents (IMSFP).

As noted in Figure 1, there is a specific WP for managing technical, financial and legal aspects of the project (WP1, MUCO) and another one (WP7, COREDIS) for efficiently articulate the communication and dissemination activities so that technical outcomes of MUSA reach as many stakeholders as possible and the resulting enhancement of nuclear safety reaches the generic public. A special attention will be given to facilitate such transfer towards young researchers and Masters/PhD students.

These WPs aside, the technical WPs (i.e., WP2-WP6) distribute 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 WP block" (i.e., WP4, WP5 and WP6). In the following further technical details will be given on each of them.

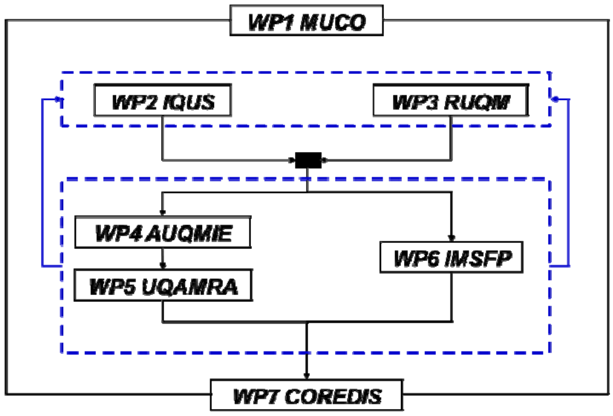

Figure 1. MUSA Work Package interlink

As shown in Figure 2, the "application block" represents roughly two thirds of the total workforce anticipated in MUSA, 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).

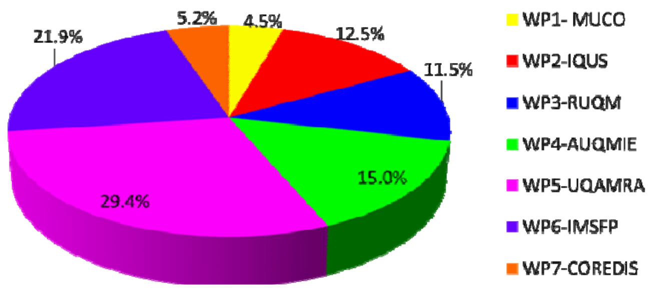

Figure 2. Workforce distribution

3. MAJOR MUSA FEATURES

Some MUSA specific features strengthen the project significance, e.g.:

- 28 organizations from 3 continents are MUSA partners (Figure 3). This extensive participation ensures a wide range of competences and experience on SA phenomena and ST investigations with different perspectives (TSOs, utilities, research centres and academia). In addition, it guarantees a wide spread of the MUSA results.

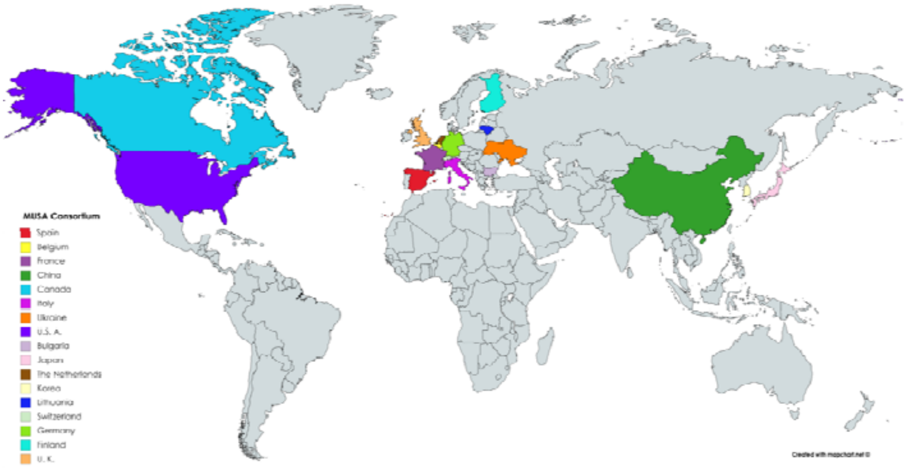

Figure 3. MUSA member countries

Table 1 gathers the organizations involved in each WP; the organizations responsible for each WP are highlighted in bold.

Table 1. Partners distribution in WPs

WP	PARTNERS
MUCO	**CIEMAT**, LGI
IQUS	CIEMAT, BELV, CEA, CNSC, ENEA, Energorisk, EPRI, **GRS**, INRNE, IRSN, KIT, LEI, PSI, SSTC, TRACTEBEL, TUS, USNRC, VTT, WOOD
RUQM	CIEMAT, BELV, CNSC, ENEA, Energorisk, EPRI, FRAMATOME, GRS, INRNE, IRSN, JAEA, **KIT**, LEI, NINE, SSTC, TRACTEBEL, TUS, UNIRM1, VMU, WOOD
AUQMIE	CIEMAT, CEA, CNPRI, CNSC, **ENEA**, Energorisk, EPRI, GRS, INRNE, IRSN, KIT, LEI, PSI, SSTC, TUS, UNIPI, UNIRM1, USNRC, VTT
UQAMRA	CIEMAT, BELV, CNPRI, CNSC, ENEA, Energorisk, EPRI, FRAMATOME, GRS, INRNE, IRSN, JAEA, **JRC**, KAERI, KIT, LEI, NINE, PSI, SSTC, TRACTEBEL, TUS, UNIRM1, USNRC, VTT, WOOD
IMSFP	CIEMAT, CEA, CNPRI, CNSC, ENEA, Energorisk, EPRI, INRNE, **IRSN**, KAERI, LEI, PSI, SSTC, TUS, UNIRM1, USNRC
COREDIS	CIEMAT, ENEA, GRS, IRSN , JRC, KIT, **LGI**, NINE, **UNIPI**

- The focus on ST analysis stems naturally from the ultimate goal of SA codes and it is consistent with the aftermath vindicated during and after the Fukushima accident. The role played by ST 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 ST. The huge participation in MUSA will contribute to the harmonization of the confidence level on ST estimates.
- The integrating nature of MUSA is outstanding. Despite the specific application on the ST area (i.e., release, transport, and chemistry), the project integrates all the aspects of both in-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 LWR types.
- The 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 project

Advisory Board and the End-Users Group are heavily populated by scientists and engineers coming from those communities; their link to the project is shown in Figure 4.

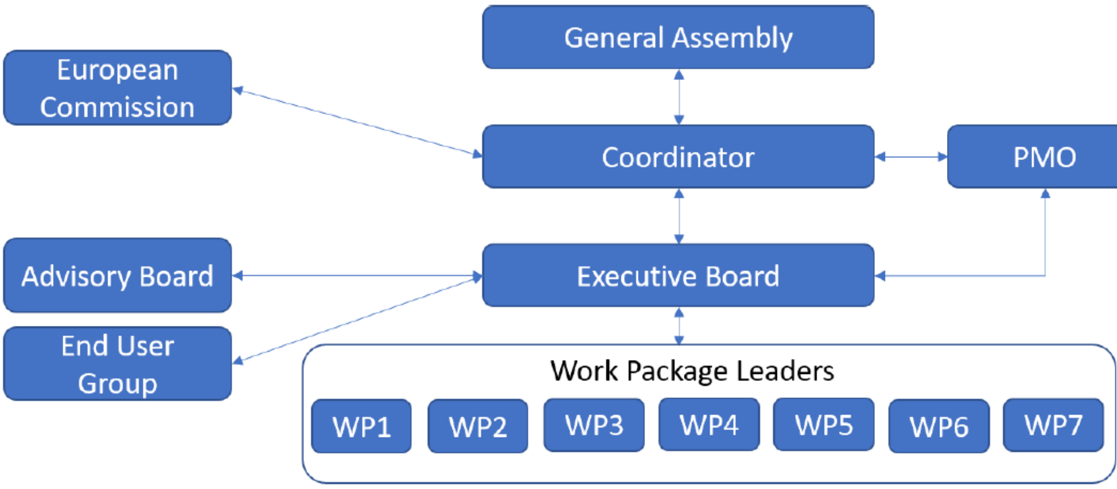

Figure 4. Overall project structure

- The already available elements the project is supposed to work with, like experimental data coming from earlier projects previously supported under the EURATOM framework (e.g. PHEBUS-FP) and the analytical tools (both SA codes and UQ software).

Selected key project milestones are listed hereafter:

- Identification of key SA processes/phenomena affecting the ST and quantification of their associated uncertainties,
- Identification and quantification of key parameters of AM measures implemented in the SA affecting the ST, and their associated uncertainties,
- Evaluation of applicable methods of UQ (sensitivity analyses included) to the SA field and definition of best UQ application practices in SA analyses,
- Trial of Uncertainty and Sensitivity Analysis (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, and
- Recommendations for improvement and/or new innovative AM measures for both reactor and SFP scenarios.

4. WORK PACKAGES DESCRIPTION & CURRENT STATUS

The technical content of MUSA is split into five technical WPs, as introduced in section 2. The Gantt chart displaying the project planning is in Figure 5. Ignoring the second level structure (sub-WPs), the WP "preparatory block" WP2/WP3 starts with the project and their first working period lasts about 1 year, and features a last working period to harvest insights from the WP "application block" located 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.

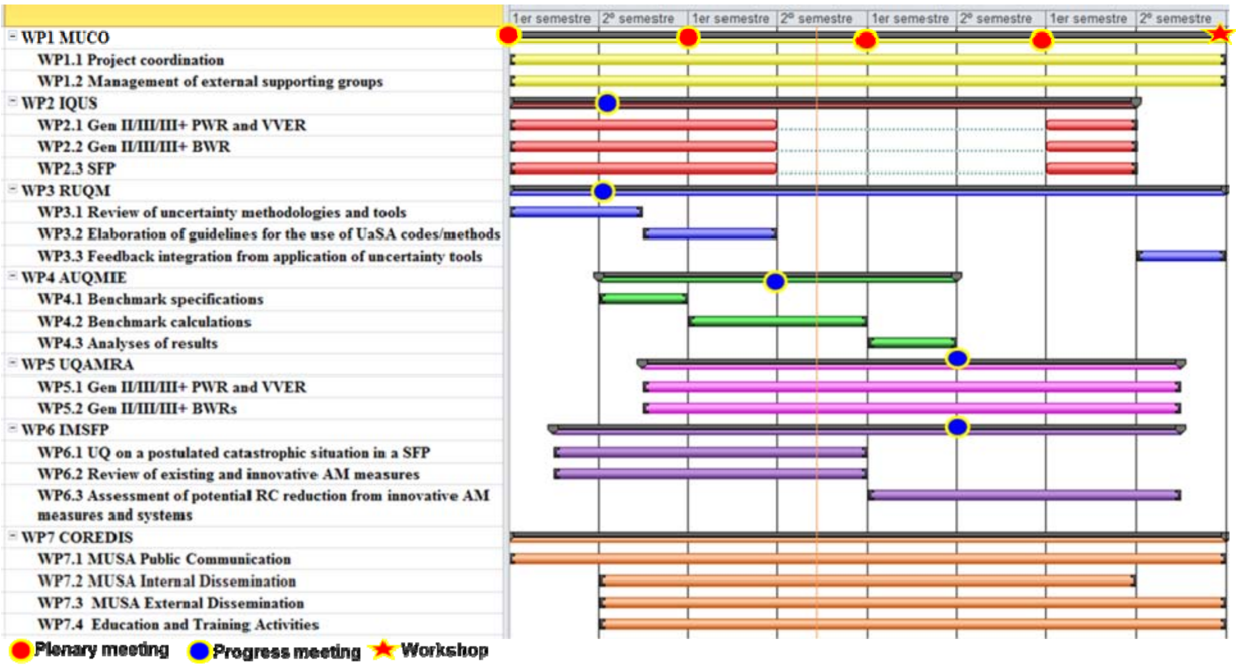

Figure 5. Work and meetings planning

Next, a brief description of each technical WP is given.

4.1 Identification and Quantification of Uncertainty Sources (IQUS)

IQUS identifies and partially quantifies the major sources of uncertainties of any type of processes and phenomena during SAs affecting the ST – here defined as the releases of radionuclides from a plant into the environment. 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 SA with the focus on ST and will also include application to AM measures - both in the reactor of various LWR types (GEN II and GEN III) and the SFP.

The WP is structured in three sub-WPs according to the application domain (reactor designs of GEN II/III/III+ are within the MUSA scope): PWR; BWR; SFP. Three main tasks are to be conducted in each sub-WP: selection of severe accident phases and phenomena; consideration of requirements from SA codes and UQ methods; and determination of uncertain variables, parameters and models to be used. Hence, the main WP outcome will be a “knowledge-based matrix” containing the selected variables, parameters and models and its uncertainty ranges which shall be applied by the code users within the uncertainty and sensitivity studies in the “application” WPs (AUQMIE, UQAMRA, and IMSFP).

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4.2 Review of Uncertainty Quantification Methodologies (RUQM)

The objective of RUQM is to review and assess promising methodologies and codes used for uncertainty quantification and sensitivity analyses and their applicability for the analysis of severe accident scenarios without and with AMs 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 SA domain are planned to be written.

In short, the outcome of the activity would be a set of different uncertainty quantification 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 “application” WPs (AUQMIE; UQAMRA; IMSFP), which should provide feedback to RUQM to optimize methodologies and guidelines.

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4.3 Application of UQ Methods against Integral Experiments (AUQMIE)

Aimed at getting some experience and insights into the application of the RUQM methodologies against recognised integral ST-experiments, AUQMIE will be the first chance to test both the IQUS and RUQM outcomes on a simplified, still representative, SA scenario (neither ex-vessel phase nor SFP accident included). AUQMIE will be, hence, a drill for other application WPs and an opportunity to provide some early feedback to RUQM. The test selected belongs to the PHEBUS-FP project [4]: the PHEBUS FPT1. By no means, this is intended as a data-code or a methodology benchmark; the only reason why reliable and representative data have been proposed is to have full and credited details of the scenario and data that might help to calibrate the final model to be used.

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

UQAMRA 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 different tools investigated by the partners. The results achieved by propagating uncertainties through different integral SA codes will be assessed using UaSA codes, and governing uncertainties will be determined.

In addition to the outlining uncertainty bands affecting ST estimates, two other major outputs are to be produced: a sort of agreed best-practice protocol and an identification of areas where further research is needed to effectively reduce uncertainties affecting ST estimates. Consistently with IQUS, two sub-WPs are set for PWR and BWR designs, respectively. It is worth highlighting that AM measures are to be considered (in both timing and efficiency).

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4.5 Innovative Management of SFP Accidents (IMSFP)

IMSFP is to a good extent similar to UQAMRA as for the RUQM methodologies application, but a significant emphasis is placed on reviewing existing or contemplated AM mitigation measures and systems and proposing innovative ones, which benefits should be assessed in terms of reduction the radiological consequences.

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4.6 Communication and DISsemination (COREDIS)

The COREDIS WP7 has been also very active during the first 6 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, suspended at the beginning of 2020 for the COVID-19 emergency. In addition to the MUSA internal workspace (https://app.lgi-consulting.org/ecm/musa-ecm), a public website has been set up (http://musa-h2020.eu/) as well as a MUSA LinkedIn page (https://www.linkedin.com/company/musa-h2020-project/) and other communication tools (internal and external newsletters[1], project leaflet, general presentation poster, templates for documents and presentations, ecc.). Presently, discussions are ongoing concerning a scientific publication strategy compatible with the EC policy in this regard but however some general papers on the project initial achievements have been submitted to international conferences (BEPU 2021, NURETH-19) or nuclear forum (SNETP Forum 2021, EUROSAFE 2021).

[1] For the subscription of the MUSA public newsletter: https://app.lgi-consulting.org/gdpr/index.php?v=26

In the near future, the restarting of the mobility actions is foreseen as well as of the other activities linked to the project educational and training aspects, as the on-line learning modules. At least three learning modules compiling the major outcomes from MUSA project, will be built to disseminate the MUSA outcomes to a generic audience. They will address the following topics:

- Major sources of uncertainties in Severe Accidents, with particular emphasis on ST.
- Methodologies for uncertainty assessment in Severe Accidents, with particular emphasis on the ST estimates.
- Assessment of ST Uncertainties in Fukushima-like scenarios.

6. FINAL REMARKS

The MUSA project, officially launched on June 1st 2019, is a well-structured project aimed at bringing the BEPU approach into the SA analysis, including AM in reactor and SFP scenarios, by building an uncertainty matrix of input variables and by adapting methodologies used in other nuclear safety domains. Source Term is to be the focus and has already inspired the definition and agreement of FOMs. In addition to awareness of the SA 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 ST estimates, and AM optimization of accident management by either better implementing already foreseen actions or even proposing innovative ones.

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