NUCOBAM

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Summary

The purpose of the document is to present two possibilities to introduce the results of the NUCOBAM project in a standardization process, especially for nuclear codes. The document is divided in the following parts: * Part1: introduction, * Part 2: ASME proposal (see appendix 1) * Part 3: RCC-M proposal (see appendix 2) * Part 4 : Achievements, Limitations and Perspectives of the NUCOBAM Project (see appendix 3)

Approval

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Disclaimer

Preface

This project named NUCOBAM NUclear COmponent Based on Additive Manufacturing has received funding from the EURATOM research and training programme 2014-2018 under grant agreement No. 945313. The partners are:

- CEA: Commissariat à l'énergie atomique et aux Energies Alternatives,
- EDF: Electricité de France,
- LABORELEC: Belgisch Laboratorium van de Elektriciteitsindustrie Laborelec,
- TRACTEBEL: Tractebel engineering,
- NAVAL: Naval group,
- FRAMATOME: Framatome SAS,
- CIEMAT: Centro de investigaciones energeticas, medioambientales y tecnologicas-ciemat,
- USFD: The university of Sheffield,
- VTT: Technical Research Centre of Finland Ltd,
- SCK.CEN: Centre d'étude de l'énergie nucléaire fondation d'utilité publique,
- JRC: Joint Research Centre- European commission,
- RAMEN VALVES: Ramen valves ab,
- IRSN: Institut de radioprotection et de sureté nucléaire.

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Executive Summary

The following document is the result of the previous task (1.1 to 1.3) of the project. The task 1.1, led by JRC, consisted of gathering the latest available guidelines, standards and documentation on additive manufacturing and their qualification that are relevant for the qualification methodology envisaged in this project. The task results were listed and provide a repository of relevant guidelines, standards & documentation. They were used as input for task 1.2.

Based on these results, a first draft of the qualification methodology was issued. This first draft was also an input data for WP (Work Package) 2 to 5.

In line with the results of all WPs, the task 1.3 brought the draft methodology report to an improved version.

And as a final stage, the finalized methodology was considered as the basis for nuclear codes evolution proposals. A mapping of the different possibilities for standardization (ISO, nuclear codes, IAEA, OECD…) highlighted that two nuclear codes were targeted for proposals:

- ASME BPVC section III (ASME Boiler & Pressure Vessel Code, rules for construction of nuclear facility components),
- AFCEN RCC-M (Design and Construction Rules for Mechanical Components of PWR Nuclear Island).

Tractebel and Laborelec participated to the standardization of the text in view of potential submission of material to the ASME committee. EDF, Framatome and CEA participated to the standardization of the text in view of potential submission of material to the AFCEN committee. IRSN, VTT, NAVAL GROUP, USFD and JRC participated to the standardized text reviewing.

The result of the task 1.4 is a code evolution proposal for each code, on the basis of the process evolution defined in ASME and AFCEN, presented in this document.

Keywords

Nuclear, additive manufacturing, standardization, nuclear code

Abbreviations and Acronyms

Acronym	Description
AFCEN	Association française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières électro-nucléaires
AM	Additive Manufacturing
AMPS	Additive Manufacturing Procedure Specification
ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
CMP	Component Manufacturing Plan
IAEA	International Atomic Energy Agency
ISO	International Organization for Standardization
OECD	Organisation for Economic Co-operation and Development
p-AMPS	preliminary Additive Manufacturing Procedure Specification
PBF-LB/M	Powder Bed Fusion - Laser Beam/ Metals
PWR	Pressurized Water Reactor
RCC-M	Règles de Conception et de Construction des Matériels Mécaniques
WP	Work Package

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1. Introduction

1.1. Purpose and content

The purpose of the document is to present two possibilities to introduce the results of the NUCOBAM project in a standardization process, especially for nuclear codes.

As the project starts from the powder procurement up to the tests on the as built component, it was relevant to select a code that covers the entire process from rough material procurement up to delivery of the component. It was also relevant to consider the codes and standards knowledge available within the project stakeholders. Two nuclear codes were selected: ASME and RCC-M.

Tractebel and Laborelec participated to the standardization of the text in view of potential submission of material to the ASME committee. EDF, Framatome and CEA participated to the standardization of the text in view of potential submission of material to the AFCEN committee. IRSN, VTT, NAVAL GROUP, USFD and JRC participated to the standardized text reviewing.

The document is divided in the following parts:

- Part 1: introduction,
- Part 2: ASME proposal (see appendix 1),
- Part 3: RCC-M proposal (see appendix 2),
- Part 4: Achievements, Limitations and Perspectives of the NUCOBAM Project (see appendix 3).

2. ASME evolution proposal

This document is designed in line with the NUCOBAM methodology and constitutes part of deliverable D1.4 within Task 1.4, "Conversion of the methodology into a standardized text," with the potential aim of submitting material to the ASME committee (submission not included in the NUCOBAM project). The purpose of this document is to adapt the previous WP1 document, D1.3 "Qualification Method," into a standardized ASME text.

The document focuses on the qualification of a component manufactured using the Laser Powder Bed Fusion (PBF-LB/M) process with AM 316L material, in compliance with nuclear requirements. These qualification criteria aim to meet both ex-core and potential in-core applications, with the goal of producing a 3D-printed valve body component that adheres to ASME standards and ensures compliance with the nuclear industry.

The document addresses key technical aspects such as powder requirements (certification, chemical composition, storage, reuse), the qualification of the additive manufacturing process (process specifications, stability and repeatability, validation platforms), and the necessary heat treatments, such as solution annealing to homogenize the microstructure and prevent corrosion. The qualification process

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includes the creation of a Component Manufacturing Plan (CMP) that outlines the production steps, along with quality management and inspections at every stage.

This document proposes a comprehensive and standardized methodology for qualifying components produced by additive manufacturing in 316L stainless steel, meeting the strict requirements of the nuclear industry and ASME standards.

3. RCC-M evolution proposal

This document follows the RCC-M code's guidelines for non-referenced manufacturing processes. It outlines the qualification requirements for components manufactured in 316L stainless steel using the Laser Powder Bed Fusion (PBF-LB/M) process, in accordance with the RCC-M 2020 code, intended for use in nuclear power plants (PWR). It mandates the submission of a procurement specification, including detailed product and shop qualifications, before component manufacturing.

It is divided into two main parts:

- Qualification of the manufacturing process (M180): This section covers the qualification of both the process and the workshop, with requirements for process stability and repeatability, validated through assessment platforms. It also defines the Additive Manufacturing Procedure Specification (AMPS), ensuring key process parameters are controlled before production begins,
- Part procurement specifications (M3500): This part details the specifications for manufacturing 316L valve bodies, including powder composition criteria, required mechanical properties, heat treatments, and surface and dimensional inspections to ensure compliance with nuclear standards.

The overall goal of the document is to ensure that additively manufactured components produced through PBF-LB/M meet the RCC-M standards for use in nuclear installations, particularly for high-pressure valve bodies. By adhering to these requirements, the final products are expected to meet the demanding service conditions of the nuclear industry.

4. Achievements, Limitations and Perspectives of the NUCOBAM Project

- A first section highlighting the main objectives of the NUCOBAM project and providing some summary details of the work packages achievements,
- A second section listing a series of concepts or ideas used in the NUCOBAM project but that needs to be refined or reconsidered for future codification activities,
- A third section enumerating the technical topics that have not been fully addressed within NUCOBAM and that could be included in future studies or projects to come.

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5. Conclusion

In conclusion, the various documents and summaries clearly highlight the significant progress made within the NUCOBAM project regarding the qualification of additively manufactured components for the nuclear sector, while also outlining perspectives for future improvements.

The ASME evolution proposal focuses on adapting a qualification methodology to ASME standards, ensuring that 3D-printed components in 316L stainless steel meet nuclear requirements. The document presents a standardized methodology that covers the entire manufacturing process, from powder management to heat treatments, within a stringent quality control framework.

Similarly, the RCC-M evolution proposal aligns with non-referenced manufacturing processes and proposes the qualification of 316L components produced through PBF-LB/M, in accordance with the RCC-M 2020 standards. This approach aims to ensure the stability and repeatability of the process, while meeting the specific requirements of the nuclear industry, particularly for the production of high-pressure valve bodies.

Finally, an analysis of the achievements, limitations, and perspectives of the NUCOBAM project highlights the objectives achieved, while identifying concepts that require further optimization in future codification activities. It also mentions technical topics that were not fully explored, suggesting areas for future research.

In summary, significant progress has been made, the project 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.

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APPENDIX 1 : ASME DELIVERABLE D1.4

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Disclaimer

The content of this document reflects only the author's view. The European Commission is not responsible for any use that may be made of the information it contains.

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This project named NUCOBAM NUclear COmponent Based on Additive Manufacturing has received funding from the EURATOM research and training programme 2014-2018 under grant agreement No 945313. The partners are:

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Executive Summary

NUCOBAM, "Nuclear Component Based on Additive Manufacturing," develops a qualification process and provides an evaluation of the in-service behavior, enabling the use of additively manufactured (AM) components in nuclear installations.

WP1 focuses on establishing a methodology for additive manufacturing qualification standardization.

This document constitutes part of deliverable D1.4 within Task 1.4, "Conversion of the methodology into a standardized text" — with a view toward the potential submission of material to the ASME committee (submission not included in the NUCOBAM project).

The purpose of this document is to adapt the previous WP1 document, D1.3 "Qualification Method," into a standardized ASME text.

This standardization builds on the work conducted throughout the NUCOBAM project, utilizing AM 316L material and the PBF-LB/M manufacturing process, with the goal of producing a 3D-printed valve body.

Keywords

Nuclear, additive manufacturing, qualification, ASME, valve body

Abbreviations and Acronyms

Acronym	Description
AM	Additive Manufacturing
AMPS	Additive Manufacturing Procedure Specification
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CMP	Component Manufacturing Plan
EDM	electric discharge machining
EN	European standards (EuroNorm)
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
JQCP	Job Quality Control Plan
p-AMPS	Preliminary – Additive Manufacturing Procedure Specification
PBF-LB/M	Powder Bed Fusion - Laser Beam/ Metals
PEEK	Polyether ether ketone
PQR	Procedure Qualification Record
PTB	Position Task Books
PWR	Pressure Water Reactor
QA	Quality assurance
QM	Quality Management
SDS	Safety Data Sheet
UTS	Ultimate Tensile Strength
WP	Work Package

1. SCOPE ASME

This document presents the qualification methodology for completing ASME Code Case PTB-13-2021 for stainless steel 316L (X2CrNiMo17-12-2 (1.4404)) pressure and non-pressure retaining components produced by additive manufacturing (AM) for use in nuclear installations, specifically for the Laser Beam Powder Bed Fusion (PBF-LB/M) process.

This ASME proposition qualification methodology, covers all aspects needed to qualify a final component produced by AM, as a complement to already existing code and standard in particular ASME PTB-13-2021. This document defines specific requirements that may be influenced by the material.

Repairs in case of non-acceptable flaws or indications on qualification platforms or the final qualified part are not in scope of the qualification methodology.

With some adaptations in the specific requirements the same qualification methodology may be applied to obtain a final qualified component made of another material.

This document covers 316L austenitic stainless steel valve bodies additively manufactured with the laser powder bed fusion (PBF-LB/M) process for PWR nuclear power plants. The characteristics of the valve used as a demonstrator for completing the ASME Code Case are the followings:

- Valve type : ball sector valve (trunnion type),
- Nominal Diameter: DN40,
- Seat : PEEK seat (leakage class V acc. to EN 60534),
- Design pressure : 27 bar (acc. to EN 12516-1),
- Pressure rating : PN40 (~Rating class 300, acc. ASME B16.34),
- Fluid : primary fluid,
- Actuation: manual,
- Pipe connection: non particular requirements, flanged.

The product shall be obtained through a qualified process.

2. REFERENCES

For AM-specific terminology the following standards may be used for guidance or as reference: ISO/ASTM 52900, ISO/ASTM 52921, F2924, B243.

The chapter powder requirements is mainly based on the structure of standard ASTM 52907. The statement of powder conformity should follow ISO/ASTM 52907 (see appendix B) or ISO/IEC 17050-1.

A material certificate in accordance with EN 10204 type 3.1 is required to prove that the powder is in compliance with the powder acceptance specifications and the qualification methodology.

The ASME PTB-13-2021 standard details the criteria for pressure retaining metallic components using AM and completes this specification.

3. DOCUMENTATION

This chapter specifies documentation requirements which are an essential part of the process to manufacture a qualified AM manufactured component and includes requirements which are actually not yet covered by the ASME Code Case PTB-13-2021. These requirements can be embedded in a contractual framework.

3.1. Documents to be issued before signing of contract

- Equipment Specifications,
- Powder acceptance specifications.

3.2. Documents to be issued before the AM process qualification

- Component manufacturing plan (CMP),
- List of all applicable documents regrouping all references of documents used throughout the powder procurement, qualification and manufacturing process. This list of documents provides an overview of the documentation for the compilation at the end of manufacturing report. The list is completed during the above activities.

If no AM Procedure Specification (AMPS) has been obtained yet:

- Preliminary AM procedure specification (p-AMPS),
- CAD File,
- Job Quality Control plans (one for every platform),
- Job Sheet template.

3.3. Documents to be issued before fabrication of the final qualified component

- AM Procedure Qualification Record (PQR)
- AM procedure specification (AMPS)
- Procedures for all activities defined in the component manufacturing plan and the different Job Quality Control Plans: technical documents that the Contractor plans to use to complete his task (drawings, procedures, internal instructions, paragraphs of the equipment specification or qualification methodology document, …)

3.4. Documents to be issued during manufacturing

Report(s) on the steps defined in the component manufacturing plan, in case a specific platform is being established for AM process qualification, steps defined in the Job Quality Control Plan:

- Test reports (on powder and specimens depending on the sequence),
- Heat treatment reports,
- Non-conformity reports, if any,
- Job sheets containing all variables of the process.

3.5. Documents to be issued after completion of the component fabrication

3.5.1. Declaration of conformity

The declaration of conformity states that the final component and the process used to produce it are compliant with the design specification and the qualification methodology. This document when it is needed is defined in the reference standard of the component and may contain:

- The name and the contact information of the Contractor,
- Identification of the equipment,
- Reference to the technical and contractual specifications, list of any derogations to the equipment specification and qualification methodology document,
- Reference to the PQR.

The declaration of conformity is to be dated and signed by the manufacturer.

3.5.2. Appendix of manufacturing report

The manufacturing report can include, as an appendix, a list of all documents that have been created during the process, for the purpose of confirming that the final quality of the component conforms to the technical specifications and relevant standards, and that the manufacturing process was implemented as qualified. The list in the appendix of the manufacturing report shall contain:

- Declaration(s) of conformity,
- List of all applicable documents,
- Reports,
- PQR and AMPS,
- Procedures and instructions for tests & inspections.

The appendix is completed gradually during the manufacturing process.

4. POWDER REQUIREMENTS

This chapter is mainly based on the structure of standard ASTM 52907. The statement of conformity should follow to ISO/ASTM 52907 or ISO/IEC 17050-1.

Powder acceptance specifications must be provided to the powder supplier/manufacturer in order to formulate specific requirements that may depend on the specific needs of the application or AM machine. These requirements may be part of the Equipment Specification, and the present chapter's requirements must be taken into account.

The recommended acceptance criteria on the powder properties are the following:

- Particle size distribution with D90 to be as close as possible to 45µm, and powder particle size below 10µm as low as possible,
- Morphology analysis based on shape factor,
- Static angle of rest below 28°,
- Carney flow below 10s for 150g of powder,
- Typical Hall flow time of 13-15s for 50g of powder
- Chemical composition following ASTM F3184-16.

The qualification of the final qualified component is obtained through the AM process qualification. The manufacturing program used by the powder manufacturer must not be changed. In case of any changes, the powder manufacturer shall inform the Customer and identify the impact on the powder delivered. The powder supplier is responsible for issuing the relevant documentation.

To ensure traceability, statements of conformity and inspection documents shall specify the following:

- A unique document reference,
- Name and the address of the supplier,
- Reference of powder lot,
- Product description, including chemical composition particle size distribution, standard and/or trade/common name,
- Nature of powder production process (including e.g. type of gas used, environment condition),
- Packaging description, including the packaging, the nature of the shielding gas and the desiccant bag if relevant,
- Date of analysis,
- Storage and preservation instructions,
- All information to ensure traceability (e.g. order number, applicable specification, standard).

The report value shall be linked to the test method used and the corresponding standard. Powder characteristics shall be subjected to a prior customer/supplier agreement.

The product shall be supplied with its material safety data sheet (SDS).

4.1. Certification

The acceptance tests are performed by the powder manufacturer or upon receipt by the part manufacturer, to certify that the powder characteristics are in accordance with the qualification methodology and powder acceptance specification requirements.

A material certificate in accordance with EN 10204 type 3.1 is required to prove that the powder is in compliance with the powder acceptance specifications and the qualification methodology.

4.2. Sampling

In general, it is necessary to have a sample per batch/lot of sufficient quantity to perform all the required analyses, with a recommended quantity of 1 kg to provide sufficient margin.

The sampling method should follow ASTM B215.

Equipment cleanliness procedures shall be in place prior to any sampling to prevent cross-contamination of powder.

The collected sample needs to be kept in a safe container. This sample shall be labelled with the following information:

- Date of sampling, sample identification numbers,
- Machine type and serial number,
- Material grade (SS316L) and batch reference,
- Condition (number of recycling if possible),
- Job reference number of the printed platform.

The sampling method should follow ASTM B215. Testing of the following properties should be done in a controlled environment.

The following tests shall be performed in order to demonstrate the compliance of the powder with the specification after each platform production:

- Particles size distribution,
- Chemical analysis,
- Flowability, as appropriate.

Results of tests

The acceptance criteria shall be indicated in the powder procurement specification.

4.3. Chemical composition

The test method to determine the chemical composition of the powder and associated acceptance criteria are defined in ASME II SA 751. The powder supplier must guarantee that the powder has the required chemical composition.

4.4. Packaging, handling and storage

The powder should be stored in a dry place to prevent humidity ingress and significant temperature variations. Ideally, a temperature- and humidity-controlled cabinet is recommended for storing powder containers. If this configuration is not possible, alternative solutions can be used, such as drying the powder at moderate temperature (e.g., 60°C, with a sufficient amount of drying time without altering it) in vacuum, or performing powder sieving in inert gas (argon, nitrogen). The containers should be kept sealed as long as possible before use. If silica bags and/or inert environment are present, they should be removed before powder manipulation, and any un-used powder should be returned to containers to maintain dryness. The number of sieving cycles experienced by the powder should be indicated, when possible, on the container. Powder recycling cycles should not alter the chemical composition outside the ASTM F3184-16 specifications, and should not induce changes to powder features that affect the printing operations, such as flowability and stability of the powder bed. No standards are currently defining a maximum number of cycles for the L-PBF 316L. As a result, industrial experience combined with continuous quality control agreed between parties should monitor powder quality in case of recycling strategy.

Powder traceability shall be secured. Labels should include the following:

- Name of the supplier,
- Reference of powder lot,
- Quantity of the packaging unit,
- Packaging description, including the nature of the shielding gas and desiccant bag,
- Product description (standard or trade/common name),
- Safety notice in accordance with local regulations (pictograms if required).

Additional information such as customer order number, powder production process details, and packing date should be included in the certificate if not on the label.

If desiccant bags are used, guidance can be found in DIN 55474 and BS 1133-19. Storage conditions for reusable powder must comply with regulations applicable to the local facility. After use, storage containers should be securely closed and, if possible, filled with inert gas (argon or nitrogen) to prevent moisture ingress.

The powder supplier may impose restrictions on powder usage, and the manufacturer must verify that these restrictions align with the manufacturing process requirements.

4.5. Reuse of powder

It is recommended to indicate the number of sieving cycles the powder has undergone. For systems with closed-loop sieving, the powder remains continuously inside the system, and fresh powder is regularly added to maintain an appropriate blending ratio. The machine should be refreshed with powder from the same batch/lot.

It is mandatory to track the input of powder batches into the machine. The quantity of powder, a reference to the powder certificate, and the date of insertion must be recorded. Any powder prepared for reuse must meet the original size limits and tolerances before being accepted for the additive manufacturing (AM) process.

For separate sieving systems, the number of sieving cycles should be recorded to track recycling steps. This is especially important when different containers are mixed to enable large platform printing. A unique serial number for each container is not mandatory, but it is recommended to note the number of sieving cycles the powder has undergone throughout the production process whenever possible.

If reused powder is employed in the manufacturing process, the same chemical composition, morphology, and flowability tests should be performed as for fresh powder.

5. QUALIFICATION OF THE ADDITIVE MANUFACTURING PROCESS

This qualification ensures that a part, additively manufactured by PBF-LB/M according to a specified program (Additive Manufacturing Procedure Specification, AMPS), meets fabrication, quality, and service conditions. Product qualification determines the part's characteristics, including singularities and testability.

Before using a part manufactured under a given AMPS, the following must be completed:

- Part qualification,
- Shop qualification.

A preliminary AMPS (p-AMPS) is first developed for a specific application, based on previous AMPS or experience. Stability and repeatability are demonstrated using key performance indicators on stability and repeatability assessment platforms. Essential variables are fine-tuned through iterations in the p-AMPS until stability and repeatability are achieved. Meeting stability (§5.3.1) and repeatability (§5.3.2) requirements is a prerequisite before confirming that PBF-LB/M material performance meets qualification standards. Re-qualification can be done by testing re-qualification samples instead of printing a full stability and repeatability platform.

The assessment includes the stability and repeatability results, powder requirements (§4), changes in feedstock properties from the previous (qualified) AMPS and the new p-AMPS intended for qualification. Other factors that may trigger re-qualification include:

- Significant hardware changes (e.g., gas flow upgrades, machine relocation, component repairs),
- Changes in laser scanning or melting parameters,
- Any events that could affect machine performance.

The next step involves manufacturing an "AM process qualification platform" to verify that the material meets the defined characteristics. Additional platforms may be required for specific applications (e.g., high-temperature testing).

The final step is the validation of specific geometry and optional heat treatment on a Production Validation Platform, which completes the Procedure Qualification Record (PQR). Once validated, a final AMPS (§6.2) is drafted, incorporating the essential and non-essential parameters confirmed by the PQR (§5.4). These parameters are applied during production to ensure the qualification of the AM build.

Process qualification may not be needed if an existing AMPS conforms to essential variables of an existing PQR. The manufacturer may define a valid range for certain essential variables.

5.1. Preliminary AM procedure specification (p-AMPS)

The Preliminary AM Procedure Specification (p-AMPS) is a document that provides strict instructions for the operator to follow as part of the additive manufacturing process. This document specifies the essential and non-essential variables of the process.

The p-AMPS contains general hardware information, software information, feedstock material information, job specific information (machine parameters, part geometry, configuration,…), follow up records, post processing procedures,…. This information is indicated directly or indirectly by referencing to separate documents or files, for instance:

- Computer Aided Design (CAD) file (component geometry, CAD models…),
- Job configuration file (baseplate, number of parts, orientation, support strategy…),
- Parameter set file,
- Laser scan trajectory file,
- Machine file.

Considering there are numerous PBF-LB/M process parameters involved during a build job, and the confidential nature for each PBF-LB/M manufacturer, the parameter set file and all associated data are listed in the AMPS or p-AMPS as a fixed file reference that shall remain unchanged. The verification of the content and correct usage of these reference files is verified by the inspector.

The first revision of the p-AMPS is developed based on the requirements of the equipment specification and the qualification methodology. It is based on experience of the manufacturer and, if possible, other previously issued AMPS. It shall address, as a minimum, the specific key and non-key parameters that are applicable to the AM machine and process.

The p-AMPS is referred in a Job Quality Control Plan (JQCP). The JQCP gathers all relevant information of the build job and defines all the sequence of steps achieved to produce the build, ensuring the traceability in a Quality Assurance framework. Guidelines for the establishment of a component manufacturing plan are applicable to this JQCP.

The first page of the JQCP contains general information such as:

- Reference documents,
- Machine/hardware information,
- Program/software information,
- Feedstock material information.

This information is not expected to change under normal conditions. However, the document should be updated when a fresh or unused powder batch is used or when a major update is performed in the software or hardware.

The JQCP also contains job specific activities:

- Job-specific information (serial number),
- Pre-printing controls (machine-dependant parameters),
- Printing follow-up Quality Control records,
- Post-print Quality Control record,
- Post processing (atmosphere, time and temperature of heat treatment, machining, cleaning method…).

Every p-AMPS shall be marked with a unique identifier and revision number, and shall be incrementally revised each time essential or non-essential parameters / variables are modified.

5.2. Qualification report

A complete qualification report file must be completed to validate that the p-AMPS is qualified in the form of an AMPS.

Only the AMPS shall be used to manufacture the final qualified component and shall not be modified.

The qualification report documents cover all the AM Process qualification documents and test results record of the specimens of the build platform configurations. It shall indicate the key process and non-key process variables of the AM-machine and process based on all p-AMPS performed during the qualification process and the iterations made.

The documents that should be referred to, in certain sequences of the component manufacturing plan, include but are not limited to the following items:

- AMPS,
- List of guidance, norms and standards applicable for the process, the material, testing and post-processing,
- Reference of the manufacturer instructions and procedures for the use of the printer and the manufacturing process,
- Reference to the operator qualification system (requirements, training, experience, evaluation),
- Reference to maintenance program of the AM machine,
- Reference to Powder Certificate of Compliance,
- Reference to the powder sampling and visual inspection instructions,
- Job sheet template, a document that 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,
- Printer log file, pictures and all other records that are generated during the printing activities. This file is considered as a report and is retrieved after the job is finished,
- Reference to post-treatment procedure (support and platform removal, heat treatment, machining…),
- Reference to procedures for the examination and test of the end product,
- Test report (metallurgical and mechanical assessment).

The Supplier must be informed of any change to a factor or parameter which is considered to affect qualification, and the consequences of this modification must be evaluated.

As a result of this evaluation the following may ensure:

- Qualification shall be extended,
- Qualification shall be extended on condition that supplementary examinations are performed,
- The part must be qualified.

5.3. Procedure qualification

Fulfilling Stability and repeatability requirements is considered as a prerequisite before demonstrating that PBF-LB/M material performance meet qualification requirement. These steps shall be performed with frozen key process variables.

The next step in the AM process qualification is performed by manufacturing an AM process qualification platform. The purpose of this step is to confirm that the material produced complies with the material characteristics.

The last step required for the development of a complete qualification report is the validation of the specific geometry and heat treatment on a Production Validation Platform. Once this is achieved, a AMPS is then drafted based on the p-AMPS (preliminary additive manufacturing procedure specification) and with final values of all key process and non-key process parameters. These qualified parameters shall be applied during production in order to ensure the qualification of the AM build.

Stability and repeatability shall be demonstrated by means of key performance indicators (homogeneity of relative density, micrographic examination, tensile & impact toughness properties) on stability and repeatability assessment platforms.

The key process variables / parameters are fine tuned in the p-AMPS with every iteration until stability and repeatability is obtained.

5.3.1. Process Stability

The process stability is assessed by measuring the variability of the properties of the components issued from the same job according to their positioning on the build plate. 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. Therefore, an initial testing plan is elaborated for mono laser machines and can be further adapted to be relevant with the characteristic of the multi-laser machines.

The stability is evaluated:

- Over the full platform surface by a homogeneous spread of the samples,
- Over the full build chamber height (meaning during the total job time) by producing a certain number of “full height” samples. The samples do not need to be heat treated in a representative condition at this stage of the process qualification,
- For different nesting factor by defining three sample heights. A relative high nesting factor applies for the lower zone of the build envelope and a low nesting factor is obtained by only the full-height samples in the higher part of the build envelope.

Several characterization and testing methods are considered to evaluate the process stability. Archimedes relative density and Charpy impact tests are used to screen the material quality in the total build envelope. One tensile test is conducted on mid-height samples (2 in case of multiple lasers). Chemical composition measurements are also conducted on the printed samples.

The stability assessment platform is composed from three sample types: Cube, Mid-height sample, Full height sample. Depending on the maximum available height of the build envelope, the height and layout of specimens of the full-height samples can vary. 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 following criteria:

- All density measurements > 99%,
- Acceptable micrography,
- All the impact test results should be within +/- 25% of the average value,
- Acceptance criteria for tensile properties after heat treatment are defined in the equipment specification for the part. It is the manufacturer's responsibility to evaluate whether the absolute tensile values in as-built condition are in line with targeted values, considering that the process qualification platform will use the same powder batch as the final qualified component and must comply with the heat treated condition. The tensile properties (yield strength, UTS and elongation) should be within +/- 20% of the average values,
- Chemical composition in agreement with the equipment specification characteristics.

If the criteria are not fulfilled, the root cause shall be identified and solved to validate the process stability. However, the tests could reveal a "dead zone" (zone where mechanical requirements or material soundness are not reached) with limited and well defined area. In that case, surface of the dead zone shall be continuous, a rectangular surface including the dead zone has to be defined and is excluded from the available printing area of the platform. This means that the component and accompanying specimens have to be printed outside of the dead zone. If it is not possible, the manufacturer shall propose additional requirements (inspection and/or tests..) to guarantee the final quality of the component.

	Small machine (single laser)	Large Machine	Large machines with multi-laser configuration (example for 4 lasers)
Laser(s)	1	1	4
Charpy Impact	5 (spread homogeneously)	8 (5 in bottom region and 3 in upper region	19 (Bottom region : 3 per laser + 1 per overlap ; For upper region : 1 per laser)
Density	10	10	30
Micrographic examination and hardness Additional specimen in the center of each area per laser 3 per overlap if applicable	4	4	11
Chemical composition	1	1	1
Tensile test	3	3	4
Visual examination	All	All	All
Witness samples in NUCOBAM: - Archimedes density measures	2 full height bars. Ideally in the corners	4 witness specimens in total, ideally in the corners	4 witness specimens in total, ideally in the corners and in the overlaps

- micrographic examination - chemical composition			
- Archimedes density measures - optical microscopy - Hardness test	2 full height bars. Ideally in the corners	One per laser area that does not contain witness samples	One per laser area that does not contain witness samples

Table 1: Qualification tests required in function of the build envelope and number of lasers of the machine

5.3.2. Process Repeatability

The assessment of process repeatability is carried out by measuring the variability of the component properties from one job to another, using the same machine and process parameters. Therefore, the same job as for the stability assessment (same platform with same p-AMPS) shall be executed and the same tests shall be performed.

For the process repeatability assessment, the same heat treatment shall be applied to the test samples when applicable. The discrepancy between the results from one job to another should fit with the following criteria:

- All density measurement > 99%,
- All the impact test results should be within +/- 25% of the average value of the “repeatability” job and this average value should be within +/- 15% compared to the 1st job (stability) average value. The average value should not be lower than 60 J at room temperature,
- Average tensile properties (yield strength, UTS and elongation) shall be within +/- 15% compared to the 1st job. Moreover, the tensile properties (yield strength, UTS and elongation) should be within +/- 20% of the average values. Acceptance criteria for tensile properties after heat treatment are defined in the equipment specification,
- Chemical composition in agreement with the equipment specification.

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. 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.

5.3.3. AM Process qualification platform

In order 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 (§4) 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 tests, 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.

The tests on the specimens of the process qualification platform and the number of required samples are listed in table 2 below.

Analysis / Test	**Sample orientation**	**Sample dimensions**	**Number of samples**
316L Archimedes for relative density	Density measurements are carried out at the bottom and at the top of the witness bars.		
Tensile properties	Z-, XY- and 45° direction	Following ASME Section II, Part A	3 specimens for each build direction
Charpy Impact V-notch	Z-, XY- and 45° direction	Following ASME Section VIII, Division 1 or Section III	5 specimens for each build direction
Witness samples : - archimedes density measures - optical microscopy - chemical composition	Z (full-height)	12*12 mm *h with h the height of the higher part produced for chemical composition	Single-laser: 2 witness samples, ideally in the corner Multi-laser : 4 witness samples in total, ideally in the corners
Requalification samples: - archimedes density measures - optical microscopy - chemical composition	Z (full-height)	12*12*h with h the maximum height allowed by the machine	Single laser : 2 Multi-laser : 1 per laser without witness sample + 1 per overlap

Table 2: Tests to be performed for the AM process qualification platform

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.

A visual examination shall be performed on all samples.

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The discrepancy between the results from one job to another should fit with the following criteria:

- All density measurement > 99%,
- All the impact test results should be within +/- 25% of the average value of the "repeatability" job and this average value should be within +/- 15% compared to the 1st job (stability if heat treated) average value. The average value should not be lower than 60 J at room temperature,
- Average tensile properties (yield strength, UTS and elongation) shall be within +/- 15% compared to the 1st job. Moreover, the tensile properties (yield strength, UTS and elongation) should be within +/- 20% of the average values. Acceptance criteria for tensile properties are defined in the equipment specification,
- Chemical composition shall be in agreement with the equipment specification.

5.3.4. Product validation platform

The reliability of the final qualified component is demonstrated by performing a simulation on a specific geometry known as the product validation platform that is identical to the final qualified component:

- The specific geometry of the final qualified component shall be manufactured according to the p-AMPS,
- The product validation platform shall be heat treated (§7) according to the requirements of the equipment specifications (§6.1),
- Tests performed on witness samples (§5.3.5) shall be performed,
- The component(s) shall be finished according to the requirements of the equipment specifications and (§9),
- The following examinations could be performed on the component according to equipment specification requirements :
    - Radiographic test,
    - Visual examination,
    - Liquid penetrant test,
    - Ultrasonic test according to examination (§10) should be performed if possible.
    - A tomography examination may be performed,
    - Dimensional Check.
- The product validation part shall be tested according to the requirements of the equipment specifications.

If the dimensions of the build envelope allow it, the specific geometry intended for the product validation platform or AM qualification platform may be printed together with the final qualified component. Heat treatment can be performed simultaneously on the shared build platform. Witness samples placed strategically on the baseplate of the specific geometry are compared to the requirements (§5.3.2) 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.

The product validation platform shall be marked by a serial number and indication of the orientation.

5.3.4.1. Acceptance criteria

Once the data has been collected, it must be possible to establish the following:

- acceptance test examinations used to verify that product quality is uniform,
- examination criteria which take into account manufacturing contingencies, substantiation requirements and the need for maximum economic efficiency.

The link between product qualification and acceptance requirements must be properly appreciated. Examination of the qualification may necessitate different acceptance tests from those initially stipulated in the procurement specification.

5.3.5. Witness samples

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.

5.4. Procedure qualification records (PQRs)

The PQR documents cover all the AM Process qualification documents and test results record of the specimens of the build platform configurations. The PQR shall indicate the key process and non-key process variables of the AM-machine and process based on all p-AMPS performed during the qualification process and the iterations made. The PQR shall be certified by the organisation's QC system and shall be accessible to the inspector(s).

6. MANUFACTURING OF THE COMPONENTS & TEST SPECIMEN

6.1. Equipment specifications – technical files

Equipment specifications or technical files are issued by the owner for the contractor / manufacturer. Their purpose is to specify all requirements to produce, inspect & test and to deliver the component.

Their content are described in the codes or standards related to the manufactured product:

- Description of the material (function, performance),
- Scope of supply or work to be carried out,
- Applicable references (codes, standards, rules, regulations, others),
- QA requirements,
- Design requirements of the material,
- Powder requirements, as appropriate,
- Studies to be performed,
- Manufacturing and construction requirements,
- Packaging, transport, storage,
- Requirements for the erection of the material in the installation,
- Inspections and tests,
- Documentation.

6.2. AM procedure specification (AMPS)

A complete PQR (§5.4) must be completed to validate that the p-AMPS is qualified in the form of an AMPS.

This AMPS should mention the class of the components (1, 2 or 3). The final qualification requirements and testing plan will be therefore adapted according to the application and the class of the component.

Only the AMPS shall be used to manufacture the final qualified component and shall not be modified.

6.3. Component manufacturing plan (quality control)

The component manufacturing plan (CMP) is a QC document and outlines in chronological order all the steps for the production of the final qualified component.

Generally, the CMP or an equivalent file is required by the nuclear code applied and detailed in it, when needed.

7. HEAT TREATEMENTS / THERMAL TREATEMENT

7.1. General

High temperature recrystallization annealing is recommended for reactor components to ensure homogeneous microstructure and prevent stress corrosion cracking initiation in high temperature water. Solution annealing (§7.2.1) may be important for some critical components because it can further minimize the porosity.

Residual powder on the build shall be cleaned prior to heat treatment.

Heat treatments should be performed while the components are attached to the build platform. If not, it is suggested to perform a stress relief prior to removing the samples in order to avoid deformations.

Thermal processing equipment should meet the requirements of AMS 2750.

7.2. Procedure

7.2.1. Solution annealing

Additive manufactured parts shall be delivered in the as-treated condition (Solution annealing).

The atmosphere shall consist of a neutral gas (Ar of He with purity ≥ 99.995%) with P ≤ 1.33 Pa. When inert gas is used, the dew point should be ≤ -51°C as the gas enters the furnace.

Solution annealing shall be performed by holding the platform, parts or specimen during a soaking time given in Table 3 between 1050°C and 1150°C with a tolerance of +/-14°C. A set temperature of 1066°C is recommended. In any case, the parts shall be held for sufficient time to ensure that

the centre of the most massive section has reached temperature and the necessary transformation and diffusion have taken place.

The soaking time can be found in AMS 2759. The minimum soaking time shall be chosen for the minimum dimension of the heaviest section of a part or it's baseplate. In order to have representative heat treatment on the qualification platforms and the final qualified part, the soaking time and cooling rate used for the qualification process shall be of the same as the soaking time for the final qualified part.

Diameter or thickness of maximum section[1] [mm]	Minimum soaking time (atmosphere furnace)		Minimum soaking time (salt bath)	
	Time	Tolerance [minutes]	Time	Tolerance [minutes]
Up to 2.54	20 minutes	+15/-0	17 minutes	+5/-0
Over 2.54 to 6.35	25 minutes	+15/-0	18 minutes	+5/-0
Over 6.35 to 12.70	45 minutes	+15/-0	35 minutes	+5/-0
Over 12.70 to 25.4	1 hour 0 minutes	+15/-0	40 minutes	+5/-0
Over 25.4 to 38.1	1 hour 15 minutes	+15/-0	45 minutes	+5/-0
Over 38.1 to 50.8	1 hour 30 minutes	+15/-0	50 minutes	+5/-0
Over 50.8 to 63.5	1 hour 45 minutes	+15/-0	55 minutes	+5/-0
Over 63.5 to 76.2	2 hours 0 minutes	+15/-0	1 hour 0 minutes	+5/-0
Over 76.2	2 hours 15 minutes + 15 minutes per 12.7mm over 76mm	+15/-0	1 hour 5 minutes + 5 minutes per 12.7mm over 76mm	+5/-0

Table 3: Soaking times for solution annealing of 316L parts in function of the maximum thickness of the whole

7.2.2. Cooling

After holding at the set temperature for solution annealing configuration, cooling should be performed under an inert atmosphere (e.g. vacuum gas quench).

If the parts are subsequently machined (e.g. samples for mechanical testing), cooling in air is acceptable.

7.2.3. Solution annealing with prolonged soaking time or others

Any other heat treatment can be agreed upon the purchaser and the component supplier and can be proposed if the designer demonstrates the capacity of the material to fulfil service requirement.

[1] Thickness is the minimum dimension of the heaviest section of a part or baseplate or nested load of parts.

7.3. Report/Certification

The heat treating processor shall furnish a report (preferably a certified quality assurance report, e.g. 3.1 certificate according to NF EN 10204) stating that the parts were heat treated in accordance with the requirements of this document. The report should include:

- Part number or product identification,
- Identification of furnace used,
- Alloy,
- Quantity of parts,
- Atmosphere type,
- Type of load thermocouples used,
- Processing temperature and time used,
- Pressure (if applicable),
- Heat treatment chart (temperature-time diagram) including pressure (if applicable).

8. POST PROCESSING OF PRINTED PARTS

For post-processing of printed parts, AM components must be cleaned to remove residual powder before heat treatment or finishing. Any visible rust is to be removed with a cloth soaked in a cleaning and pickling product. Cleaning methods shall be sufficiently efficient to ensure satisfying visual examination as per ASTM A380, water wetting and drying techniques, or immersion in demineralized water for 48 hours followed by air exposure,

If carbon steel contamination is suspected after cleaning and examination, the Ferroxyl test per ASTM A380 is used to detect ferritic incrustation. If contamination is found, pickling and passivation are required; if not, only passivation is performed, followed by a retest.

Support material should be removed using a band saw or electric discharge machining (EDM), and areas machined, ground, or polished must undergo liquid penetrant testing.

9. Inspections and Tests

The tests proposed in this chapter cover the test to be performed during the manufacturing of the final component.

The technical specification needs to mention the tests to be performed, and reference can be made to the tests and inspections in chapters §5 and §6. The minimum tests to be foreseen are covered by the tests below.

The method and acceptance criteria need to be defined with the owner and following standards. A failed test or inspection may lead to the rejection of the inspected component. Non-conformities shall be reported to the Owner. Repairs are not considered in the scope of the methodology for the time being.

QA requirements applicable to the laboratory / operators performing the tests and the certification are covered by §11.

9.1. Chemical properties

As mentioned in §4.3, the test method to determine the chemical properties of the final qualified component and associated acceptance criteria are defined in ASME II SA 751.

9.2. Microstructure

Microstructure examinations should be carried out after the specimens have undergone a representative heat treatment as the final qualified component they represent. The preparation of the metallographic samples is carried out according to ASTM E3. Their location in the material is defined according to the type and the purpose of the examination or specified in the technical specifications of the equipment supply.

The polishing of the samples may be done by mechanical or electrolytic means.

The chemical attack could be carried out in such a way as to highlight the constituents designated by the Owner. Two different types of attack for comparison may be requested, where appropriate.

The chemical attack of the sample is carried out in accordance ASTM E3.

The micrographs are taken in accordance with ASTM E2.

The grain size shall be assessed in accordance with ASTM E112 and shall be defined in specification.

9.3. Intergranular corrosion test

The purpose of this test is to ensure that the product will resist intergranular corrosion well enough to withstand the manufacturing and service conditions to which it will be subjected.

Test conditions will be more or less stringent depending on the requirements of the equipment specification specific to the supply of the equipment.

The test may be carried out in accordance with the latest edition of the ASTM A262 Practice E specification.

10. EXAMINATION

The examinations proposed cover the following phases:

- Examinations during the AM Qualification process,
- Examinations during the manufacturing of the final qualified component.

The several examinations that can be performed are:

- Visual testing: components are checked for cleanliness by naked eye or rubbing with a dry, lint-free cloth, which should remain white after use according ASME B31.3 and ASME section V,
- Penetrant testing: methods and procedures are detailed in ASME section V,
- Ultrasonic testing: a basic calibration block with reflectors should be used to establish the primary reference response of the ultrasonic equipment. This block should be made from the same material as the component and undergo representative thermal treatment. Methods and procedures are detailed in ASME section V,
- Tomography Testing: methods and procedures are detailed in ASME section V,
- Radiographic testing: radiographic testing is optional if tomography is performed. Methods and procedures are detailed in ASME section V,
- Dimensional Check: the dimensional characteristics of parts after final heat treatment and final machining shall comply with the procurement drawing.

A failed examination may lead to the rejection of the inspected part. The non-conformity shall be reported to the Owner. Repairs are not considered in the scope of the methodology for the time being.

11. Quality assurance

The Owner of the nuclear installation shall ensure that the powder supplier, the AM manufacturer and/or entity in charge of the AM process qualification have an adequate Quality Management (QM) system in place, complying with the national nuclear regulation applicable to the nuclear facility. In order to maintain consistency between the suppliers at different tiers, an audit of the powder supplier, manufacturer and sub-suppliers of stipulated requirements may be required by the construction code, to demonstrate the reliability of the (powder) manufacturing process, procedures and documentation.

Quality assurance (QA) requirements may comply with the national nuclear regulation for nuclear facilities and the chosen construction code. Thus, QA requirements may vary depending on the country.
Tests and inspections defined in §9 and §10 have to be performed in accordance with a written procedure by a qualified operator. For all examinations, the contractor submits its qualified procedures for approval to the facility owner.

A Quality Management system has to be in place to give confidence that the specific requirements of the qualification methodology document, powder acceptance specifications and equipment specifications are met. These requirements address:

- Powder procurement,
- Manufacturing,
- Inspections & tests,
- Documentation & certification.

12. Shop qualification

12.1. Facilities

The qualification has to be performed on a specific AM machine manufacturer and model number.

AM machines shall be equipped with suitable facilities.

A description of the following must be provided (including details of geographical location):

- major items of equipment used,
- heat treatment facilities,
- destructive and non-destructive examination facilities,
- major facilities for chemical analysis and metallurgical research.

If the Supplier's shops are not equipped with adequate heat treatment or examination facilities the Supplier shall state in the qualification report the conditions under which these activities are subcontracted and shall provide the pertinent data for the operations involved.

A change of AM facility within the same company invalidates AM part qualification.

12.2. Industrial experience

The part manufacturer shall provide evidence of knowledge or feedback available to the manufacturer concerning:

- The robustness of the process,
- Machine homogeneity and repeatability,
- The material characteristics,
- Defectology.

13. Operator qualification

The objective of the operator qualification is to demonstrate the ability of AM machine operators to deliver AM component builds on a given AM, supposing a set of minimum requirements.

The qualification has to be performed on a specific AM machine manufacturer and model. As a consequence, operator qualification is only valid for the specific machine model (a full qualification is needed for any other model regardless of AM process or machine manufacturer). However, completion of partial requalification requirements is needed in case of any change in software version.

For an AM machine operator the qualification is only valid for the associated AM machine model and powder material group.

The qualification of the operator shall following of AWS D20.1/D20.1M:2019 and include theoretical test, practical test, and evidence of visual acuity. The practical test shall include training, practical Examinations and Demonstration Build.

13.1. Training

The following actions have to be handled during training:

- Feedstock storage and safety,
- Feedstock handling,
- Cleaning requirements,
- Machine calibration devoted to operators,
- Common build defects,
- Environmental controls,
- Loading of qualified build parameters,
- AM machine preventive maintenance,
- Running and monitoring AM build cycles, and recording AM build cycle data,
- Recovery from planned and unplanned build cycle interruptions,
- Build platforms and components removal,
- Equipment and subcomponent safety.

A minimum of 40 hours of training to the use of the specific AM machine (manufacturer and model number) are requested.

Training records should be part of the qualification records.

The training hours of operators who perform only limited portions of AM machine operation may be less than specified, provided the time and type of training is documented and any limitation or restriction on the qualification is described in the certification records.

13.2. Practical examination

Qualification of an AM machine operator requires that the operator complete a examination that consists of demonstrating an understanding of all applicable topics:

- Feedstock material storage,

- Feedstock material safety,
- Feedstock material setup,
- Equipment and component cleaning requirements,
- Performance of machine calibrations that are done by operations personnel,
- Common build defects,
- Environmental controls,
- Loading of qualified build parameters,
- AM machine preventative maintenance,
- Running and monitoring AM build cycles,
- Recording AM build cycle data,
- Recovery from planned and unplanned build cycle interruptions,
- Removing completed components and build platform from AM machine.

Completion of a practical examination is requested to demonstrate an understanding of the topics covered by the Training Program specifically defined for a given AM machine model and software version.

For operators performing limited portions of the AM machine operations, only the portions of the training can be verified and documented accordingly in the training records.

13.3. Demonstration build

Demonstration build is manufactured in accordance with a qualified AMPS for which the operator is qualified.

AM procedure qualification pre-production test build can be used for the AM operator qualification.

13.4. Qualification validity

The qualification is valid for 2 years after the date of issuance of the certificate.

AM machine operator qualification is maintained by successful production of an AM build on dedicated AM machine with targeted component classification level at least once per 6-month period. In that case, documentation of AM builds to maintain AM operator qualification is to be recorded.

A partial operation requalification in case of any change of AM machine software version, a completion of an additional training is required and eventually a completion of new demonstration build, depending on the qualification class.

13.5. Documentation

The qualification file includes the following records for AM Operator Qualification:

- Name of employee and qualification level for each AM machine and software version,
- Details of qualification limitations if not qualified for all aspects of AM machine operation,
- Version of the Qualification Program to which the operator is qualified,
- Records documenting the completion of the training, as well as the results of written and practical examinations signed by the relevant person (intern or extern),
- Records of the demonstration build, including the qualified AMPS and the inspection results meeting the specifications if needed,
- Records of AM builds completed to maintain the qualification,
- Certification record signed by the Qualifier to document operator qualification for a given AM machine model and software version, including potential limitations, date of the last build…

14. DEFINITIONS Additive Manufacturing Code et Standard

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 §5.

Blended powder :

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

Build :

The part 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 :

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

Essential variables[2]:

Refers to the variables 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.

[2] The term “parameters” may also be used, having the same meaning as “variables” in this context.

Manufacturer :

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

Nesting factor :

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[1]:

Refers to variables 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 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 analysed only in case of a re-qualification without re-assessment of machine stability and repeatability.

Reused powders :

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 §5.3 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.

References

EN 10088-1 : Acier inoxydable - Liste des aciers inoxydables.

ASME PTB-13-2021 : Code des critères pour les composants métalliques sous pression utilisant la fabrication additive (Additive Manufacturing - AM).

EN 60534 : Vannes de régulation industrielles.

EN 12516-1 : Vannes industrielles - Conception par calcul - Partie 1 : Pression, température et dimensions.

ASME B16.34 : Vannes de canalisation - Brides et raccords filetés.

ISO/ASTM 52900 : Fabrication additive - Principes généraux – Terminologie.

ISO/ASTM 52921 : Fabrication additive - Principes de base - Terminologie pour les coordonnées des pièces et des ensembles et indications sur les tolérances.

ASTM F2924 : Spécifications pour les alliages de titane fabriqués par fusion sur lit de poudre

ASTM B243 : Terminologie relative aux matériaux et produits en aluminium.

ASTM 52907 : Fabrication additive - Méthodes d'essai pour la poudre métallique utilisée dans la fabrication additive par lit de poudre.

ISO/IEC 17050-1 : Évaluation de la conformité - Déclaration de conformité du fournisseur - Partie 1 : Exigences générales.

EN 10204 type 3.1 : Documents de contrôle des produits métalliques - Type 3.1.

ASTM B215 : Pratiques standard pour la pulvérisation des poudres métalliques.

ASME II. SA 751 : Méthodes d'essai pour la détermination de la composition chimique des matériaux.

DIN 55474 : Rubans adhésifs pour l'emballage.

BS 1133-19 : Emballages - Partie 19 : Protection des angles et des bords.

AMS 2750 : Pyrométrie (norme pour le contrôle de la température dans le traitement thermique).

AMS 2759 : Traitement thermique des aciers.

NF EN 10204 : Documents de contrôle des produits métalliques.

ASTM E3 : Pratiques standard pour la préparation des spécimens métallographiques.

ASTM E2 : Terminologie relative aux essais mécaniques de matériaux métalliques.

ASTM E112 : Méthode standard pour la détermination de la taille des grains.

ASTM A262 Practice E : Méthodes standard pour détecter la sensibilité à la corrosion intergranulaire des aciers inoxydables austénitiques.

ASTM A380 : Nettoyage, décapage et passivation des aciers inoxydables.

ASME B31.3 : Code des canalisations de procédés.

ASME Section V : Code des essais non destructifs.

AWS D20.1/D20.1M:2019 : Spécifications pour la qualification des opérateurs et des équipements de fabrication additive pour les métaux.

ASTM F3184-16 : Spécification standard pour la fabrication additive en lit de poudre métallique des alliages de titane.

APPENDIX 2 : RCC-M DELIVERABLE D1.4

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1. Requirements from the RCC-M code (2020)

M 116 SPECIFIC USE OF A NON-REFERENCED MANUFACTURING PROCESS

Manufacturing processes not referenced by the RCC-M can exceptionally be proposed by the Manufacturer, for a particular application. In these conditions, and prior to the procurement of the materials, the Manufacturer must submit the following items to the Contractor for approval:

a) A procurement specification; for this purpose, it shall most frequently use a similar existing Reference Technical Specification, or a compatible standard, stating the options systematically adopted
b) A first part qualification, according to the principle described in M 140
c) A document package justifying the use of the grade for the targeted application. This document package shall include at least the following items:

- References to the existing standards and technical specifications,
- The data needed for design,
- Evidence that the material obtained by this new manufacturing process is suitable to be employed for the targeted application,
- Evidence that the acceptance (destructive and non-destructive tests) is appropriate for the inspections of the products resulting from this new manufacturing process,
- Performance under the service conditions, for the targeted application,
- Experience feedback: status for similar applications.

M 140 PRODUCT AND SHOP QUALIFICATION

Use of a product manufactured in accordance with a given manufacturing process in a given shop must be preceded by the following qualification:

- Product qualification,
- Shop qualification.

The parts or products covered by M 141 shall be the object, prior to procurement, of a **qualification report** specifying all of the elements and information requested below. This report shall be drawn up by the Supplier of the product, and shall comprise the following documents:

- **the manufacturing programme :**
  Parameters which the Supplier considers to be "major parameters" since they directly affect product quality, as stipulated by the Contractor, shall be specified and listed in a manufacturing programme. The points which must, at least, be taken into consideration are described below in paragraphs a), b), c), d), and e)[1].
  In certain special cases difficulty may be encountered in applying these requirements: they should be notified and the manufacturing programme modified accordingly.
  In addition, the Supplier may find it necessary in his manufacturing programme to define special requirements (examination and/or control procedures) taken to ensure suitability for use or the quality of the product, notably for guaranteeing the absence of such defects as cracks, segregation cracks, etc.
- **the programme of tests to check the properties of the product or part** (see M 143.6),
- **the results of these tests.**

[1] These paragraphs can be found in RCC-M code.

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2. Modification proposal

The following modification is constituted by two parts: one dedicated to the process and part qualification, that is planned to be integrated in the section II of the RCC-M (Material), in the chapter M100 (General provision). And the other one will be integrated in the procurement specification part for stainless steel (M3000 chapter).

2.1. Part 1: Qualification according to M116, implementation of the process and part qualification

M 180 316L LASER POWDER BED FUSION ADDITIVE MANUFACTURING (PBF-LB/M) PART QUALIFICATION

M 181 GENERAL CONCEPTS

M 181.1 Terminology

For AM-specific terminology the following standards may be used for guidance or as reference: ISO/ASTM 52900, ISO/ASTM 52921, F2924, B243, with the following precisions:

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

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.

pAMPS or AMPS:
The pAMPS (preliminary Additive Manufacturing Procedure Specification) or AMPS is a unique document dedicated to a specific print job, build job, 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.

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

Build:
The part resulting from a job is called a build.

Build platform configuration:
A predetermined configuration (with a given parameter set) 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).

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

Dead zone:
Zone where specification requirements and/or stability assessment tests are not reached.

Inspector:
This physical or legal person is an independent inspector, mandated (approved) by the Client or 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 to be filled by 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.

Key process variables[2]:
Refers to the variables of the PBF-LB/M process that will affect the required properties of the build (mechanical, chemical, corrosion resistance, dimensional requirements …..). If any key process 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.

Non-key process variables[2]:
Refers to variables of the PBF-LB/M process that are not known to have an observable impact on the required characteristics of the build. They are conditions in which a change, as described in the specific variables, is not considered to affect the material quality and performance of the build.

[2] The term “parameters” may also be used, having the same meaning as “variables” in this context.

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

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.

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

PBF-LB/M Process Repeatability Platform:
The PBF-LB/M Process Repeatability 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 machine (same serial number) using the same powder (same batch/lot and same number of sieving cycles, same manufacturer, same technical procurement specification), with the same operating conditions and key process variables, but at different moments.

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…).

Powder sampling :
Samples that are collected from the powder bed at the end of the production by the AM manufacturer.

Powder supplier/manufacturer
Powder manufacturer: according to NF EN 10204.
Powder supplier: intermediary according to NF EN 10204. An audit of the powder manufacturer, AM part manufacturer and sub-suppliers may be required by the construction code to help receive insight on the reliability of the (powder) manufacturing process, procedures and documentation.
Material supplier: provider of material/feedstock to be processed in an additive manufacturing system [EN ISO/ASTM 52900:2021, §3.1.8].
Feedstock manufacturer: entity that produces the feedstock. Note: In additive manufacturing, the feedstock manufacturer can often be a different entity than the feedstock supplier [EN ISO/ASTM 52900:2021, §3.6.6].
Feedstock supplier: feedstock vendor provider of feedstock. Note: In additive manufacturing, the feedstock supplier can often be a different entity than the feedstock manufacturer [EN ISO/ASTM 52900:2021, §3.6.7].

Production Platform (containing the final qualified part):

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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.

Product 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. during serial production 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.

Requalification samples:
Samples that are produced on every process qualification platform but that are analysed only in case of a re-qualification without re-assessment of machine stability and repeatability. This case has not been covered in the frame of the project.

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.

Witness samples:
Samples that are produced on every platform alongside specific specimens and/or industrial components to monitor the quality of the printed material.

M 181.2 Objectives

This qualification is used to check that a part, additively manufactured by PBF-LB/M in accordance with a specified program (so called Additive Manufacturing Procedure Specification, AMPS), will respond satisfactorily to fabrication operations, quality and service conditions; product qualification is the time when the characteristics of the product may be determined, particularly singularities and testability.

The use of a part/product manufactured in accordance with a given AMPS in a given shop must be preceded by the following qualification:

- part qualification,

- shop qualification.

AM qualification is performed in accordance with the requirements of M 182 and M183 to ensure that it is fit for its intended use and that the acceptance operations and criteria are

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representative: products are then procured on the basis of a series of tests known as "acceptance tests" specified in the procurement specification.

M 182 PART QUALIFICATION

M 182.1 Qualification report

A complete qualification report file must be completed to validate that the p-AMPS is qualified in the form of an AMPS.

Only the AMPS shall be used to manufacture the final qualified component and shall not be modified.

The qualification report documents cover all the AM Process qualification documents and test results record of the specimens of the build platform configurations. It shall indicate the key process and non-key process variables of the AM-machine and process based on all pAMPS performed during the qualification process and the iterations made.

The documents that should be referred to, in certain sequences of the component manufacturing plan, include but are not limited to the following items:

- AMPS,
- List of guidance, norms and standards applicable for the process, the material, testing and post-processing,
- Reference of the manufacturer instructions and procedures for the use of the printer and the manufacturing process,
- Reference to the operator qualification system (requirements, training, experience, evaluation),
- Reference to maintenance programme of the AM machine,
- Reference to Powder Certificate of Compliance,
- Reference to the powder sampling and visual inspection instructions,
- Job sheet template, a document that 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,
- Printer log file, pictures and all other records that are generated during the printing activities. This file is considered as a report and is retrieved after the job is finished,
- Reference to post-treatment procedure (support and platform removal, heat treatment, machining…),
- Reference to procedures for the examination and test of the end product,
- Test report (metallurgical and mechanical assessment).

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M 182.2 Validity of qualification

The Supplier must be informed of any change to a factor or parameter which is considered to affect qualification, and the consequences of this modification must be evaluated.

As a result of this evaluation the following may ensure:

- qualification shall be extended,
- qualification shall be extended on condition that supplementary examinations are performed,
- the part must be qualified.

M 182.3 Manufacturing programme

M 182.31 General approach

The figure M 182.3 details the steps of the qualification process.

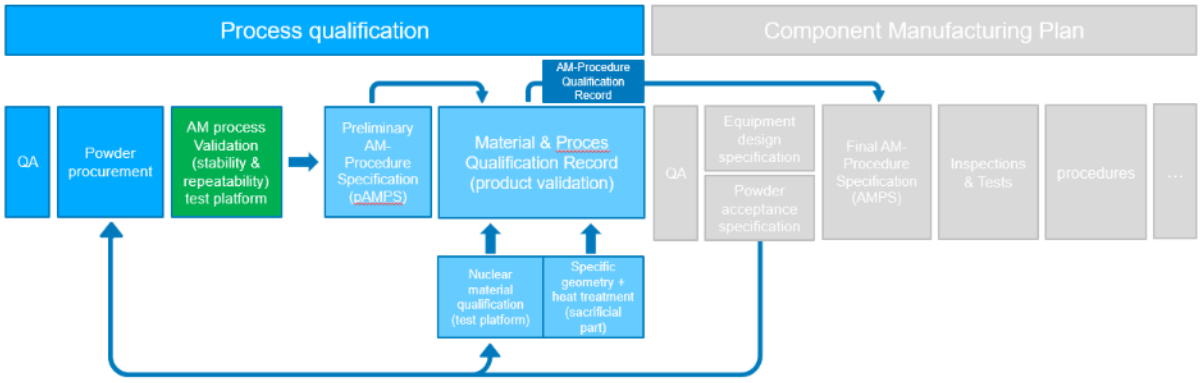

Figure M 182.3: flowchart of the AM process qualification

Fulfilling Stability and repeatability requirements is considered as a prerequisite before demonstrating that PBF-LB/M material performance meet qualification requirement. These steps shall be performed with frozen key process variables.

The next step in the AM process qualification is performed by manufacturing an AM process qualification platform. The purpose of this step is to confirm that the material produced complies with the material characteristics.

The last step required for the development of a complete qualification report is the validation of the specific geometry and heat treatment on a Production Validation Platform. Once this is achieved, a AMPS is then drafted based on the p-AMPS (preliminary additive manufacturing procedure specification) and with final values of all key process and non-key process parameters. These qualified parameters shall be applied during production in order to ensure the qualification of the AM build.

Stability and repeatability shall be demonstrated by means of key performance indicators (homogeneity of relative density, micrographic examination, tensile & impact toughness properties) on stability and repeatability assessment platforms.

The key process variables / parameters are fine tuned in the p-AMPS with every iteration until stability and repeatability is obtained.

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The points which must, at least, be taken into consideration in the qualification manufacturing programme are described below:

- raw materials (powder M 182.32),
- AM process qualification operations in chronological order:
  - . p-AMPS establishment M 182.33,
  - . Process stability demonstration 182.34,
  - . Process repeatability demonstration 182.35,
  - . Process Validation Platform 182.36,
  - . Part Validation Platform 182.37,
- witness specimens for acceptance tests,
- position of part and specimen in the platform,
- manufacturing operations in chronological order:
  - . part manufacturing,
  - . machining (when needed),
  - . heat treatment,
  - . removal of test samples (when needed),
  - . non-destructive examination,
  - . drawings of the part showing the rough profile, the profile for heat treatment and the as-delivered profile,
- intermediate heat treatment and final heat treatment (for mechanical properties),
- drawing showing position of test specimens within test samples.

M 182.32 Powder procurement

Powder acceptance specifications are usually written by the owner and must be provided to the powder supplier /manufacturer in order to formulate specific requirements that may depend on specific needs for the application or AM machine (it may be part of the Equipment Specification). Requirements of the present chapter shall be taken into account.

The qualification of the final qualified component is obtained by the AM process qualification. The manufacturing program used by the powder manufacturer shall not been changed. In case it changes, the powder manufacturer shall inform the Customer and identify the impact on the powder delivered.

IDENTIFICATION

The following information is issued by the powder supplier:

- A unique document reference,
- Name and the address of the supplier,
- Reference of powder lot,
- Product description, including chemical composition, particle size distribution, standard and/or trade/common name,
- Nature of powder production process (including e.g. type of gas used, environment condition),
- Packaging description, including the packaging, the nature of the shielding gas and the desiccant bag if relevant,
- Date of analysis,
- Storage and preservation instructions,
- All information to ensure traceability (e.g. order number, applicable specification).

The report values shall be linked to the tests methods used and the corresponding standards.

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TESTS ON POWDER

Sampling and test methods

In a general way, it is necessary to have a sample per batch/lot of sufficient quantity to perform all the required analyses. Equipment cleanliness procedures shall be in place prior to any sampling to prevent cross contamination of powder. The collected sample needs to be kept in a safe container. This sample shall be labelled with the following information:

- Date of the sampling, sample identification numbers,
- Machine type and serial number,
- Material grade and batch reference,
- Condition (number of recycling if possible),
- Job Reference number of the printed platform.

The acceptance tests are performed by the powder manufacturer or by the manufacturer after reception to certify the powder characteristics are in accordance with the qualification methodology and powder acceptance specification requirements.

Number and type of tests

Testing of the following properties should be done in a controlled environment.

The following tests shall be performed in order to demonstrate the compliance of the powder with the specification after each platform production:

- Particles size distribution,
- Chemical analysis,
- Flowability ,as appropriate.

Results of tests

The acceptance criteria shall be indicated in the powder procurement specification.

CERTIFICATION

A material certificate in accordance with EN 10204 type 3.1 is required to prove that the powder is in compliance with the powder acceptance specifications and the qualification methodology.

REUSE OF POWDER

It is recommended to indicate the number of sieving cycles that the powder has experienced in the container. For systems with closed-loop sieving systems, the powder remains continuously inside the system and fresh powder is regularly added to maintain a blending ratio that guarantees sufficient powder in the system. The machine shall be refreshed with the same batch/lot powder.

It is mandatory to track the input of powder batches in a machine. The quantity and a reference to the powder certificate, together with the date of insertion in the machine, must be recorded. In any case, powder prepared for reuse shall meet all original size limits and tolerances prior to acceptance as reuse powder for an AM process.

The number of sieving cycles performed should be recorded when possible, in order to track the number of recycling steps the powder went through. This is made possible for separate sieving units, while close-loop sieving systems do not allow a tracking of sieving cycles. To do so, an annotation of the sieving cycle on containers is performed, especially when different containers are mixed in order to allow the printing of big platforms. A unique serial number per

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container is not mandatory. When possible, it is recommended to mention the number of sieving cycles that has been encountered by the powder during the full production route.

In case reused powder is used for the manufacturing process the same chemical composition, morphology and flowability tests are performed as for fresh powder.

M 182.33 Preliminary Additive Manufacturing Procedure Specification (p-AMPS) establishment

The p-AMPS contains general hardware information, software information, feedstock material information, job specific information (machine parameters, part geometry, configuration,…), follow up records, post processing procedures,…. This information is indicated directly or indirectly by referencing to separate documents or files, for instance:

- Computer Aided Design (CAD) file (component geometry, CAD models…),
- Job configuration file (baseplate, number of parts, orientation, support strategy…),
- Parameter set file,
- Laser scan trajectory file,
- Machine file.

Considering there are numerous PBF-LB/M process parameters involved during a build job, and the confidential nature for each PBF-LB/M manufacturer, the parameter set file and all associated data are listed in the AMPS or p-AMPS as a fixed file reference that shall remain unchanged. The verification of the content and correct usage of these reference files is verified by the inspector. The unique references of the aforementioned reference files used for a job are indicated on the job sheet (M182.1).

The first revision of the p-AMPS is developed based on the requirements of the equipment specification and the qualification methodology. It is based on experience of the manufacturer and, if possible, other previously issued AMPS. It shall address, as a minimum, the specific key and non-key parameters that are applicable to the AM machine and process.

The p-AMPS is referred in a Job Quality Control Plan (JQCP). The JQCP gathers all relevant information of the build job and defines all the sequence of steps achieved to produce the build, ensuring the traceability in a Quality Assurance framework. Guidelines for the establishment of a component manufacturing plan are applicable to this JQCP.

The first page of the JQCP contains general information such as:
- Reference document,
- Machine/hardware information,
- Program/software information,
- Feedstock material information.

This information is not expected to change under normal conditions. However, the document should be updated when a fresh or unused powder batch is used or when a major update is performed in the software or hardware.

The JQCP also contains job specific activities:
- Job-specific information (serial number),
- Pre-printing controls (machine-dependant parameters),
- Printing follow-up Quality Control records,
- Post-print Quality Control record,
- Post processing (atmosphere, time and temperature of heat treatment, machining, cleaning method…).

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Every p-AMPS shall be marked with a unique identifier and revision number, and shall be incrementally revised each time an essential or non-essential parameter / variable is modified.

M 182.34 Process stability demonstration

The process stability is assessed by measuring the variability of the properties of the components issued from the same job according to their positioning on the build plate. 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. Therefore, an initial testing plan is elaborated for mono laser machines and can be further adapted to be relevant with the characteristic of the multi-laser machines.

The stability is evaluated:

- Over the full platform surface by a homogeneous spread of the samples,
- Over the full build chamber height (meaning during the total job time) by producing a certain number of "full height" samples. The samples do not need to be heat treated in a representative condition at this stage of the process qualification,
- For different nesting factor by defining three sample heights. A relative high nesting factor applies for the lower zone of the build envelope and a low nesting factor is obtained by only the full-height samples in the higher part of the build envelope.

Several characterization and testing methods are considered to evaluate the process stability. Archimedes relative density and Charpy impact tests are used to screen the material quality in the total build envelope. One tensile test is conducted on mid-height samples (2 in case of multiple lasers). Chemical composition measurements are also conducted on the printed samples.

The stability assessment platform is composed from three sample types: Cube, Mid-height sample, Full height sample. Depending on the maximum available height of the build envelope, the height and layout of specimens of the full-height samples can vary. 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 characterization and testing methods defined in Table M 182.34 shall be used to evaluate the process stability.

The discrepancies between the results from one component to another for the 'stability' job should fit within the following criteria:

- All density measurements > 99%,
- Acceptable micrography,
- All the impact test results should be within +/- 25% of the average value,
- Acceptance criteria for tensile properties after heat treatment are defined in the equipment specification for the part. It is the manufacturer's responsibility to evaluate whether the absolute tensile values in as-built condition are in line with targeted values, considering that the process qualification platform will use the same powder batch as the final qualified component and must comply with the heat treated condition. The tensile properties (yield strength, UTS and elongation) should be within +/- 20% of the average values,
- Chemical composition in agreement with the equipment specification characteristics.

If the criteria are not fulfilled, the root cause shall be identified and solved to validate the process stability. However, the tests could reveal a "dead zone" (zone where mechanical

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requirements or material soundness are not reached) with limited and well defined area. In that case, surface of the dead zone shall be continuous, a rectangular surface including the dead zone has to be defined and is excluded from the available printing area of the platform. This means that the component and accompanying specimens have to be printed outside of the dead zone. If it is not possible, the manufacturer shall propose additional requirements (inspection and/or tests..) to guarantee the final quality of the component.

Table M182.34

	Small machine (single laser)	Large Machine	Large machines with multi-laser configuration (example for 4 lasers)
Laser(s)	1	1	4
Charpy Impact	5 (spread homogeneously)	8 (5 in bottom region and 3 in upper region	19 (Bottom region : 3 per laser + 1 per overlap ; For upper region : 1 per laser)
Density	10	10	30
Micrographic examination and hardness Additional specimen in the center of each area per laser 3 per overlap if applicable	4	4	11
Chemical composition	1	1	1
Tensile test	3	3	4
Visual examination	All	All	All
Witness samples in NUCOBAM: - Archimedes density measures - micrographic examination - chemical composition	2 full height bars. Ideally in the corners	4 witness specimens in total, ideally in the corners	4 witness specimens in total, ideally in the corners and in the overlaps
- Archimedes density measures - optical microscopy - Hardness test	2 full height bars. Ideally in the corners	One per laser area that does not contain witness samples	One per laser area that does not contain witness samples

M 182.35 Process repeatability demonstration

The assessment of process repeatability is carried out by measuring the variability of the component properties from one job to another, using the same machine and process parameters. Therefore, the same job as for the stability assessment (same platform with same p-AMPS) shall be executed and the same tests shall be performed.

For the process repeatability assessment, the same heat treatment shall be applied to the test samples when applicable. The discrepancy between the results from one job to another should fit with the following criteria:

- All density measurement > 99%,

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- All the impact test results should be within +/- 25% of the average value of the “repeatability” job and this average value should be within +/- 15% compared to 1st job (stability) average value. The average value should not be lower than 60 J at room temperature,
- Average tensile properties (yield strength, UTS and elongation) shall be within +/- 15% compared to 1st job. Moreover, the tensile properties (yield strength, UTS and elongation) should be within +/- 20% of the average values. Acceptance criteria for tensile properties after heat treatment are defined in the equipment specification,
- Chemical composition in agreement with the equipment specification.

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. 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.

M 182.36 AM Process validation platform

In order 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 **M 182.32** 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 tests, 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. Depending on the machine dimensions, several platforms may be needed to perform the AM process qualification.

The tests on the specimens of the process qualification platform and the number of required samples are listed in table M **182.36**.

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Table M 182.36

Analysis / Test	Sample orientation	Sample dimensions	Number of samples
316L Archimedes for relative density	Density measurements are carried out at the bottom and at the top of the witness bars.		
Tensile properties	Z-, XY- and 45° direction	RCC-M Tome III MC 1000	3 specimens for each build direction
Charpy Impact V-notch	Z-, XY- and 45° direction	RCC-M Tome III MC 1000	5 specimens for each build direction
Witness samples : - Archimedes density measures - optical microscopy - chemical composition	Z (full-height)	12*12 mm *h with h the height of the higher part produced for chemical composition	Single-laser: 2 witness samples, ideally in the corner Multi-laser : 4 witness samples in total, ideally in the corners
Requalification samples: Archimedes density measures - optical microscopy - chemical composition	Z (full-height)	12*12*h with h the maximum height allowed by the machine	Single laser : 2 Multi-laser : 1 per laser without witness sample + 1 per overlap

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.

A visual examination shall be performed on all samples.

The discrepancy between the results from one job to another should fit with the following criteria:

- All density measurement > 99%,
- All the impact test results should be within +/- 25% of the average value of the “repeatability” job and this average value should be within +/- 15% compared to 1st job (stability if heat treated) average value. The average value should not be lower than 60 J at room temperature,
- Average tensile properties (yield strength, UTS and elongation) shall be within +/- 15% compared to 1st job. Moreover, the tensile properties (yield strength, UTS and elongation) should be within +/- 20% of the average values. Acceptance criteria for tensile properties are defined in the equipment specification,
- Chemical composition in agreement with the equipment specification.

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M 182.37 Product Validation Platform

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:

- The specific geometry of the final qualified component shall be manufactured according to the p-AMPS,
- The part validation platform shall be heat treated according to the requirements of the equipment specifications,
- Tests performed on witness samples should be performed,
- The component(s) shall be finished according to the requirements of the equipment specifications,
- The examinations shall be performed according to the equipment specification,
- The part validation shall be tested according to the requirements of the equipment specification,

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. Heat treatment can be performed simultaneously on the shared build 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.

The product validation platform shall be marked by a serial number and indication of the orientation.

M 182.371 Verification of product properties

It may be necessary to perform examinations and tests, on the basis of the elements given above in order to:

- Check the internal soundness of the product,
- Evaluate the homogeneity of the chemical analysis and the mechanical properties of the product,
- Study in greater detail singularities identified by the manufacturing program and, when necessary, obtain valid data on material behavior in these zones,
- Ensure that acceptance tests are representative (with respect to parts) and that the non-destructive examinations are suitable for the shape of the part and the type of defects associated with the fabrication process.
- Ensure non-susceptibility to intergranular corrosion, preferably on part.

M 182.372 Acceptance tests

Once the data has been collected, it must be possible to establish the following:

- Acceptance test examinations used to verify that product quality is uniform,
- Examination criteria which take into account manufacturing contingencies, substantiation requirements and the need for maximum economic efficiency.

The link between product qualification and acceptance requirements must be properly appreciated. Examination of the qualification may necessitate different acceptance tests from those initially stipulated in the procurement specification.

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M 182.373 Witness samples

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 .

M 183 SHOP QUALIFICATION

M 183.1 Facilities

The qualification has to be performed on a specific AM machine manufacturer and model number.

AM machines shall be equipped with suitable facilities.

A description of the following must be provided (including details of geographical location):

- Major items of equipment used,
- Heat treatment facilities,
- Destructive and non-destructive examination facilities,
- Major facilities for chemical analysis and metallurgical research.

If the Supplier's shops are not equipped with adequate heat treatment or examination facilities the Supplier shall state in the qualification report the conditions under which these activities are subcontracted and shall provide the pertinent data for the operations involved.

A change of AM facility within the same company invalidates AM part qualification..

183.2 Industrial experience

The part manufacturer shall provide evidence of knowledge or feedback available to the manufacturer concerning:

- The robustness of the process,
- Machine homogeneity and repeatability,
- The material characteristics,
- Defectology.

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M 184 OPERATOR QUALIFICATION

M 184.1 General

The objective of the operator qualification is to demonstrate the ability of AM machine operators to deliver AM component builds on a given AM, supposing a set of minimum requirements.

The qualification has to be performed on a specific AM machine manufacturer and model. As a consequence, operator qualification is only valid for the specific machine model (a full qualification is needed for any other model regardless of AM process or machine manufacturer). However, completion of partial requalification requirements is needed in case of any change in software version.

For an AM machine operator the qualification is only valid for the associated AM machine model and powder material group.

M 184.2 Qualification Requirements

The qualification of the operator shall include theoretical test, practical test, and evidence of visual acuity. The practical test shall include training, practical Examinations and Demonstration Build.

Training :

The following actions have to be handled during training:

- Feedstock storage and safety,
- Feedstock handling,
- Cleaning requirements,
- Machine calibration devoted to operators,
- Common build defects,
- Environmental controls,
- Loading of qualified build parameters,
- AM machine preventive maintenance,
- Running and monitoring AM build cycles, and recording AM build cycle data,
- Recovery from planned and unplanned build cycle interruptions,
- Build platforms and components removal,
- Equipment and subcomponent safety.

A minimum of 40 hours of training to the use of the specific AM machine (manufacturer and model number) are requested.

Training records should be part of the qualification records.

The training hours of operators who perform only limited portions of AM machine operation may be less than specified, provided the time and type of training is documented and any limitation or restriction on the qualification is described in the certification records.

Practical examination:

Qualification of an AM machine operator requires that the operator complete a examination that consists of demonstrating an understanding of all applicable topics:

- Feedstock material storage,
- Feedstock material safety,
- Feedstock material setup,

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- Equipment and component cleaning requirements,
- Performance of machine calibrations that are done by operations personnel,
- Common build defects,
- Environmental controls,
- Loading of qualified build parameters,
- AM machine preventative maintenance,
- Running and monitoring AM build cycles,
- Recording AM build cycle data,
- Recovery from planned and unplanned build cycle interruptions,
- Removing completed components and build platform from AM machine.

Completion of a practical examination is requested to demonstrate an understanding of the topics covered by the Training Program specifically defined for a given AM machine model and software version.

For operators performing limited portions of the AM machine operations, only the portions of the training can be verified and documented accordingly in the training records.

Demonstration build:

Demonstration build is manufactured in accordance with a qualified AMPS for which the operator is qualified.

AM procedure qualification pre-production test build can be used for the AM operator qualification.

M 184.3 Qualification validity

The qualification is valid for 2 years after the date of issuance of the certificate.

AM machine operator qualification is maintained by successful production of an AM build on dedicated AM machine with targeted component classification level at least once per 6-month period. In that case, documentation of AM builds to maintain AM operator qualification is to be recorded.

A partial operation requalification in case of any change of AM machine software version, a completion of an additional training is required and eventually a completion of new demonstration build, depending on the qualification class.

M 184.4 Documentation

The qualification file includes the following records for AM Operator Qualification:

- Name of employee and qualification level for each AM machine and software version,
- Details of qualification limitations if not qualified for all aspects of AM machine operation,
- Version of the Qualification Program to which the operator is qualified,
- Records documenting the completion of the training, as well as the results of written and practical examinations signed by the relevant person (intern or extern),
- Records of the demonstration build, including the qualified AMPS and the inspection results meeting the specifications if needed,
- Records of AM builds completed to maintain the qualification,
- Certification record signed by the Qualifier to document operator qualification for a given AM machine model and software version, including potential limitations, date of the last build…

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2.2. Part 2: Part procurement specification 316L PBF-LB/M additively manufactured valve bodies

M 3500

PART PROCUREMENT SPECIFICATION

316L PBF-LB/M ADDITIVELY MANUFACTURED VALVE BODIES

0 SCOPE

This specification covers 316L austenitic stainless steel valve bodies additively manufactured with the laser powder bed fusion (PBF-LB/M) process for PWR nuclear power plants. The main valve characteristics are the followings:

- Valve type : ball sector valve (DN40, trunnion type),
- Seat : PEEK seat (leakage class V acc. to EN 60534),
- Design pressure : 27 bar (acc. to EN 12516-1),
- Rating : PN40 (~class 300, acc. ASME B16.34),
  Fluid : primary fluid,
- Actuation: manual,
- Pipe connection: non particular requirements, flanged ok.

The product shall be obtained through a qualified process (M 180).

1 POWDER REQUIREMENTS

The chemical composition requirements are given in Table 1 below.

The recommended acceptance criteria on the powder properties are the following:

- Particle size distribution with D90 to be as close as possible to 45µm, and powder particle size below 10µm as low as possible,
- Morphology analysis based on shape factor,
- Static angle of rest below 28°,
- Carney flow below 10s for 150g of powder,
- Typical Hall flow time of 13-15s for 50g of powder.

Containers need to be kept in a safe place to avoid any incident. The powder should be stored in a dry place to be protected for any humidity ingress and without significant variation of temperature. Ideally, a temperature and humidity controlled cabinet is recommended to store the powder containers. In case such configuration is not possible, alternative solutions could be implemented, such as drying the stainless steel powder at moderate temperature (for example 60°C) in vacuum, or perform powder sieving in inert gas (argon, nitrogen).

The received containers need to be kept sealed as long as possible before use. Depending on the powder supplier, the containers can potentially contain silica bags that should be removed before powder manipulation.

A specific physical separation should be defined to avoid mixture of fresh powder, recycled powder and waste products.

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After opening, the un-used powder should be placed back inside the containers with silica bags in order to keep the powder as dry as possible (note 1).

When possible, the container should indicate the number of sieving cycles that the powder has experienced.

The quality of the powder is monitored during the whole production program in order to monitor any deviation in terms of chemical composition, size distribution and flowability.

NOTE 1: When a desiccant bag is in contact with the powder, it can be source of contamination. Particular precaution should be taken (e.g. validation of the bag type).

Table 1: chemical composition

Grade :		
Elements	**Powder (%)**	**Product (%)**
Carbon ----------	<0.03	<0.03
Silicon ----------	≤ 1.0	≤ 1.0
Manganese ----------	<2.0	<2.0
Phosphorous. ----------	≤ 0.03	≤ 0.03
Sulphur----------	≤ 0.015	≤ 0.015
Chromium ----------	16.00 - 18.00	16.00 - 18.00
Nickel----------	10.00 - 14.00	10.00 - 14.00
Molybdenum----------	2.00 – 3.00	2.00 – 3.00
Copper ----------	≤ 1.0	≤ 1.0
Nitrogen----------	-	-
Oxygen----------	-	-
Cobalt ----------	≤ 0.04	≤ 0.04
Tantalum----------	≤ 0.15	≤ 0.15
Boron ----------	≤ 0.0015	≤ 0.0015

2 CHEMICAL REQUIREMENTS

2.1 REQUIRED VALUES

Chemical composition, as determined by powder and part analyses, shall comply with the requirements given in table 1.

Requirements relative to cobalt content shall be stipulated in the equipment specification or other relevant contractual documents, in accordance with sub-chapters B 2400, C 2400, D 2400 and G 2400.

2.2 CHEMICAL ANALYSES

The powder manufacturer shall supply an analysis associated to the suitable certificate (3.1 or 3.2).

3 MANUFACTURE

3.1 MANUFACTURING PROGRAMME

Prior to commencement of manufacturing operations, the manufacturer shall draw up a Component Manufacturing plan according to M 180.

PROTOTYPE PART
The manufacturing method shall be tested using a prototype part produced in accordance with the requirements of M 180.

3.2 DELIVERY CONDITION - HEAT TREATMENT

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Additive manufactured parts shall be delivered in the as-treated condition (Solution annealing).

The heat treatment atmosphere shall consist of a neutral gas (Ar or He with purity ≥ 99.995%) with P ≤ 1.33 Pa.

Solution annealing shall be performed by holding the platform, parts or specimen at a temperature between 1050°C and 1150°C with a tolerance of +/-14°C, with a holding time commensurate to the size of the heat treatment charge. A set temperature of 1066°C is recommended. In any case, the parts shall be held for a sufficient amount time to ensure that the center of the most massive section has reached temperature and the necessary microstructural transformation and diffusion have taken place.

Records shall be evaluated by the Supplier.

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4 MECHANICAL PROPERTIES

4.1 REQUIRED VALUES

Mechanical strength requirements are shown in table 2 below. Micrography shall be performed (acceptance criteria are given in the equipment specification).

Table 2: mechanical properties

Name of test	**Test temperature (°C)**	**Properties** (1)	**Required value**
Tensile	Room	$R_{p0.2}$	≥ 175 MPa
		Rm	450 to 490 MPa
		A (5d)	≥ 45 %
	350	$R_{p0.2}$	≥ 105 MPa
Charpy V-notch impact	+ 20	KV (Average value on 3 test specimens)	≥ 100J long
(1) values obtained after solution annealed			

4.2 SAMPLING

Test samples are constituted by specimens placed on the platform such as the test results are representative of part mechanical properties. The samples shall be of sufficient size to ensure that the necessary number of test specimens may be taken for the tests prescribed and for any retests required. The smallest dimension of the sample cross section shall be representative of the maximal thickness of the part. The notch of the impact specimens is oriented perpendicular to the direction of construction. An another notch orientation may be proposed on the basis of the results obtained from the qualification process. The direction of the notch shall be specified in the manufacturing program. The dimensions of the part, as well as the dimensioned drawing of the location of the test specimens within the platform, shall be specified in the manufacturing program.

4.3 TESTING

4.3.1 Number and content of tests

The mechanical properties of each specimen shall be determined.

4.3.2 Test procedure

A - TENSILE TESTING AT ROOM TEMPERATURE AND AT HIGH TEMPERATURE

a) Test specimens

Test specimens shall be as specified in MC 1000.

b) Test method

The tensile test shall be performed in compliance with MC 1000. The following values shall be recorded:

- Yield strength at 0.2% offset, in MPa,
- Ultimate tensile strength, in MPa,
- Percentage elongation after fracture,
- Percentage reduction of area after fracture.

c) Results

Results obtained shall meet the requirements given in table 2.
If this is not the case and the test specimen has a physical defect (which does not affect the usefulness of the product) or if unsatisfactory test results are due to incorrect mounting of the specimen or a testing machine malfunction, the test shall be repeated using another specimen.

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If the results of the second test are satisfactory, the part shall be accepted; if not, the following paragraph shall apply.

Where unsatisfactory results cannot be attributed to any of the above-mentioned causes, two retests may be performed for each unsatisfactory result obtained. The second set of test specimens shall be taken close to those which were defective. If the results of the retests are satisfactory, the part shall be accepted; if not, it shall be rejected.

B - IMPACT TESTS

a) Test specimens and test method

KV impact test specimens shall be taken from adjacent locations. The shape and dimensions of these specimens and test conditions shall be as specified in MC 1000. Test temperature shall be 20°C.

b) Results

The energy absorbed by breakage requirements at 20°C shown in table 2 must be met.
The part shall be rejected if it fails to meet any one of these requirements.

However, where the only unsatisfactory result is an individual value which is lower than the required minimum value and all other requirements have been met (satisfactory average, no more than one result lower than the required value), retests may be performed in accordance with the following procedure; two sets of three test specimens taken on the platform close to the defective specimens shall be tested at the same temperature as the first set. If results for either of the two sets of three test specimens do not comply with the requirements, the part shall be rejected.

5 SURFACE EXAMINATION - SURFACE DEFECTS - VOLUMETRIC EXAMINATION

Surface examination and volumetric examination shall be performed. Methods to be used and acceptance criteria are defined in that equipment specification.

6 DIMENSIONAL CHECK

The dimensional characteristics of parts after final heat treatment and final machining shall comply with the procurement drawing.

7 MARKING

The Supplier shall specify the identification and marking methods used, in compliance with B and C 1300.

8 CLEANLINESS -PACKAGING -TRANSPORTATION

Requirements shall be specified in the purchase order.

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9 TEST REPORTS

The following reports shall be drawn up by the part manufacturer after each individual test and, in any case, prior to delivery of the part:

- Powder and product analyses,
- Charts of major repairs,
- Mechanical tests,
- Non-destructive examinations,
- Dimensional checks,
- Heat treatment (temperature ranges and holding times).

These reports shall include:

- Heat number and part reference number,
- Supplier's particulars,
- Purchase order number,
- Name of the inspection agency, where applicable,
- Test and retest results together with required values.

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APPENDIX 3 : ACHIEVEMENTS LIMITATIONS AND PERSPECTIVES

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1. Achievements, Limitations and Perspectives of the NUCOBAM Project

This paragraph is composed of the following sub-sections:

- A first section highlighting the main objectives of the NUCOBAM project and providing some summary details of the work packages achievements,
- A second section listing a series of concepts or ideas used in the NUCOBAM project but that needs to be refined or reconsidered for future codification activities,
- A third section enumerating the technical topics that have not been fully addressed within NUCOBAM and that could be included in future studies or projects to come.

1.1. Summary of achievements of the NUCOBAM project

Many achievements have been done throughout the NUCOBAM project in the effort of qualifying the PBF-LB/M additive manufacturing process. This section highlights the main objectives of the project and provides some summary details of the work packages achievements.

OB1 Objective:

- Establish a qualification methodology for AM nuclear components to be proposed for standardisation and to be communicated to nuclear design code committees.

WP1 Achievements:

- Proposal of a qualification methodology document to be used in the NUCOBAM project by other Work Packages,
- Proposal of a nuclear code modification document for both ASME and RCC-M codes, based on NUCOBAM experience.

OB2 Objective:

- Develop a laser powder bed fusion manufacturing plan that ensures and demonstrates process stability, repeatability and reproducibility that meet nuclear quality standards

WP2 Achievements:

- Proposal of a manufacturing plan and methodology,
- Proposal of shop manufacturing and quality assurance documentation,
- Evaluation of four machine performances through the production and testing of samples from three built platforms (Stability S, Repeatability/Homogeneity R,

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Qualification Q), using frozen parameters (but without access to the detailed parameter set values, under manufacturer's confidentiality),
- Production of the samples for the WP3 testing campaign, on four different machines, using 3 different heat treatments and one HIP (Hot Isostatic Pressing) treatment, using the same frozen parameter set than on S, R and Q platforms,
- Evaluation of new testing methods (small impact testing),
- Evaluation of in-process monitoring solutions.

OB3 Objective:

- Demonstrate that laser powder bed fused material performance meets qualification requirements.

WP3 Achievements:

- Fulfillment of tests on samples produced in WP2 (material from four different machines, three different heat treatments and one HIP treatment,
- Fulfillment of analysis and synthetical comparison of the results for different material states:
  - ✓ Material at nominal state (no aging nor irradiation),
  - ✓ Material after irradiation from WP4 (for in-core application),
  - ✓ Material after thermal aging from WP5 (for ex-core application),
  - ✓ Material after Stress Corrosion Cracking (SCC) from WP5 (for ex-core application).

OB4 Objective:

- Demonstrate that laser powder bed fused in-core use case meets its safety-related function and operational requirements.

WP4 Achievements:

For in-core applications:

- Exposition to neutronic irradiation of some of the samples produced in WP2 (material from one machine, three different heat treatments and one HIP treatment),
- Fulfillment of tests on irradiated samples.

OB5 Objective:

- Assess the operational performance of ex-core AM components regarding safety-related function and operational requirements.

WP5 Achievements:

For ex-core applications:

- Manufacture an additive manufacturing ex-core component (valve body),
- Fulfillment of Non-Destructive Tests (NDT) on the part,
- Fulfillment of final functional tests on the part,

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- Fulfillment of thermal aging tests on samples produced in WP2 (material from four different machines, three different heat treatments and one HIP treatment),
- Fulfillment of Stress Corrosion Cracking (SCC) tests on samples produced in WP2 (material from four different machines, three different heat treatments and one HIP treatment).

OB6 Objective:

- Disseminate and prepare the exploitation of results with nuclear industries and regulatory bodies in support to codification and industrialisation of AM.

WP6 Achievements:

- Project summary, achievements and perspectives,
- Publishing of scientific papers,
- Presentation of NUCOBAM achievements to several international events.

1.2. Summary of concepts used in the NUCOBAM project needing to be reconsidered for future nuclear codes

Based on 4 years long project experience, it appears that the following concepts or ideas defined at the early stages of the NUCOBAM project may need to be refined or reconsidered for future nuclear codification activities:

- **Terminology:** The use of the term “Stability” in NUCOBAM may be misunderstood as it does not deal with demonstrating the process stability in time but, instead, with demonstrating the homogeneity of the material quality fused within the manufacturing volume of the machine on one single platform. Therefore, the term “**Stability platform**” could be replaced by “**Homogeneity platform**” to avoid any confusions,
- **Process Qualification:** Qualification focused on product validation (“part qualification”) was used in NUCOBAM based on history from other conventional manufacturing processes and is convenient only for small series of PBF-LB/M productions. Another aspect has not been examined in Nucobam and may be interested: to distinguish “**Process qualification**” from “**Part qualification**”. “Process qualification” does make sense economically for PBF-LB/M process for production of various large series of parts, as in medical or aeronautical fields. When applicable, several “Part qualifications” could then be supported by a generic “Process qualification”, thus reducing Non-Recurring Costs (NRC) of each individual “Part qualification”,
- **Shop Qualification:** This aspect has not been applied in the Nucobam project. The requirements addressing the “**Shop qualification**” for PBF-LB/M process could be detailed further, in line with standards **NF EN ISO/ASTM 52920** and **ISO/ASTM 52930**. During the “Shop Qualification”, the manufacturer must demonstrate the robustness of the process parameters, their exhaustivity and their tolerances (upper and lower limits) and ensure compliance with the material / part quality and performance requirements. During the “Shop Qualification”, the manufacturer must also demonstrate the process repeatability through extensive experience using PBF-

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LB/M process and machines for several years in production, following a management system compliant with quality assurance requirements,

- **Period of validity:** Add a requirement defining a period of validity (2 years? More?) for each qualification; i.e. Shop Qualification, Process Qualification, Part Qualification, Operator Qualification…
- **Powder:** Add a requirement defining the minimal conditions allowing the part manufacturer to mix or blend several powder batches during production. The following conditions shall be considered in the discussions: history of reused powder availability, sieving procedure availability, blending procedure availability, availability of intermediate and final powder analysis results fully compliant to the applicable powder specification, Customer agreement needed, etc,
- **Manufacturing:** Clarify that every platform built shall be manufactured as per a specific p-AMPS/AMPS document, since positioning of parts or samples on a manufacturing platform is unique and corresponds to a unique machine program number. The other process parameters of the AMPS remain identical for every platform built within the same domain of qualification. Current NUCOBAM wording is not specific enough: several platforms of different compositions may be manufactured with the same AMPS,
- **Testing:** Confirm that testing samples at mid-height on the manufacturing platforms is relevant. For metallography and mechanical testing, bottom and full height samples may seem sufficient to cover the entire manufacturing volume,
- **Testing:** Confirm that production of 45° angled test specimen (for tensile and toughness) is relevant. Industrial practice tends to test only X, Y and Z axis,
- **Testing:** Clarify the type of corrosion tests requested and the rational for requesting the test (e.g. intergranular corrosion may be useful for product acceptance to verify that the heat treatment has been done correctly),
- **Testing:** Add a requirement requesting that the nature, location and number of test samples at each stage (Homogeneity, Repeatability, Qualification, Series production…) on the different manufacturing platforms areas shall be agreed between the Manufacturer and the Customer,
- **Testing:** The NUCOBAM project focused on testing density, but density testing does not replace metallographic analysis. Indeed, many types of defects (other than porosity) are detected by metallographic testing instead of density testing. Metallographic analysis allows to characterize precisely every type of defects on a material section. Instead, density testing provides an average value over the volume of the sample, only for porosities and without information relative to their shapes or location within the sample's volume. Therefore, a requirement could be added requesting that a sufficient number of metallographic samples shall be produced on the manufacturing platforms at each stage: Homogeneity, Repeatability, Qualification, Series production,
- **Acceptance Criteria:** The NUCOBAM acceptance criteria have been proposed at the beginning of the project based on assumptions, engineering judgments, and partially from AWS D20.1 and ASTM F 3184 standards. The criteria are relative to material quality and performances, homogeneity, repeatability and qualification, dispersion… These criteria need to be reconsidered and updated based on experience gathered from the NUCOBAM results, latest available standards, wider

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industrial production feedbacks on the latest available machines, and a defined statistic approach.

1.3. Fields of technical interests for future projects to come

Alike any project, NUCOBAM has its own limitations and did not cover all the fields of technical interest. The following topics have not been fully addressed within the NUCOBAM project, and could be included in future studies or projects to come:

- **List of Key Parameters for Powder Specification:** Evaluation of the influence of feedstock parameters (chemical composition, Particle Size Distribution, contamination, foreign objects…) on material / part quality and performance needs to be performed in order to define a list of robust feedstock acceptance criteria used in the powder specification. Feedstock acceptance criteria have not been addressed in great detail within the NUCOBAM project, as existing ASTM F 3184 standard has been used to purchase off-the-shelf powders on the market,
- **List of Key Parameters:** Definition of a detailed list of PBF-LB/M key process parameters, and classification of their degree of influence (primary or secondary) on material / part quality and performance. The NUCOBAM project only freezes the list of parameters used on each machine model without providing parameters values (manufacturer's confidentiality),
- **Parameters Process Window:** Evaluation of the process window for each PBF-LB/M parameter by defining its nominal value and upper / lower limits and ensuring compliance with the material / part quality and performance requirements. No parameters sensitivity and range of validity study has been done in the NUCOBAM project,
- **Library of Material Defects:** Definition of a library of material defects based on micrographic and NDT test results. No library of material defects has been done in NUCOBAM project,
- **Non-Destructive Testing (NDT):** NDT methods and associated criteria have not been fully evaluated within NUCOBAM project, and need to be addressed in future studies or projects. These NDT methods and criteria should also be suitable for complex shapes only achievable by PBF-LB/M manufacturing (e.g. internal cavities, heat exchangers inner pipes…),
- **Acceptance Criteria:** The NUCOBAM acceptance criteria have been proposed at the beginning of the project based on assumptions, engineering judgments, and partially from AWS D20.1 and ASTM F 3184 standards, and need to be reconsidered and updated based on sufficient test data. Therefore, future studies or projects need to include sample production campaigns generating sufficient test data in order to better define the acceptance criteria applicable to PBF-LB/M process. The criteria are relative to material quality and performances, homogeneity, repeatability and qualification, dispersion… These production campaigns should be done on a variety of industrial machines, using known (i.e. explicit) parameters and manufacturing conditions ensuring repeatability. Standard statistical approaches and rules should also be defined,
- **Material Database for Design Dimensioning:** Material performances database has not been not addressed within NUCOBAM project as not enough test data is

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available for each individual test condition. Robust material performances database from various machine types, known (i.e. explicit) parameters and manufacturing conditions, and with sufficient test data needs to be generated from future studies or projects. This material database is needed for design dimensioning and eventually for standardization purpose,

- **Multi-lasers technology:** The use of multi-lasers technology has not been addressed in great detail within the NUCOBAM project. Evaluation of the influence of multi-lasers parameters (overlap areas, gas flow, flumes and lasers interactions, lasers performances control…), on material / part quality and performance needs to be performed in order to define robust manufacturing requirements, adequate lasers settings verification, sufficient tests samples in multi-lasers areas and specific acceptance criteria,
- **Heat Treatment:** Define the minimal conditions allowing the part manufacturer to redo the heat treatment operation when first heat treatment has failed. Corrective heat treatment has not been addressed within the NUCOBAM project,
- **Assembly of Parts by Welding:** Assembly of PBF-LB/M parts by welding has not been addressed within the NUCOBAM project,
- **Future Materials:** Future studies or projects should address other material of interest in the nuclear industry for future PBF-LB/M components. In NUCOBAM project, only PBF-LB/M 316L stainless steel has been addressed,

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