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EASI SMR

# EASI SMR D6.1 – Methodology for Process Validation

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# Table of Contents

List of Figures....................2
1. Document information....................3
2. History....................3
3. Summary....................4
4. Keywords....................5
5. Abbreviations and acronyms....................5
6. Definitions....................6
7. Introduction....................11
8. General approach for the process qualification strategy....................11
8.1. Qualification methodology for laser powder bed fusion....................12
8.1.1. Record templates for quality assurance and quality control....................13
8.1.2. Powder specifications....................13
8.1.3. Process stability platform....................14
8.1.4. Process repeatability platform....................14
8.1.5. Process qualification platform....................15
8.1.6. Product validation platform....................16
8.2. Qualification methodology for directed energy deposition....................17
8.2.1. Record Templates for Quality Assurance and Quality Control....................18
8.2.2. Powder Specifications....................18
8.2.3. DED material/process parametrization....................19
8.2.4. DED platforms for machine qualification....................19
8.2.5. DED-LB/Mp process qualification....................20
8.2.6. Product validation platform....................21
8.2.7. Analysis and testing....................22
8.2.8. Qualification Variables....................23
8.3. General considerations on specimen labelling....................24
9. Test Matrix for product validation....................25
10. Conclusions....................32



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# List of Figures

*Figure 1. Flowchart of the AM process qualification methodology ....... 12*

# List of Tables

*Table 1. Qualification variables for DED-LB/Mp ....... 23*
*Table 2. Example of labelling strategy during the qualification process ....... 24*
*Table 3. Specimen designs for mechanical and corrosion testing. Additional specimens for thermal ageing and Eddy current measurements are also considered ....... 25*
*Table 4. Test matrix per conditioned material for the product qualification using laser powder bed fusion 29*
*Table 5. Test matrix per material for the process and product qualification using direct energy deposition: platform A and platform B ....... 30*

# 1. Document information

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# 3.Summary

The EASI SMR project aims to provide insights and facilitate licensing for European LW-SMR (Light Water Small and Modular Reactors) industrial projects. Additive manufacturing (AM) is seen as an enabling technology for improving the compactness and modularization of Nuclear Steam Supply System internals. It offers significant advantages such as prototyping of components with complex geometries, much faster production than conventional manufacturing and increased component performance. This work package aims at providing qualification guidelines for using additively manufactured components in SMRs in a safe manner. These qualification guidelines could also be applicable to other nuclear components not directly related to SMRs, and that could benefit from the use of AM parts: e.g. for spare parts supporting the long term operation of the nuclear industry as a whole due to the challenges with component obsolescence. This work package involves two main additive manufacturing processes: Powder Bed Fusion using laser beam for metal powders (PBF-LB/M) and Laser beam Directed Energy Deposition using metallic powder (DED-LB/Mp).

The primary objective of the methodology is to ensure that the AM processes provide stable and reproducible results in terms of material performance. The methodology involves validating the PBF-LB/M process prequalification guidelines, which was previously developed in the NUCOBAM project, and adapting it for the DED-L process to enhance the qualification procedures available in the published standards. The qualification strategy includes four pillars:

- Defining dedicated record templates for Quality Assurance and Quality Control.
- Formulating build platform configurations to demonstrate machine stability and repeatability.
- Executing a manufacturing program to qualify the processes.
- Defining a testing matrix for material characterization.

The validation methodology for PBF-LB/M and DED-LB/Mp processes consists of three main steps:

- Machine Stability Validation Build Job: Ensures material properties are homogeneous within the build envelope.



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- Machine Repeatability Validation Build Job: Ensures material properties are reproducible between similar build jobs.
- Process Qualification Build Job: Ensures the material produced meets the minimum requirements of a material specification.

The project defines specific record templates for DED to ensure the registration and traceability of key manufacturing variables. These templates include the preliminary AM procedure specification (p-AMPS), job sheets, and job quality control plans (JQCP). The powder specifications for both processes are also detailed to ensure conformity and traceability. For PBF-LB/M, the documentation generated as part of the NUCOBAM project will be employed.

The project includes a comprehensive testing matrix for both PBF-LB/M and DED-LB/Mp processes. The tests cover mechanical properties and other relevant characteristics to ensure the material meets the required standards.
Finally, it is preliminary included a production validation qualification step, in order to provide a more comprehensive understanding of the global qualification process, covering both process and component. However, more deep assessment of the product qualification methodology will be covered by the corresponding deliverable.

The EASI SMR project WP6 aims to qualify AM processes for SMR applications, ensuring that the produced components meet the stringent requirements of the nuclear industry. The methodology and validation steps outlined in this document provide a robust framework for achieving this goal.

# 4. Keywords

Nuclear, Additive manufacturing, Powder Bed Fusion, Directed Energy Deposition, metallic powders, qualification

# 5. Abbreviations and acronyms

| Acronym | Description |
|---|---|
| WP | Work Package |
| C&D | Communication & Dissemination |
| PBF-LB/M | Powder Bed Fusion using laser beam for metal powders |
| DED-LB/Mp | Laser Beam Directed Energy Deposition using metal powders |
| AMPS | Additive Manufacturing Procedure Specification |
| SMR | Small Modular Reactor |
| LW-SMR | Light Water Small Modular Reactor |
| NDT | Non-Destructive Testing |
| SSRT | Slow Strain Rate Test |
| SPT | Small Punch Test |
| AWS | American Welding Society |
| ASTM | American Society for Testing and Materials |



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# 6. Definitions

Application(s)-related Material Qualification Platform:

The Application(s)-related Material Qualification Platforms aim at demonstrating that the material produced on a dedicated machine, and according to a specific component-manufacturing plan (which defines the heat treatment procedure), fulfils the requirements for a nuclear-specific application.

AM process qualification:

AM process qualification is the qualification of the fabrication process itself, including the machine, the operating procedure and the personnel. It defines the actions to be taken, and related acceptance criteria, in order to demonstrate that an AM specific process can deliver, if correctly applied the required product. This aspect is addressed in §8.1.

Blended powder:

It is obtained by mixing virgin powder and unfused powder, or unused powder with unfused powder (from the same powder lot).

Build:

A part or a group of parts resulting from a job is called a build.

Build platform configuration:

A predetermined configuration of test specimens or test specimens with a part on a build platform that is used to assess the resulting properties of a build. An example of a build platform configuration is the stability assessment platform used to demonstrate the stability (and thereby, the repeatability and AM process qualification).

Component manufacturing plan (CMP):

The CMP is a quality control document that details, in chronological order, all the steps that are planned for the production of a final qualified part, which is defined at a preliminary meeting with all parties involved in the production, follow-up of contractual documentation or inspections before the production process is started. The CMP shall list, in a chronological order, all steps required for the production of the part with each sequence referring to the applicable document (drawings, procedures, internal instructions, paragraphs of the equipment specification or qualification methodology document, report to be filled in during/after the sequence…).

Contractor:



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The physical or legal person to whom the order for a final qualified component has been awarded.

Essential variables:

Refers to the variables or parameters of the AM process that will affect the required mechanical properties of the build (mechanical, chemical, corrosion resistance…). If any essential variable has to undergo changes beyond the qualified process range, and the change is not an editorial revision to correct an error, requalification of the procedure specification is required.

Inspector:

This physical or legal person is an independent inspector, mandated (approved) by the Client of by the Safety Authority.

Job:

A job is the process of producing any part with the specified AM machine.

Job Quality Control Plan (JQCP):

The CMP may get too complex if all the small steps required for the execution of a job are listed. The number of jobs to perform and the number of steps to specify per job may increase the complexity of the CMP. This is the reason why JQCPs are defined in this qualification methodology. The JQCP is a quality control document and enables documentation, verification and validation that all activities planned for a certain job conform to the specifications and qualification methodology. The JQCP is prepared by the quality department to validate that all operations and requirements before the start of the job. The steps/actions/sequences are signed during the process for validation and traceability of the process.

Job sheet:

The job sheet (one per job) is a document that provides guideline for the operator during the printing activities of a dedicated build job and records all mandatory information, including any modification of process parameters and deviating values during the manufacturing process, compared to the nominal values defined in the manufacturing plan.

Manufacturer:

The manufacturer owns the AM machine and fulfils all the operator's needs in order for the material to be produced.

Nesting factor:



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The nesting factor is defined as the ratio between the surface of printed samples for a given build height and the total platform surface.

Non-essential variables:

Refers to variable or parameters of the AM-process that are not known to have an observable impact on the required characteristics of the build.

Operator:

The physical person operating the additive manufacturing machine.

Owner:

The legal person responsible for the installation for which the final qualified component is intended and who is placing an order to the contractor. The Owner may be represented by the Engineer (or engineering company) that is empowered to carry out the Owner's tasks under the responsibility of the latter.

p-AMPS or AMPS:

The p-AMPS (preliminary Additive Manufacturing Procedure Specification) or AMPS is a unique document dedicated to a specific print job (build), independently of other jobs. It gathers all relevant information (key manufacturing inputs, variables and work sequence) that are required to produce a specific build job. It defines all the sequence of steps to be achieved to produce a build platform.

PBF-LB/M Process Qualification Platform:

The PBF-LB/M Process Qualification Platform aims at demonstrating that the material produced on a dedicated machine according to a specific component manufacturing plan (which defines the heat treatment procedure) matches the minimum requirements of a material specification (standard, norm…). In this prospect, the requirements to fulfil this AM process qualification step are generic (chemical composition, tensile properties, hardness…).

PBF-LB/M Process Repeatability Platform:

The PBF-LB/M Process Repeatability Platform aims at demonstrating that the properties of the produced material are similar/reproducible between 2 similar build jobs, produced on the same printer using the same powder, with the same operating conditions and essential parameters, but at different moments.

PBF-LB/M Process Stability Platform:

The PBF-LB/M Process Stability Platform aims at demonstrating that the material



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characteristics/properties are homogeneous within the complete build envelope on a dedicated machine: on the whole surface of the build plate (X/Y position) and along the full height, which means during the total build job time (Z position).

Production Platform (containing the final qualified part):

The Production Platform refers to the platform containing the component to be printed, and witness samples, once all qualification steps are fulfilled, including process stability, process repeatability, AM process qualification, application-related material qualification and production validation (= final qualified part). The Production Platform contains the components that will be delivered to a final customer, after a series of post-processing activities, non-destructive inspection and functional testing.

Production Validation Platform:

The Production Validation Platform aims at demonstrating that the production of specific component(s) (and their corresponding geometries) fulfils the requirements for a nuclear-specific application. The platform contains witness samples and is to be heat treated according to the same requirements as the final qualified part. The components of the platform are to be post processed according to the same requirements as the final qualified part as well.

Qualification methodology:

The Qualification methodology specifies requirements and provides recommendations about all activities related to the production of the final qualified part in order to guarantee that the produced part is qualified, i.e. it will have the required characteristics that enable it to achieve its intended function in service conditions. These requirements and steps comprise Requirements for feedstock; AM process qualification; Verification during the fabrication; Verification of the product after fabrication; Specific quality assurance aspects for PBF-LB/M documentation and certification.

Sample:

Refers to samples that are used for test and/or inspection purposes, and may include one or more test specimens that may need supplementary machining in order to be used as test specimen. It may also have multiple forms, any build platform covered in this methodology contains samples.

Requalification samples:

Samples that are produced on every process qualification platform but that are analyzed only in case of a re-qualification without re-assessment of machine stability and repeatability.

Reused powders:



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Reused powders include unfused and/or unused powders used for another manufacturing cycle after sieving.

Unfused powder:

Unfused powder is powder that has been deposited in the build chamber but not fused. This powder can be reused after sieving.

Unused powder:

Unused powder is powder that has not been deposited in the build chamber.

Scrap powder:

Sample powder is the powder that remains in the sieve and/or for which the characteristics no longer conform to the requirements of §8.1.2 after testing, and thus cannot be reused. It shall be kept physically separated and safely disposed.

Virgin powder:

Virgin powder is the powder received from the powder supplier, coming out of the closed container.

Witness samples:

Samples that are produced on every platform alongside specifics specimens and/or industrial components to monitor the quality of the feedstock and the printed material.



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# 7. Introduction

The EASI SMR project aims to provide insights and facilitate licensing for European LW-SMR industrial projects. Additive manufacturing (AM) is seen as an enabling technology for improving the compactness and modularization of Nuclear Steam Supply System internals. This work package aims at providing qualification guidelines for using additively manufactured components in SMRs in a safe manner. This work package involves two main additive manufacturing processes: Powder Bed Fusion using laser beam for metal powders (PBF-LB/M) and Laser beam Directed Energy Deposition using metallic powder (DED-LB/Mp).

This document presents the methodology proposed to qualify the Powder Bed Fusion using laser beam for metal powders (PBF-LB/M) and Laser beam Directed Energy Deposition using metallic powder (DED-LB/Mp) Process. The methodology for PBF-LB/M has been previously developed as part of the NUCOBAM project and will be adopted for the current effort. The general qualification approach will be adapted to match DED-LB/Mp process characteristics and presented in this document. This document corresponds to the task T6.1, included in WP6. This first version of the methodology will be consolidated with the manufacturers and end-users during the printing operations within WP6. A final version of this methodology will be issued at the end of the printing operations to collect the return of experience from the manufacturers.

This methodology should demonstrate and ensure that the PBF-LB/M and DED-LB/Mp processes provide stable and reproducible results in terms of materials performance. The concepts underlying process “stability” and “repeatability” will be described in the present report. Fulfilling these requirements is a prerequisite before demonstrating that PBF-LB/M and DED-LB/Mp material performance fulfil qualification requirements, and that PBF-LB/M and DED-LB/Mp demonstrators meet their safety-related functions and operational requirements

# 8. General approach for the process qualification strategy

The methodology proposed to qualify the two additive manufacturing processes follows the PBF-LB/M methodology developed as part of the NUCOBAM project and is adapted for the current qualification effort and involves four different pillars:

1. The definition of dedicated record templates content (pAMPS, job sheet, control plan, test record template, etc.) to ensure the registration and traceability of the key manufacturing variables regarding Quality Assurance and Quality Control. A pAMPS template lists all the key manufacturing inputs, variables, and the sequence for each build job. Each build job is linked to a unique pAMPS, filled in with its specific key manufacturing data. The structure of this document is further



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described/proposed in NUCOBAM D1.4 Standard Text[1]. Further, Appendix A provides the above-mentioned templates for DED-LB/Mp.

2. The formulation of a set of build platform configurations (a defined number of test specimens, as well as their positioning and geometries) aiming at demonstrating machine stability and machine repeatability. The assessment of variability among machines is also covered in this proposal for PBF-LB/M.
3. The execution of the corresponding manufacturing program, also defined as Qualification Process in WP6 (printing a sequence of build jobs) in accordance with defined manufacturing and handling guidance.
4. The definition of a dedicated testing matrix for material characterization (metallographic and mechanical assessment) to ensure that the output values meet the requirements that are defined by the EASI SMR consortium to demonstrate process stability and repeatability on each machine and assess process variability among the different machines.

A global flowchart of the described process qualification is represented in Figure 1. The proposed methodology for PBF-LB/M and DED-LB/Mp processes individually consist of the production of at least three build jobs that will be further described in the section 8.1 and 8.2 respectively:

- Machine Stability Validation Build Job
- Machine Repeatability Validation Build Job
- PBF-LB/M and DED-LB/Mp Process Qualification Build job

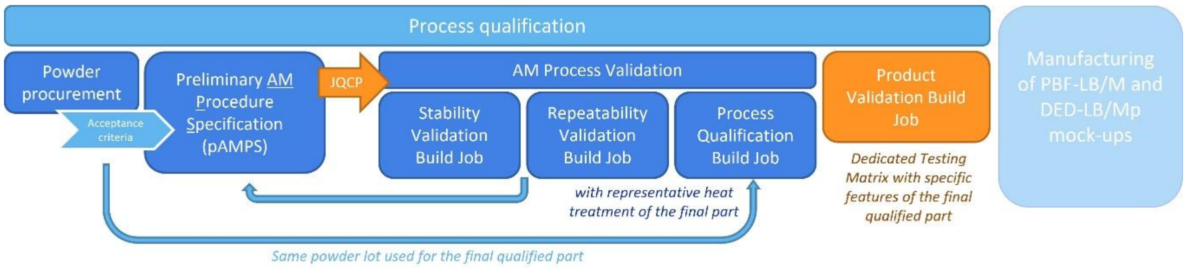


**Figure 1. Flowchart of the AM process qualification methodology**

## 8.1. Qualification methodology for laser powder bed fusion

The methodology for qualification of the PBF-LB/M process is to ensure that the PBF-LB/M material performance meets qualification requirement. The prerequisite for qualification procedure is to guarantee that the PBF-LB/M fulfils the requirements for process stability and process repeatability and the metal powders used for the printing are within the acceptance criteria. Furthermore, the specific record templates and reference documents for the different build jobs are defined. The detailed description

[1] The referenced document is a public document which can be made available on request to the NUCOBAM consortium



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of the individual steps followed in the qualification of the process can be referred from NUCOBAM D1.4 Standard Text, Section 5. The qualification done in EASI-SMR will follow exactly the steps developed in NUCOBAM

### 8.1.1. Record templates for quality assurance and quality control

The definition of dedicated record templates content is to ensure the registration and traceability of the key manufacturing variables regarding Quality Assurance and Quality Control. Record templates are defined and filled for each build job to collect detailed information of the essential and non-essential characteristics and activities of the manufacturing process during qualification. The record templates to be defined include, preliminary AM procedure specification template (pAMPS), job sheet, and job quality control plan (JQCP).

The preliminary AM procedure specification template (p-AMPS) is a unique document providing instructions to the machine operator to follow as part of the manufacturing process. The document details all relevant information regarding machine specifications (hardware and software), key manufacturing inputs (product information, product geometry, configurations, etc.), variables/parameters of the machine, and sequence of operations for each specific build job. The p-AMPS is used to collect all relevant information planned for a specific build job and is frozen before the printing/production starts. The frozen P-AMPS is then used as a reference to define the other record templates.

The job sheet is filled in during a build job (one job sheet per build job) and serves as guideline during the printing operations and records all mandatory information during the printing operation.

The job quality control plan (JQCP) will verify and validate that all activities planned in the p-AMPS are fulfilled based on the available records (job sheets, log files, etc.). The information collected in the p-AMPS is referred in the JQCP to gather the information of the build job and to define the sequence of steps achieved to produce the build to ensure traceability in line with the quality assurance framework. This is done to validate that all operations and requirements are fulfilled during the AM production of a dedicated build job. The detailed list of information collected in JCQP can be found in NUCOBAM D1.4 Standard Text, Section 5.1.

### 8.1.2. Powder specifications

Powder acceptance specification must be provided for both additive manufacturing processes (PBF-LB/M and DED-LB/Mp) to the powder supplier to formulate requirements that address the specific needs of the application or AM machine. The detailed list of recommended acceptance criteria on the powder properties as well the list of requirements to be specified can be referred from NUCOBAM D1.4 Standard Text, Section 4. In addition to the powder properties, statements of conformity and inspection documents must also be obtained from the powder supplier to ensure traceability. The documents must specify supplier information, order information, powder description



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(including chemical composition, particle size distribution, standard, etc.), packaging, storage, and analysis information, and material safety data sheets.

The acceptance tests for powder are performed by the supplier to certify that the powder properties are in accordance with the qualification methodology and powder acceptance specification requirements. The test can also be performed upon receipt of product by the part manufacturer.

The test method to determine the chemical composition of the powder and associated acceptance criteria for the two metals used in EASI SMR will be defined by the consortium members in D6.3. The powder manufacturer/supplier must guarantee that the powder has the required chemical composition.

### 8.1.3. Process stability platform

The process stability is the fact that the material characteristic/properties are homogeneous within the complete build envelope: on the whole surface of the build plate (X/Y position) and along the full height (Z position), which means during the total build job time. A sufficient number of specimens are printed over the entire platform to identify potential "dead-zone" (zone where specification requirements are not reached) in a representative manner.

The stability assessment platform is composed of three sample types: small cube, mid-height samples, and full height samples. Depending on the maximum available height of the build envelope, the height and layout of specimens of the full-height samples can vary. The varying samples height enables generating different nesting factor (i.e., surface scanned per layer) over the build area. It is designed such that that bottom of a job will have a high nesting factor and the top will have a low nesting factor. The stability assessment platform shall be produced as per applicable p-AMPS and shall be marked by a serial number and indication of the orientation. The number of samples shall be defined to be representative of the build envelope.

The discrepancies between the results from one component to another for the 'stability' job should fit within the accepted criteria established by the EASI SMR project (it will be defined in D6.3). If the criteria are not fulfilled, the root cause shall be identified and solved to validate the process stability. If it is not possible, the manufacturer shall propose additional requirements (inspection and/or tests) to guarantee the final quality of the component. A detailed procedure for carrying out the process stability assessment for PBF-LB/M process can be referred from NUCOBAM D1.4 Standard Text, Section 5.3.

### 8.1.4. Process repeatability platform

The process repeatability is the fact that the properties of the produced material are similar/reproducible between two similar build jobs, produced on the same printer using the same powder, with the same conditions and parameters, but at different moments. For the process repeatability assessment, the same heat treatment shall be applied to



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the test samples when applicable. The discrepancy between the results from one job to another should fit within the accepted criteria established by the EASI SMR project.

The key process and non-key process variables have been identified for the p-AMPS and may have to be updated during process stability assessment. When the stability was demonstrated, variables have been applied for the demonstration of the repeatability. Thus, it is to be noted that the prerequisite for fulfilling stability and repeatability shall be performed with frozen key process variables. If the criteria for repeatability demonstration have not been fulfilled, the root cause shall be identified and solved to validate the process repeatability. This implies a new iteration of the p-AMPS. The key process variables / parameters are fine tuned in the p-AMPS with every iteration until stability and repeatability is obtained.

The detailed assessments to be carried out on the components produced for process stability and process repeatability build jobs and accepted criteria for test results from both builds are presented in detail in NUCOBAM D1.4 Standard Text, Section 5.3.

### 8.1.5. Process qualification platform

Finally, the process qualification is the fact that the material produced on a machine, according to a specific pAMPS (that also defines the heat treatment) matches the minimum requirements of a material specification (standard, norm.). In this prospect, the requirements to fulfil this process qualification step are generic (chemical composition, tensile properties, hardness, etc.). The standard ASTM BA409 and ASME/BPVC – 1325-7 will be used as a reference for the minimum mechanical properties of the Alloy 800. The standard ASTM B443 and B446, or the equivalent ASME SB-443 and SB-446 will be used as reference of Inconel 625.

To assure the qualification of the final qualified component for nuclear applications, this platform is meant to assess the material characteristics resulting from the p-AMPS. The powder used for this platform shall be procured according to powder procurement and the platform shall undergo a heat treatment that is representative for the heat treatment of the final qualified part.

The AM process qualification platform shall be marked by a serial number and all specimens shall be marked with an indication of the orientation. For each type of test, a certain number of samples and building orientations are required. Archimedes density, and micrographic analysis and chemical composition measurements are performed on cubic samples of 12x12x12 mm. Regarding mechanical testing three orientations are considered related to the building direction: perpendicular (horizontal samples), 45° and parallel (vertical samples).

All the samples and specimens shall be heat-treated before testing and the same heat treatment than the stability platform shall be applied to the test samples. Depending on the machine dimensions, several platforms may be needed to perform the AM process qualification. Additionally, witness samples help maintaining assurance of the repeatability between platforms in order to enable the use of multiple platforms for one intended qualification step such as process qualification.



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The tests on the specimens of the process qualification platform and the number of required samples are adopted from NUCOBAM D1.4 – Standard Text, Section 5.3.

When the stability and the repeatability are demonstrated, and when the qualification proves that the material matches the material specifications determined by the EASI SMR project members, the printer and its process are considered as "qualified".

In the framework of the EASI SMR project, fulfilling this process qualification step is mandatory before launching the component qualification of the test specimens that will be used to address the specific additional requirements imposed by the nuclear industry (corrosion, irradiation, fatigue, thermal ageing, etc.). A brief summary of the product/component qualification is presented in Section 8.1.6. A detailed account of the component qualification method and specific application specific requirements for acceptance of component will be discussed as part of Deliverable 6.3.

### 8.1.6. Product validation platform

For the production of demonstrator with specific geometries (use cases), a sacrificial validation job which contains witness pieces, and the use case parts will be destructively examined. The sacrificial print job is part of the product validation platform where the reliability of the final qualified component is demonstrated by performing an assessment on a specific geometry known as the product validation platform that is identical to the final qualified component. This activity is performed to ensure the reliability of the use case components.

While the methodology procedure explained in 8.1 involves the qualification of the PBF-LB machine and associated printing process for metal powders, considering the material qualification of the metal powders used for the nuclear specific application, it is not sufficient to guarantee the material properties and integrity of the dedicated part design. Thus, this additional step is implemented where the production of the demonstrators' specific geometries (use cases) will be subjected to a series of functional tests.

If the dimensions of the build envelope allow it, the specific geometry intended for the product validation platform may be printed together with the final qualified component. The product validation platform shall be marked by a serial number and indication of the orientation. Heat treatment can be performed simultaneously on the shared build platform.

Witness samples are used to monitor the process repeatability in order to monitor a potential change in characteristics between the process qualification platform, the production platform, and the product validation platform. Witness samples placed strategically on the baseplate of the specific geometry are compared to the requirements to ensure that the required material characteristics are achieved and thus repeatability is maintained. For nuclear applications, a sacrificial part may be required to characterize the effect of geometry on material properties.



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The reliability of all components is tested based on a specific testing matrix which is defined, case by case, based on the actual geometry and the application requirements.

Once the production validation job passes the tests, a second (exactly similar) job is produced wherein only the witness pieces are destructively tested. This activity is called the production platform. If the results of the destructive tests of the witness pieces (mechanical testing) of the production platform are similar to the ones from the product validation platform, the components are considered acceptable, as the stability and repeatability have been already established.

## 8.2. Qualification methodology for directed energy deposition

DED-LB/Mp is an additive manufacturing process in which focused thermal energy (in this case a laser beam) is used to fuse materials (in this case metallic powders) by melting as they are being deposited[2]. Acronym is defined following the rules described in Annex A in the standard ISO ASTM52900-2022.

The main advantages of DED-LB/Mp are (a) Large Scale (b) Multi-axis (c) Use wire or powder feedstock (d) Ability to use multiple materials in same build (e) Higher surface roughness (f) Ability to add material in a secondary operation (g) High deposition rates (h) Integration of secondary processes (machining) (i) Process feedback and closed loop control. However, this process also has some disadvantages that should be considered: (1) Residual stresses (more heat input) (2) Lower resolution (less detailed complexity) (3) Higher surface roughness (4) limited to single build for a single part.

Material properties are highly dependent on the type of process, the starting feedstock chemistry, the parameters used in the process, and the heat treatment processes used post-build. But, material properties should be developed after AM process is stable and parameters confirmed.

Key parameters in DED-LB/Mp influencing the machine and procedure performance to obtain material properties and quality are laser power, powder feed rate, travel speed, laser spot size and shape, gas flows (carrier and shield), layer thickness, hatching distance, and path planning. All these key parameters should be assessed and controlled as part of the machine and process qualification steps.

The purpose of the DED-LB/Mp procedure qualification is to demonstrate the capabilities of the DED-LB/Mp procedure to produce a specific component that meets the required properties. The prerequisite for qualification procedure is to guarantee that this technique fulfils the requirements for process stability and process repeatability and the metal powders used for the printing are within the acceptance criteria.

[2] ASTM F2792 – 12a. Standard Terminology for Additive Manufacturing Technologies.



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The qualification methodology for DED-LB/Mp should demonstrate that a DED-LB/Mp set up is capable of producing specimens that meet required properties throughout the build envelop within which components will be fabricated following the qualified DED-LB/Mp procedure. This methodology is mainly based on the standard **AWS D20.1/D20.1M:2019** that is a **Specification for Fabrication of Metal Components using Additive Manufacturing.**

In that sense, AIMEN will use a DED-LB/Mp set up consisting of a robotic cell equipped with all the peripherals needed to be used in the DED-LB/Mp process to fabricate metallic parts. AIMEN will consider this set up as the machine for the STANDARD QUALIFICATION BUILD.

The methodology will cover 3 steps:

1. Process/Material parametrization: this step includes initial material printability assessment and screening of key parameters to select the optimal ones needed for machine acceptance and process qualification according to the main features of the component.
2. Machine qualification: it will use a platform with printed blocks to extract tensile specimens together with representative main features of the part, from which also standard test specimens will be machined.
3. Procedure qualification: it will consist of a test matrix platform following the requirements to qualify the process and the material.

An extension of this test matrix to qualify the part based more on functional properties as corrosion or the integration of the build platform will be also performed as part of the product validation.

### 8.2.1. Record Templates for Quality Assurance and Quality Control

The definition of dedicated record templates content is to ensure the registration and traceability of the key manufacturing variables regarding Quality Assurance and Quality Control. Record templates are defined and filled for each build job to collect detailed information of the essential and non-essential characteristics and activities of the manufacturing process during qualification. The record templates to be defined include, preliminary AM procedure specification template (pAMPS), job sheet, and job quality control plan (JQCP). These templates are as described for PBF-LB/M (Section 8.1.1.) and in Annex A from AWS20.1/D20.1M:2019 but considering all particularities of the DED-LB/Mp process.

### 8.2.2.Powder Specifications

This chapter is mainly based on the structure of standard ASTM 52907 as described in the Section 8.1.2.

The recommended acceptance criteria on the DED-LB/Mp powder properties are the following as a minimum:

- Chemical composition: will be provided to the supplier from partners but following the ASME standards. The powder will be specified with the same composition that for PBF.



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- The Particle Size Distribution will ensure the flowability in DED process, preferably from +45µm|-90µm with a 5% max for >90 and 3% max <20.
- Morphology: spherical, no satellites
- Hall Flow time (s/50g): ideally <18 s

### 8.2.3. DED material/process parametrization

A systematic three-stage methodology based on Design of Experiments (DoE) will be used, namely: the optimization of the parameters for the geometries of single tracks, single layer multi-track coatings and 3D parts. In a first experimental step, the most promising laser power (P), robot speed (v) and Powder Flow-(F) sets together with the gas flows relationship (Carrier/shielding) will be selected from an initial screening to obtain tracks with enough quality (no porosity/cracks) and correct dimensions and relation among them (aspect ratio, dilution ratio and wetting angle). Moreover, an assessment on roughness will be made to be related with the deposition rate together with the final aspect. The strategy for coating will be only pursued for fabricating coupons for testing to be useful for qualify the process and material in a more general way than for a specific part. In that DOE the main input is the hatch distance. The third step is related with the remelting between layers as they growth and the difficulty of maintain the growing distance constant. The layer height will be in this case the main input. In any case, the study will be always more focused on obtaining the principal feature of the part to be fabricated.

### 8.2.4. DED platforms for machine qualification

This chapter covers both stability and repeatability of the DED set up using the same platform set up.

The ***DED-LB/Mp stability (S) platform*** aims at demonstrating that the material characteristics/properties are homogeneous within the complete build envelope on a dedicated set up: on the whole surface of the build plate (X/Y position) and along the full height, which means during the total build job time (Z position).

The ***DED-LB/Mp repeatability (R) platform*** aims at demonstrating that the properties of the produced material are repeatable between 2 equivalent build jobs (same input data, same process parameters and same build configuration), produced on the same set up (same all peripherals) using the same powder (same batch/lot, same manufacturer, same technical procurement specification), with the same operating conditions and key process variables, but printing occurs in different days.

These platforms will provide material for mechanical testing from build conditions parallel and normal to the surface for tensile. Impact properties will be assessed in the weak (Z) direction. These platforms also provide features representing the AM component for visual examination and to demonstrate dimensional accuracy throughout the build platform and along the height. Stability and repeatability will be considered in the main feature of the part (tube). For stability, tubes should be constant on diameter and thickness trough the height and independently on the position in the XY plane. Also, tubes should have and acceptable metallography and density (>99%). Acceptance criteria for tube tensile should be within on the ±20% of the average value.



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For repeatability, the same considerations should be applicable in terms of tensile results. The comparison with the first job (stability) should fall within ±15%.

##### 8.2.4.1. Sample dimensions

Dimensions of samples are related with the tests, specimens type and specimens number to be extracted following the corresponding standards. Blocks of 70x70x15mm will be printed to extract tensile and Charpy specimens as tubes of 19,05 and 1,09 of thickness will be also printed for ND examination and to perform subsize tensile tube tests. Also, density, chemical composition, metallography and microhardness will be performed in both, blocks and tubes.
6 blocks and 12 tubes will be printed in total for both platforms.

##### 8.2.4.2. Number of specimens

The platform will be constituted by enough samples to extract all the specimens to perform all agreed tests. Specimens to be tested will be: 8 Charpy (Z), 16 tensile (Z and Y), 30 tube tensile (Z). 12 cubes for density, 6 cubes for metallography and microhardness and 4 cubes for chemical composition. From tubes, 16 small sections will be extracted for density, 4 section for chemical composition and 8 sections for metallography and microhardness.

##### 8.2.4.3. Post-processing

No post processing is required at this stage

##### 8.2.4.4. Analysis and testing

The tubes will be analyzed using visual and dimensional inspection as NDT. Then, they will be used for microstructure/microhardness/chemical analysis together with tensile. On the other hand, tensile and fracture tests will be made on specimens extracted from blocks. Additionally, microstructure and microhardness, together with density measurements will be performed also in blocks.

#### 8.2.5. DED-LB/Mp process qualification

The DED-LB/Mp Process Qualification Platform aims at demonstrating that the material produced on a dedicated machine according to a specific component manufacturing plan (which defines the heat treatment procedure) matches the minimum requirements of a material. The platform covered in this deliverable is focused on materials properties and printing quality. In a further stage this platform will also include corrosion specimens together with other features related with the mock up (stops, build platform integration, etc.). This platform covers the material qualification considering different orientations for tensile and fracture tests. Some specific features as tubes representing the final part have been also included.

##### 8.2.5.1. Sample dimensions

Dimensions of samples are related with the tests, specimens type and specimens number to be extracted following the corresponding standards. Dimensions of the samples are defined in the Table 3. Additional orientations are considered here regarding the previous platform. The platform will consist in 5 blocks of 70x70x15 and 4 tubes of



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75mm with the same diameter and thickness than the previous one. As this platform will be printed twice for RT and HT, 10 blocks and 8 tubes will be printed

#### 8.2.5.1. Number of specimens

The platform will be constituted by enough samples to extract all the specimens to perform all agreed tests. 3 specimens (+ 1 extra) will be extracted for each tensile and Charpy tests from blocks. 3 specimens (+1 extra) will be extracted from a tube
12 tensile specimens for RT (+3 for tensile using DIC)
12 tensile specimens for HT
8 Charpy specimens for RT
4 tube tensile for RT
4 tube tensile for HT
8 discs for SPT will be extracted from the Charpy specimens)
3 small cubes will be extracted from blocks for thermal ageing.

#### 8.2.5.2. Post-processing

The platform will be thermal treated depending on the material upon agreed conditions. Machining will be agreed upon the preliminary analysis made during the first step of the qualification methodology.

Testing specimens will be extracted by machining according to the dimensions specified by standards.

### 8.2.6. Product validation platform

To produce demonstrator specific geometries (use cases), a sacrificial validation job and the use case parts will be destructively examined. The sacrificial print job is part of the product validation platform where the reliability of the final qualified component is demonstrated by performing an assessment on a specific geometry known as the product validation platform. This activity is performed to ensure the reliability of the use case components. The validation of the platform is done through a complete test matrix. While the methodology procedure explained up to 8.6 involves the qualification of the DED-LB/Mp machine and associated printing process for metal powders, considering the material qualification of the powders used for the nuclear specific application, it is not sufficient to guarantee the material properties and integrity of the dedicated part design. Thus, this additional step is implemented where the production of the demonstrators' specific geometries (use cases) will be subjected to a series of functional tests detailed after.

For product validation, a second platform will be printed, more dedicated to functional properties as corrosion testing and also assessing specific features related with the component manufacturing as the integration of the build platform into the mock up (explained in the next paragraph) or stopping during the process. This platform is more related with the product validation as it represents better the type of component to be fabricated and validated.



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When qualifying DED procedures for production DED builds that will not be removed from the build platform, three additional tension test specimens shall be extracted from a preproduction test build and tested for each integrated build platform material. These tension specimens shall consist of materials representative of the component. The tension test specimens shall contain the interface between the build platform and the DED build within the gage region. The tension test specimens may be in any orientation relative to the build platform. The integrated build platform tension test specimens may be extracted from the preproduction test build if sufficient material is available. Finally, stops during manufacturing should be also considered.

#### 8.2.6.1. Sample dimensions

For product validation, additional sample are being considered, and the dimensions are also included in Table3.

2 blocks of 30x70x15 will be printed to extract hybrid tensile specimens for RT and HT

14 tubes of 75 mm height for C-ring and SSRT tests

2 tubes of 75 mm with 1 stop for SPT

2 tubes of 50 mm to asses hybrid tube tensile

2 tubes of 150 mm for Eddy current NDT

#### 8.2.6.2. Number of specimens

The number of samples are related with the type and number of tests and conditions and are also covered in Table 5.
8 hybrid tensile specimens for RT & HT (4 each one)
24 C-ring
8 SSRT in tube (4 for specimen E and 4 for specimen F)
2 tubes of 150 mm for Eddy Current
6 hybrid tube tensile
8 SPT to assess stops

#### 8.2.6.3. Post-processing

The platform will be thermal treated depending on the material upon agreed conditions. Machining will be agreed upon the preliminary analysis made during the first step of the qualification methodology.

### 8.2.7. Analysis and testing

The test specimens considered in the test matrix for platform A & B are summarized below tensile, tensile considering the build platform, impact, microstructure, chemical analysis, small punch tests, density, corrosion (C-ring & SSRT), thermal ageing and Eddy current.



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### 8.2.8. Qualification Variables

Items in Table 1 that are marked as “M” require requalification of only the DED machine/set up. The ones marked as “P” require requalification of only the DED procedure for all classes of components. Items marked as “Q” require requalification of both the DED machine and the DED procedure.

**Table 1. Qualification variables for DED-LB/Mp**

*M: machine requalification; P: process requalification; Q: Machine & process requalification*

| EASI SMR Qualification Variables for DED-LB/Mp process | |
|---|---|
| | |
| **Build Design** | |
| Build model | P |
| Component classification | Q |
| **Material** | |
| Feedstock specification and classification | Q |
| Powder composition | Q |
| Particle size distribution | Q |
| Rheological performance | Q |
| Build platform material specification and classification | P |
| Build thickness | P |
| Powder feed rate | Q |
| **Machine** | |
| Machine location | Q |
| Machine manufacturer and model | M |
| Software version | M |
| Machine serial number | Q |
| Major equipment subcomponents | M |
| **Environment** | |
| Build platform temperature | P |
| Interpass temperature | P |
| Shielding gas composition | Q |
| Powder carrier gas flow rate | Q |
| Shielding gas flow rate | Q |
| Supplemental gas shielding | Q |
| Supply gas composition | Q |
| Environmental enclosure | M |
| **Laser characteristics** | |
| Heat input | Q |
| Pulse characteristics | Q |
| Pulsing | Q |
| Preheating by beam splitting | Q |
| Focus settings | Q |
| **Deposition characteristics** | |
| Travel speed | P |
| Scan strategy | P |



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| | |
|---|---|
| Hatch overlap | P |
| Hatch spacing | P |
| Starting working distance | Q |
| Specific settings affecting edge and surface build conditions | P |
| Programmed layer height | Q |
| **Post build heat treatment/processing** | |
| Post build cooldown procedure | P |
| Post build heat treatment | Q |
| Hot isostatic pressing (HIP) | Q |
| Surface treatment | P |
| Surface finishing | P |

## 8.3. General considerations on specimen labelling

For traceability reasons, a specific identifier (label) shall be maintained in order to track every specimen as soon as it is removed from the printing platform. This unique identifier will allow to identify the printer where it has been produced, the exact position at the building platform and the printing conditions of each induvial part (printing parameters, date, spot, etc.). Moreover, this label is linked to a Job Quality Control Plan, and therefore also to the preliminary AM procedure specification (pAMPS) or AM procedure specification (AMPS).

Labels in the EASI-SMR project should contain the information given in Table 2, following the labelling strategy applied in the previous NUCOBAM project.

**Table 2. Example of labelling strategy during the qualification process**

| Type of specimen | Orientation | Sample Nr. | Partner | Job type |
|---|---|---|---|---|
| T: Tube<br>T: Tensile CIEMAT<br>TT: Tensile tube<br>T2: Tensile for CEA<br>I: Impact<br>SP: Small punch<br>C: C-ring<br>SC: SSRT for CIEMAT<br>SJ: SSRT for JRC | Vertical<br>H: Horizontal<br>O: Oblique (45°) | 01<br>02<br>03<br>XX | V: VTT<br>A: AMRC<br>C: CEA<br>D: AIMEN | S: Stability<br>R: Repeatability<br>Q: Qualification<br>P: Product |



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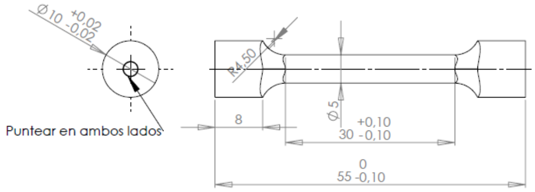
| | | | | |
|---|---|---|---|---|
| SJ: SSRT flat<br>A: thermal ageing<br>E: tube Eddy current<br>V: visual inspection<br>TU: tube with stops<br>B: cube<br>M: mid-height block<br>F: full-height block<br>W: Witness<br>Q:re-qualification sample | | | | |

Labelling will be done at the printing chamber and extra caution should be taken to avoid that the label position disturbs the planned tests. Each of the individual samples extracted from the blocks/tubes will get a unique sample ID adding a sample number to the corresponding label.

# 9.Test Matrix for product validation

For the product qualification an extensive testing matrix is considered which includes mechanical and corrosion tests as well as specific features of the final component. Table 3 shows the different specimen designs to be used in this step of the qualification process together with the dimensions of the blank to be printed.

**Table 3. Specimen designs for mechanical and corrosion testing. Additional specimens for thermal ageing and Eddy current measurements are also considered**

| | Specimen designation | Testing specimen design | Printed blank |
|---|---|---|---|
| **Tensile specimen** | Specimen A | <br>55mm x Ø 5 mm<br>Head section: cylindrical M8 | Block |



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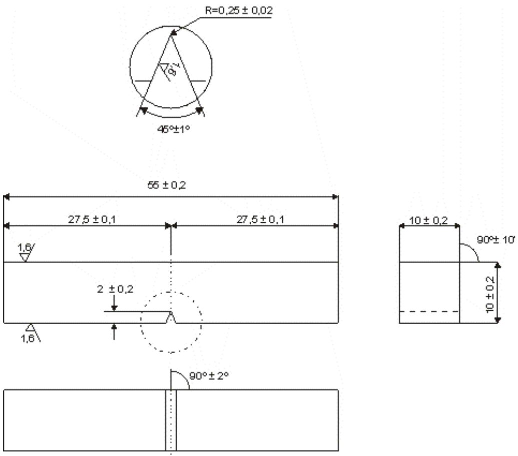
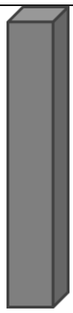
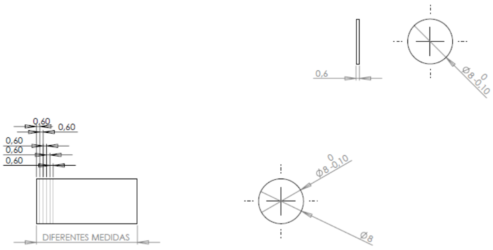
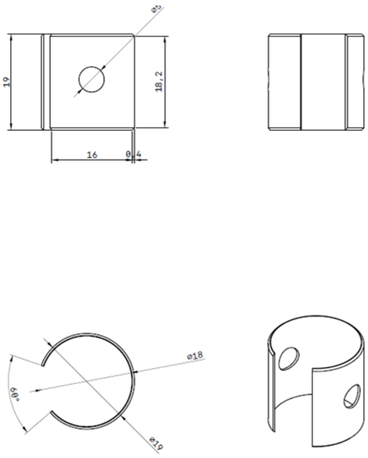
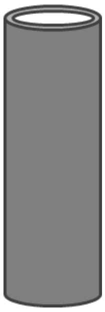
|---|---|---|---|
| **Impact specimen** | Specimen B | <br>55mm x 10 mm x 10 mm, V notched | <br>Length: 75 mm<br>Section:12x11mm |
| **Small punch specimen** | Specimen C |  | |
| **C-ring specimen** | Specimen D |  | Tube<br><br>Ø19,05 mm<br>Thickness: 1,09 mm<br>Length: 75 mm |



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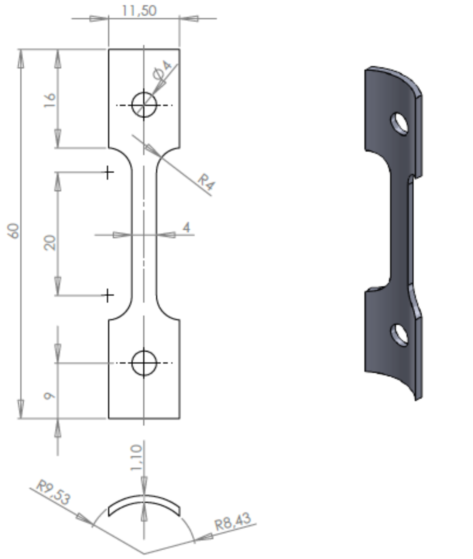
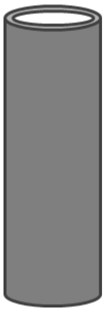
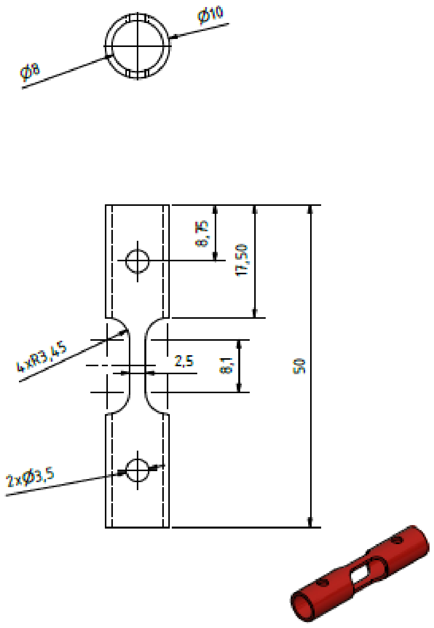
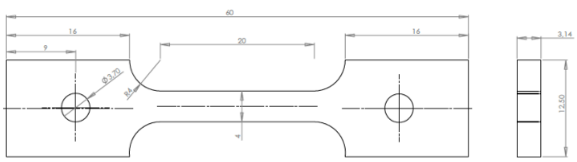
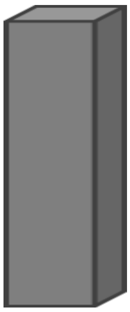
| | | | |
|---|---|---|---|
| SSRT specimen | Specimen E |   | Tube<br><br>Ø19,05 mm<br>Thickness: 1,09 mm<br>Length: 75 mm |
| | Specimen F |   | |
| | Specimen G |  | Block<br><br>Length: 75 mm<br>Section: 30x12mm |



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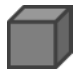
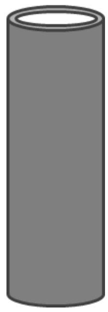
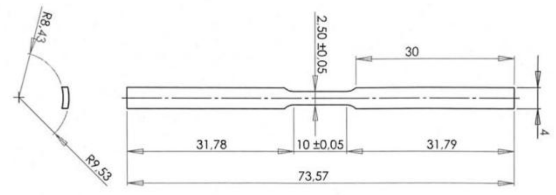
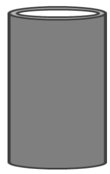
| | | | |
|---|---|---|---|
| **Thermal ageing** | Specimen H | Coupon  12x 12 x12 mm | |
| **Tube specimen to assess stop and Eddy current test** | Specimen I | Tube  Ø19,05 mm<br>Thickness: 1,09 mm<br>Length: 75 or 150 mm | |
| **Tube tensile hybrid** | Specimen J |   | Tube  Ø19,05 mm<br>Thickness: 1,09 mm<br>Length: 50 mm |

The test matrix is individually defined for each of the considered manufacturing processes, PBF-LB/M and DED-LB/Mp and shown in Table 4 and Table 5 respectively.



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**Table 4. Test matrix per conditioned material for the product qualification using laser powder bed fusion**

| TESTING SPECIMEN INFORMATION | | | | TEST CONDITIONS | | PRINTED PART INFORMATION | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Test** | **Specimen design and designation** | | **Nr. of specimens for testing** | **Nr. of specimens/condition RT** | **Nr. of specimens/condition 325°C PWR** | **Specimen design** | **Printing orientation** | **Nr. of specimens per blank** | **Nr. of printed blanks/ participant** | **Testing participant** | **TOTAL PRINTED BLANKS** |
| **Tensile test** | Subsized cylindrical | A | 2 + 1 extra | 3 | 3 | Block 75x12x11 mm | z | 1 | 6 | CIEMAT | 6 blocks |
| | Subsized cylindrical | A | 2 + 1 extra | 3 | - | | z | 1 | 3 | CEA | 3 blocks |
| **Impact test** | Notched block | B | 3 + 1 extra | 4 | - | | z | 1 | 4 | CIEMAT | 4 blocks |
| **Small punch** | Disc | C | 3 + 1 extra | 4 | 4 | | z | 20-25 | 1/2 | CIEMAT, JRC, VTT | 2 blocks |
| **TOTAL MECHANICAL SPECIMENS** | | | | | | **Block** 75x12x11 mm | z | **15 blocks** | | | |
| **C-ring** | C-ring | D | 3 + 3 extra | - | 12 | Tube Ø19,05 mm x 1,09 mm, 75mm length | z | 3 | 4 | CIEMAT, JRC | 8 tubes |
| **SSRT** | Tube | E | 1 + 1 extra | - | 4 | | z | 2 | 2 | CIEMAT | 2 tubes |
| | | F | | - | 4 | | z | 2 | 2 | JRC | 4 tubes |
| | Flat | G | 3 + 1 extra | - | 3 | 75 x 30 x 12 mm | z | 4 | 1 | CIEMAT | 1 block |
| **TOTAL CORROSION SPECIMENS** | | | | | | **Tube** Ø19,05 mm x 1,09 mm, 75mm length | z | **14 tubes + 1 block** | | | |
| **Thermal ageing** | Coupon | H | 3 | 3 | - | Coupon 12x12x12 mm | z | 1 | 3 | EDF | **3 coupons** |
| **NDT Eddy current** | Tube | I | 2 | 2 | - | Tube Ø19,05 x 1,09mm, 150 mm length | z | 1 | 2 | EDF | **2 tubes** |

(RT= room temperature)


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**Table 5. Test matrix per material for the process and product qualification using direct energy deposition: platform A and platform B**

| TESTING SPECIMEN INFORMATION | | | | TEST CONDITIONS | | PRINTED PART INFORMATION | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test | Specimen design and designation | | Nr. of specimens for testing | Nr. of specimens/condition: RT | Nr. of specimens/condition: 325°C PWR | Specimen design | Printing orientation | Nr. of specimens per blank | Nr. of printed blanks/ participant | Testing participant | TOTAL PRINTED BLANKS |
| Tensile test | Subsized cylindrical | A | 3 + 1 extra | 4 | 4 | Block 70x70x15 mm | z | 5 | 4 | CIEMAT | 6 blocks |
| | | | | | | | xy | 5 | 2 | | |
| | Subsized cylindrical | A | 2 + 1 extra | 3 | - | | z | 5 | 1 | CEA | 1 block |
| Impact test | Notched block | B | 4 + 1 extra | 4 | - | | z | 5 | 2 | CIEMAT | 2 blocks |
| Small punch | Disc | C | 3 + 1 extra | 4 | 4 | | z | 20-25 | Extracted from Charpy | CIEMAT, JRC, VTT | - |
| Tensile test hybrid | Subsized cylindrical | A | 4 + 1 extra | 4 | 4 | Block 35x70x15 mm | z | 5 | 2 | CIEMAT | 2 blocks |
| **TOTAL MECHANICAL SPECIMENS** | | | | Block 70 x 70 x 15 mm | | | z | | **11 blocks** | | |
| **C-ring** | C-ring | D | 3 + 3 extra | - | 12 | Tube Ø19,05 mm x 1,09 mm, 75mm length | z | 3 | 4 | CIEMAT, JRC | 8 tubes |
| **SSRT** | Tube | E | 1 + 1 extra | - | 4 | | z | 2 | 2 | CIEMAT | 2 tubes |
| | | F | | - | 4 | | z | 2 | 2 | JRC | 4 tubes |
| | Flat | G | 3 + 1 extra | - | 3 | 75 x 30 x 12 mm | z | 4 | 1 | CIEMAT | extracted from CEA tensile block |
| **TOTAL CORROSION SPECIMENS** | | | | **Tubes** Ø19,05 mm x 1,09 mm, 75mm length | | | z | | **14 tubes** | | |
| **Thermal ageing** | Coupon | H | 3 | 3 | - | Coupon 12x12x12 mm | z | 1 | 3 | EDF | **3 coupons** |



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|---|---|---|---|---|---|---|---|---|---|---|---|
| **NDT Eddy current** | Tube | I | 2 | 2 | - | Tube Ø19,05 mm x 1,09 mm, 150mm | z | 1 | 2 | EDF | 2 tubes |
| **Tube to assess a stop** | Tube with stop at 75 mm | I | 3<br>+ 1 extra | 4 | 4 | Tube Ø19,05 mm x 1,09 mm, 150mm | z | 4 | 2 | CIEMAT | 2 tubes for small punch |
| **Tube tensile hybrid** | Tube tensile | J | 3<br>+ 1 extra | 4 | - | Tube Ø19,05 mm x 1,09 mm, 38 mm | z | 4 | 2 | AIMEN | 2 tubes |



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# 10. Conclusions

The document presents the general methodology for qualification of the two additive manufacturing processes namely PBF-LB/M and DED-LB/M as part of WP 6, Task 1 of the EASI SMR project. The methodology demonstrates and ensures that the two manufacturing processes provide stable and reproducible results in terms of material & process performance.

The presented methodology addresses the process and component qualification approach, and the material testing required for the two processes. The document addresses these aspects by means of: 1) A dedicated qualification methodology supported by different build platform configurations of test specimens (geometry, location and number), 2) A record of the key manufacturing variables for quality assurance and quality control, 3) a design of experiments and key performance indicators (KPIs) to demonstrate the process stability and repeatability on each machine used in the EASI SMR project, and 4) Testing matrix listing the required material tests and characterization to be performed for acceptance of results.

The research emphasizes the need to continue refining approaches for the qualification of additively manufactured components in the nuclear sector, aiming for full integration and compliance with industry standards. The use of AM will allow nuclear industry to tackle component obsolescence challenges and/or manufacture and operate new components in order to increase efficiency and safety.



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