

NUCOBAM European project: NUclear COmponents based on additive manufacturing

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Abstract. NUCOBAM is an EU-funded project that aimed at developing the qualification process and providing the evaluation of the in-service behaviour allowing the use of Additively Manufactured (AM) components in a nuclear installation. Once qualified, the use of AM allows nuclear industry to tackle component obsolescence challenges and to manufacture and to operate new components with optimized design in order to increase reactor efficiency and safety. To make this ambition a success, NUCOBAM conducted studies to implement AM process in nuclear design codes and standards to manufacture nuclear reactor components. The project was based on two coupled strategies: the first part consists of a collection of the physical, mechanical, and microstructural characterization of the materials from four manufacturers that result from the AM process (using four heat treatments) in order to establish a qualification and codification process. The second part is dedicated to the evaluation of AM material behaviour in-service, especially regarding main degradation mechanisms that occur in Light Water Reactors (LWR) (thermal ageing, irradiation...). Materials are manufactured and some of them submitted to post-treatment (heat treatment or high isostatic pressure). This work allows manufacturers and designers to evaluate and deduce the main parameters required for specification. The project participants involved electricity utilities, operating nuclear assets, component manufactures, design owners, public service experts in nuclear and radiation risks as well as research and competence centres involved in mechanical assessment, metal powder qualification, metallurgical characterization, materials irradiations capabilities and nuclear power research.

1 Introduction

Additive manufacturing (AM) processes, or 3D printing, have seen rapid development and deployment in many industries. The improvements of AM process over the last 10 years now allow considering seriously these production processes in the nuclear context, in order to propose components of suitable quality with improved design, and thus delivering more safety. The AM technology would also minimize or eliminate weakened areas generated by conventional welding processes. AM is a performing way to produce complex parts limiting material use and cutting cost and time.

AM has been widely adopted in industries other than nuclear. Wide-spreading of AM in the nuclear industry is complicated by lack of standards, SDO (standard development organizations) acceptance and regulatory approval. AM presents an opportunity for nuclear power plants to replace machinery and parts with relative ease and speed

compared to conventional methods using processes such as welding, machining and casting. In order to be able to use AM in nuclear facilities, nuclear stakeholders must have confidence in the manufactured components. This means that before installing these components, they must go through rigorous testing and quality control. However, the deployment of such processes depends on the demonstration of equivalence in terms of the quality and safety of AM components compared to conventional (non-nuclear) materials and methods. To reach this demonstration, EU-funded NUCOBAM (Nuclear Components based on Additive Manufacturing) project consolidated key elements for nuclear standardization of AM in order to develop the qualification process to allow using of additively manufactured components in NPP.

1.1 Trends in the development of AM techniques for the nuclear industry

Promising metal alloy AM techniques in nuclear industry are: HIP (Hot Isostatic Pressing, powder metallurgy),

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DED (wire arc or powder Direct Energy Deposition), Powder Bed Fusion (laser L-PBF & electro-beam EM-PBF). Examples of application to Gen-II and -III reactors, and R&D to Gen-IV reactor applications of PBF and DED can be found here [1]. Other examples of first AM nuclear applications are: pump impellers (one installed at a Slovenia's Krško NPP in 2017, and another totally independent in the VVER-TOI Russian reactor), fuel channel fasteners (installed in 2021 in the Atrium 10XM boiling water reactor fuel assemblies at Framatome nuclear fuel manufacturing facility in Richland, Washington), fuel upper tie plate grids made of stainless steel (installed by Framatome in 2022 at the Atrium11 boiling water reactor of the Forsmark NPP operated by Vattenfall in Sweden) [2].

2 NUCOBAM organisation

The project started on October 2020, targeting to conduct the necessary manufacturing characterization and validation studies to assess AM for the nuclear industry, and ended on September 2024. The project consortium consists of 13 partners involving electricity utilities, operating nuclear assets, component manufactures, design owners, public service experts in nuclear and radiation risks as well as research organisations involved in mechanical assessment, metal powder qualification, metallurgical characterization, materials irradiations capabilities and nuclear power research.

The consortium partners are:

1. CEA Commissariat à l'énergie atomique et aux Energies Alternatives (France)
2. IRSN Institut de Radioprotection et de Sureté Nucléaire (France)
3. EDF Electricité de France (France)
4. NAVAL GROUP (France)
5. FRAMATOME SAS (France)
6. LABORELEC Belgisch Laboratorium van de Elektriciteitsindustrie Laborelec (Belgium)
7. SCK-CEN Centre d'étude de l'énergie nucléaire (Belgium)
8. TRACTEBEL-ENGIE (Belgium)
9. CIEMAT Centro de Investigaciones Energéticas, Medio Ambientales y Tecnológicas (Spain)
10. USFD The university of Sheffield (UK)
11. VTT Technical Research Centre (Finland)
12. RAMÉN VALVES AB (Sweden)
13. JRC Joint Research Centre (European Commission)

With CEA as project coordinator, NUCOBAM project was organized in seven working packages (WP) Figure 1: WP1 Methodology for AM qualification standardization.

WP2 AM process qualification.

WP3 Qualification as processed: NDE & mechanical properties vs microstructure.

WP4 In-pile behaviour of AM samples.

WP5 Performance assessment of ex-core user case.

WP6 Communication, dissemination and exploitation of results.

WP7 Project Management.

3 NUCOBAM scope

The EU-funded NUCOBAM project aim to develop the qualification process and evaluate the in-service behaviour of AM materials, allowing the use of additively manufactured components in nuclear installations. To this end, the project investigated the implementation of AM processes in nuclear design codes & standards to manufacture components for nuclear power plants (NPP) Figure 2. The project's results play an important role in advancing the use of AM components in the nuclear industry. To this day, AM methods have not been yet incorporated into nuclear design codes.

3.1 Main objectives

NUCOBAM project set five technical objectives (and an additional one dissemination-related objective) strongly correlated to the project methodology and the structure of the work packages. Each objective associated to a set of Key Performance Indicators (KPIs) and the means of evaluating their degree of compliance during the project:

1. to establish a Qualification Methodology for nuclear components. This methodology intended to be ready for standardisation proposal to be presented to nuclear Standard Development Organizations (SDO).
2. To develop AM technique manufacturing plan that ensures and demonstrates process stability, repeatability and reproducibility that meet nuclear quality standards.
3. To demonstrate that the AM component performance meets qualification requirements.
4. To demonstrate that AM component meets its safety-related function and operational requirements.
5. To assess the operational performance AM components regarding safety-related function and operational requirements.
6. To disseminate and prepare the exploitation of results.

The backbone of the *qualification methodology* was defined early in the project and this set all the required sections to be documented for a consistent standard harmonized with existing nuclear codes & standards. To this end, the *qualification methodology* fulfilled this objective: this methodology, the deliverable of WP1, was the repository of the outcomes coming from the rest of WP results. All discussions, key achievements and test data converged to develop the *qualification methodology*. Since the beginning, this methodology was intended to be a baseline for pre-codification reference documents. This was the ultimate objective of NUCOBAM project. In principle, this document can be declined as proposal to any code or standard.

3.2 Project expected impacts

In a short term (end of the project), the qualification methodology was decline in two pre-normative versions:

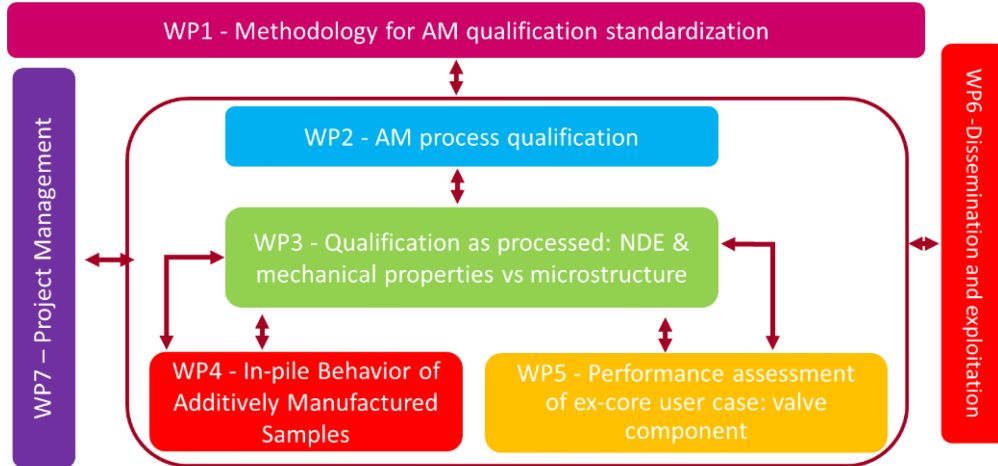


Fig. 1. Organisation of NUCOBAM project.

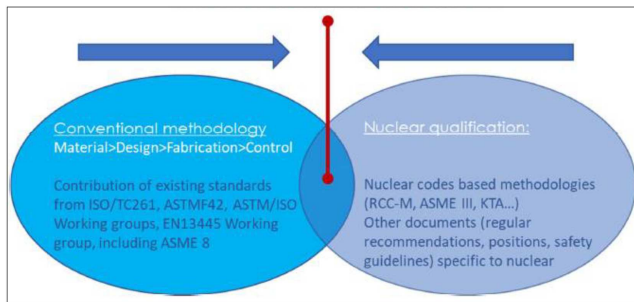


Fig. 2. NUCOBAM approach.

one for ASME (American SDO) and one for AFCEN (French SDO for RCC-M nuclear design code).

For midterm, since the qualification methodology was made available to the consortium members, a proposal to include AM in the next 2025 edition of the RCC-MRx design code is currently in instruction. It is worth mentioning that this was not originally intended in the project, but resulted anyway as positive impact.

For long term, a detailed proposal intended for AFCEN RCC-M nuclear design code is currently in preparation: this proposal covers the L-PBF and DED. This will be introduced in the next edition of the RCC-M code (AFCEN plans to release it in 2028).

4 Project results

NUCOBAM project conducted the necessary, manufacturing, characterization and validation studies for the assessment of AM for the nuclear industry [3]. NUCOBAM project investigated a new and innovative process in order to consolidate materials for nuclear components of existing Light Water Reactors (LWR) models, and while considering conventional degradation mechanisms (irradiation, mechanical loadings...) and all potential phenomena that could result in environmental assisted cracking and fracture.

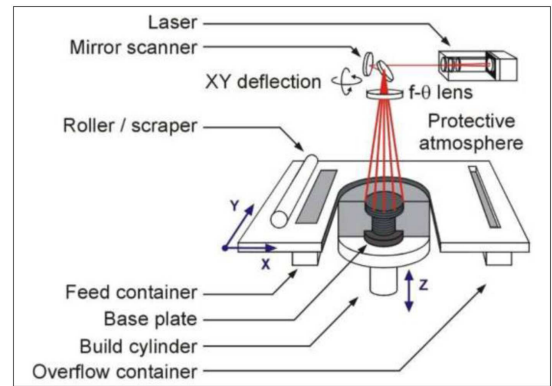


Fig. 3. Laser Powder Bed Fusion (L-PBF) technique.

4.1 AM technique of interest

Among the different AM technologies currently available and according to the project consortium partner's interest, NUCOBAM project selected Laser Powder Bed Fusion (L-PBF) technology that selectively fusions regions of a powder bed, layer-by-layer (Fig. 3), with one or several lasers (SLM – selective laser melting).

4.2 Material and component parts of study

According to consortium partners applications, the selected material of interest is the austenitic stainless steel 316L, as it is widely used in LWR for reactor internals, primary pumps, valves, etc. Two components considered for study, both in 316L (Fig. 4):

1. debris filter for fuel assemblies: component normally submitted to in-service irradiation.
2. Valve body: component submitted to in-service thermal and mechanical loads.

Built using AM, these two components are representative of the challenges typically encountered with the

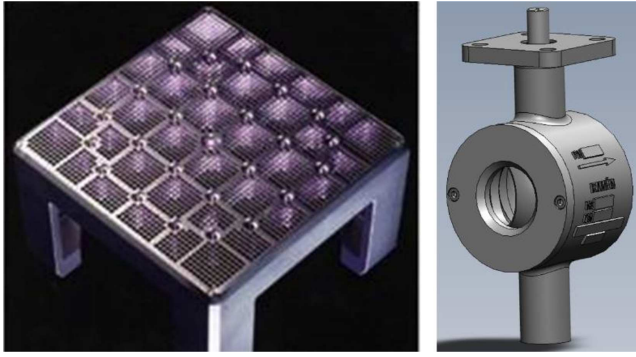


Fig. 4. Left: fuel debris filter (© Framatome SAS). Right: housing of obsolete safety valve body (© TRACTEBEL-ENGIE).

development of the new processes: optimised design configurations and reduction of the number of parts in an assembly. Corresponding demonstrators and associated samples were planned to be manufactured and some of them for post-treatment (heat treatment or high isostatic pressure). The results were analysed and compared with existing approved manufacturing processes by design codes. This work led to fill the gaps of the objectives of the project, and it helped to deduce the main parameters required for specification.

4.3 WP results

Each WP has a consortium partner leader. A summary of the main objectives and results for each WP is presented here:

- the WP1 [in charge of CEA] dedicated to the AM qualification methodology had a few baselines: to perform a comprehensive review of the existing standards and qualification processes in order to define specific nuclear requirements for the nuclear AM codification proposals. Dozens of AM standards and relevant guidelines were studied. WP1 successfully delivered a qualification methodology to be used as guideline for two different AM codification proposals: one for ASME code case, and one for AFCEN RCC-M. The last one is currently under instruction at AFCEN. Note that those intended codification proposals were not covered by NUCOBAM scope, but the consortium partners were encouraged to use the qualification methodology to do so. TRACTEBEL and LABOR-ELEC drafted the codification proposal for ASME BPVC. EDF and Framatome drafted the codification proposal for AFCEN RCC-M code. TRACTEBEL integrated the distinct manuscripts producing a final deliverable reviewed by all partners, thus concluding all activities planned under WP1.
- WP2 [in charge of VTT] for the AM process qualification: with the aim to create a general methodology for qualifying L-PBF processes in line with WP1. Four different labs manufactured identical specimens with the same qualification process on their different

AM machines. Existing process monitoring methods available but most commercially available methods are based on either melt pool monitoring (MPM) or optical tomography. During the first reporting period, VTT used a MPM system to monitor the manufacturing of all the samples corresponding to the stability, repeatability and qualification phases (see Fig. 5 left) as well as the specimens manufactured for WP3 and WP4 (see Fig. 5 right).

This WP obtained the following results: the establishment and validation of a qualified L-PBF process in terms of stability, repeatability & reproducibility, while producing test coupons for specimens of project characterizations & irradiation programme (WP3 & WP4) and components debris filter & valve housing for WP5 (Fig. 4). Some results about qualification and evaluation are presented here [4].

- WP3 [in charge of Naval Group] main objective was to demonstrate that 316L stainless steel, manufactured by L-PBF meets the material performance qualification requirements. WP3 successfully covered the Non-Destructive Examinations (NDE) of both AM components (the fuel debris and the valve body, Fig. 4) and the mechanical characterization (evaluation of mechanical properties with a testing matrix of 780 specimens Fig. 6) of the material of WP2, to ensure the qualification as processed. Samples meet at least the code properties for conventional 316L. Some results concerning fatigue can be found here [5].
- WP4 [in charge of FRAMATOME] dedicated to the assessment of the In-pile Behaviour of Additively Manufactured Samples (IBAMS) dealing with microstructure characterization, determination of the mechanical properties, irradiation conditions and related documentation. An irradiation campaign (the data that has been used is confidential) was performed to produce representative damages on 316L (L-PBF) samples and conventional cold worked (CW) wrought manufacturing route. The neutron irradiation was performed in the BR2 materials testing reactor of SCK-CEN between April 2022 and December 2023 (Fig. 7). The program consisted of irradiating three types of specimens: tensile, Charpy and TEM samples, all manufactured by L-PBF process. The results are confidential. Nevertheless, some results obtained within NUCOBAM project are public and correspond to a public article [6].
- WP5 [in charge of TRACTEBEL] handles the performance assessment of ex-core user case: valve component produced by L-PBF process manufacture in the framework of WP2. WP5 focused on the execution of functional and pressure tests and post-test examinations normally made by the valve manufacturer at the valve manufacturer's plant. The planned component inspections are the NDE for checking the possible defects, and destructive tests from the same AM build platform to assess microstructure & mechanical properties (tensile, toughness, etc.). The valve test

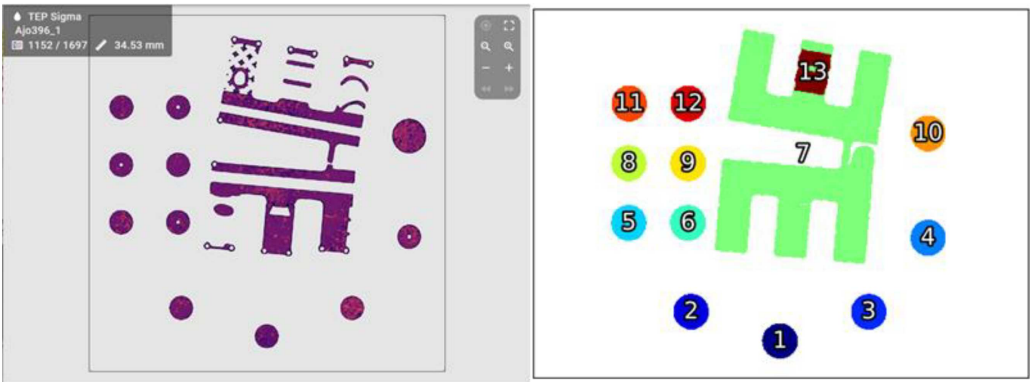


Fig. 5. Melt pool monitoring (MPM).

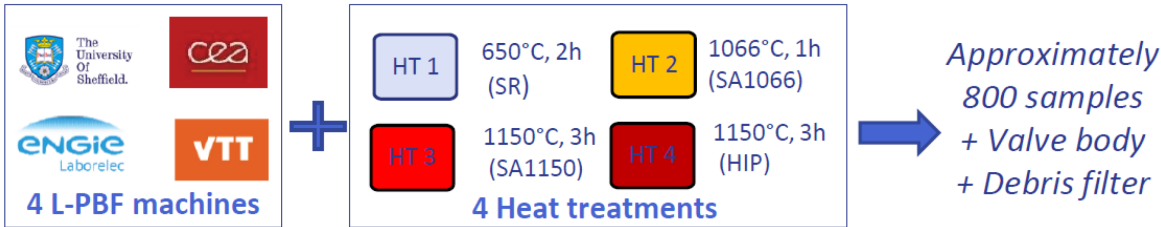
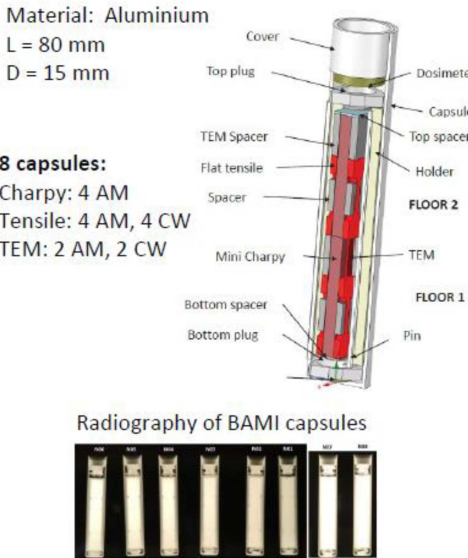


Fig. 6. Overview of WP3 Qualification Tests Program: NDE & Mechanical properties versus microstructure (post processing HT)

BAMI capsule design and qualification



BR 2 irradiation

Neutron irradiation in BR2, SCK.CEN, Mol, Belgium



Synthesis of NUCOBAM irradiation

Capsule	Samples	Temp (°C)	Dose (dpa)
NU01	A1, A2, 316L CW	317± 40	0.84±0.06
NU02	A3, A4, 316L CW	280±25	0.56±0.09
NU03	A1, A2, 316L CW	303±21	2.2±0.4
NU04	A3, A4, 316L CW	307±14	2.3±0.1
NU05	A1, A2, 316L CW	300±29	4.2
NU06	A3, A4, 316L CW	291±35	3.8
NU07	A1, A2, 316L CW	309±42	3
NU08	A3, A4, 316L CW	297±36	2.9

Fig. 7. Summary of NUCOBAM irradiation conditions and BAMI capsule design.

programme is as follows: a functionality and pressure tests (static & cyclic) on fully-assembled valve using AM valve housing; a functional test on (EDF) test-loop to qualify that this component can be used as an usual build component; and a burst test on valve housing and subsequent NDE and mechanical tests from samples retrieved from burst test (tensile, Charpy impact, hardness, etc.). The functional testing of the

valve’s internal components on the Cypres/Cythere loop could not take place due to technical issues on the test loop. “Static” pressure testing and seat leak testing could however be performed and similar results to the ones performed by Ramén Valves earlier that year were obtained. Some results concerning the performance assessment of the valve can be found here [7].

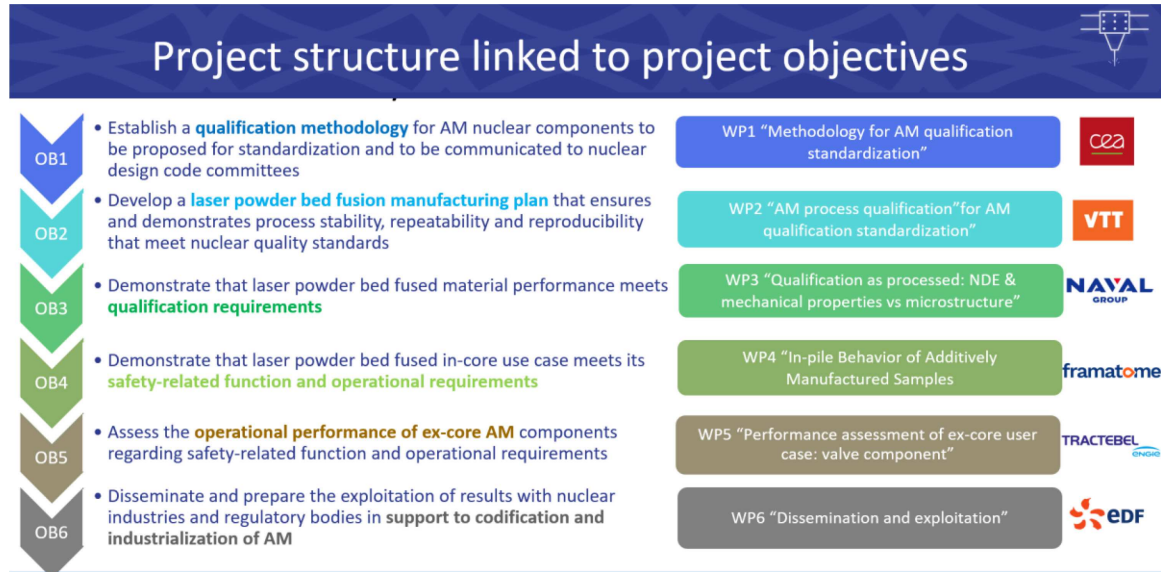


Fig. 8. Conclusion: achievement of the 6 objectives of NUCOBAM project.

- WP6 [in charge of EDF] Communication, dissemination and exploitation of results: project progress was presented in a number of conferences and technical workshops. All results were available for consortium partners. The End User Group members have received deliverable corresponding to two standardized texts for the Qualification methodology of stainless steel 316L manufactured by L-PBF ready to be proposed to codes committees. As stated before, the submission of codification proposals was not part of NUCOBAM project, but in line with the short-term objectives, some consortium partners effectively used the qualification methodology as guideline for a codification proposal to AFCEN RCC-M Code. Information about those codification proposals can be found here [8]. All these publications are available on the project's website [9].

5 Conclusion

NUCOBAM project followed two basic and coupled strategies: the first one consists of a collection of the basic physical, mechanical and microstructural characterization of the materials that result from AM process. Previously existing data collected from literature set the basis for the developed qualification process and nuclear codification. The second one, R&D performed to estimate material degradations under service conditions, taking into account specific needs of nuclear industry such as irradiation, fatigue and corrosion. The project's results play an important role in advancing the application of AM in the nuclear industry (Fig. 8).

Concerning deliverables of each of WP: for WP1 on process qualification there are two deliverables corresponding to codification proposals for ASME BPVC and AFCEN RCC-M Code. In addition, based on this deliverable, a codification request was also proposed for AFCEN

RCC-MRx and it is intended to appear at the coming RCC-MRx 2025 edition. Regarding WP4 on irradiation, one of the deliverables is public in accordance with the project's results dissemination plan and it corresponds to the article [6].

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Glossary

AFCEN Association française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières électronucléaires (French SDO)

AM Additive Manufacturing

ASME American Society of Mechanical Engineers (SDO)

BPVC Boiler and Pressure Vessel Code (ASME Code)

NDE Non-Destructive Examinations

NPP Nuclear Power Plants

L-PBF Laser Powder Bed Fusion (AM technique)

LWR Light Water Reactors

RCC-M Design & construction rules for mechanical components of PWR nuclear islands (AFCEN Code, coordinated by FRAMATOME)

RCC-MRx Design & construction rules for mechanical components of advanced reactors & innovative nuclear installations (AFCEN Code, coordinated by CEA)

SDO Standard Development Organization

SLM Selective laser melting

SMR Small Modular Reactors

WP Project Work Package

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Conflicts of interest

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

Data availability statement

Project deliverables remain the property of NUCOBAM consortium. Some of deliverables are public and available at NUCOBAM website [9]. The WP4 irradiation results are confidential. Concerning the nuclear codification proposal to AFCEN RCC-M Code, as it is not a part of NUCOBAM project; it is property of their authors.

Author contribution statement

Both authors contributed equally to this work. Conceptualization, Jorge E. MUÑOZ G. and Myriam BOURGEOIS; Validation, Jorge E. MUÑOZ G. and Myriam BOURGEOIS; Writing – Original Draft Preparation, Jorge E. MUÑOZ G. and Myriam BOURGEOIS; Writing – Review & Editing, Jorge E. MUÑOZ G. and Myriam BOURGEOIS.

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