NRC Technical Assessment of Additive Manufacturing – Laser Powder Bed Fusion

1. Introduction and Purpose

This document provides a Nuclear Regulatory Commission (NRC) technical assessment of the safety significance of the identified differences between additive manufacturing – laser powder bed fusion (LPBF) and traditional manufacturing methods and the aspects of LPBF not addressed by codes and standards or regulations. This assessment is primarily based upon the technical information and gap analysis developed by Oak Ridge National Laboratory (ORNL) in technical letter report (TLR), "Review of Advanced Manufacturing Techniques and Qualification Processes for Light Water Reactors – Laser Powder Bed Fusion Additive Manufacturing," (Agencywide Documents Access & Management System (ADAMS) Accession No. ML20351A217) [hereafter referred to as the "ORNL TLR"]. This assessment, combined with the ORNL TLR, highlights key technical information related to LPBF-fabricated components in nuclear power plants, and fulfills the deliverable for LPBF under Subtask 1A of the Revision 1 Advanced Manufacturing Technologies (AMT) Action Plan (ADAMS Accession No. ML19333B973).

2. NRC Identification and Assessment of Differences

This section describes the differences between an LPBF-fabricated component and a traditionally-manufactured component, assesses the safety significance of the identified differences, and identifies specific technical considerations related to LPBF-fabricated components. The safety significance of each identified difference in the context of this assessment refers to the impact on component performance, not overall plant safety. The overall impact to plant safety is a function of component performance and the specific component application, e.g., its intended safety function. The impact on plant safety is not included in this report as such an assessment would not be possible without considering a specific component application.

Staff identified the differences between LPBF fabrication and traditional manufacturing processes by reviewing the information and gap analysis rankings from the ORNL TLR, as well as other relevant technical information (e.g., NRC regulatory and research experience, technical meetings and conferences, codes and standards activities, Electric Power Research Institute and Department of Energy products and activities). The identified differences originated either as important aspects or gaps of the LPBF process or product performance as defined here:

- Important aspect: part of the AMT fabrication process or product performance that needs to be considered and carefully controlled during manufacturing (e.g. powder quality for LPBF)
- Gap: part of the AMT fabrication process or product performance that either lacks knowledge or understanding due to limited information/data

The results of this technical assessment are provided in two tables. Table 1 includes the material-generic differences for LPBF process and product performance compared to traditional manufacturing. Table 2 includes additional material-specific differences for 316L stainless steel, which is the alloy relevant to LPBF-fabricated nuclear applications with the greatest quantity of information currently available in the open literature. While Table 2 is based on the available information in the open literature for 316L, the differences identified in Table 2 involving material-specific properties and performance would likely need to be considered for any new material to be fabricated using LPBF. In general, an important need for any nuclear LPBF-fabricated component is material-specific data for the proposed processing and post-processing parameters to ensure adequate component performance in environment, including various properties (e.g., fracture toughness, tensile strength) and aging mechanisms (e.g., thermal aging, irradiation effects, and stress corrosion cracking [SCC]).

Tables 1 and 2 below identify and provide technical information for the LPBF process and product performance through the following columns:

- **Difference**:
  - **Corresponding ORNL Gaps**: Identification of corresponding gaps from Section 3.4 of the ORNL TLR.
- **Definition**: Brief description of LPBF process difference.
- **NRC Ranking of Significance:**
  - **Importance:** Impact on final component performance.
    - A *High* ranking would signify that the difference has a significant impact on component performance.
    - A *Medium* ranking would signify that the difference has a moderate impact on component performance.
    - A *Low* ranking would signify that the difference has a minimal impact on component performance.
  - **Knowledge / Manageability:** Description of how well-understood and manageable the difference is.
- **Technical Information**: Technical information for consideration of LPBF-fabricated components for use in nuclear power plants.

3. Codes and Standards

Section 3.5 of the ORNL TLR provides a comprehensive overview of the existing standards relevant to LBPF as well as a detailed analysis of standards identified as highly relevant to nuclear power plants (NPPs). The ORNL TLR indicates that three specific standards (AWS D20.1M, MSFC-STD-3717, and MSFC-STD-3716) “provide a reasonable basis for machine, process, and component inspection qualification procedures.” Although NRC staff has not reviewed these standards, we recommend close consideration of the approaches in those standards when developing codes and standards for LPBF for nuclear applications.

In addition, the ORNL TLR provides recommendations for areas where standards development is most needed to support LPBF-fabricated components for NPP applications. NRC staff generally agree with these recommendations. In particular, codes and standards development, and the corresponding research to support their development, would be most valuable in the following areas to support LPBF use in nuclear applications:

- Material-specific criteria for powder recycling and sieving should be developed to prevent powder degradation from significantly impacting final component performance.
- Adequately assessing microstructural and material property heterogeneity and developing statistically driven requirements for the number, location and orientation of

witness specimens required to quantify the effects of heterogeneity is an important area for codes and standards development. This should also consider the positive impact of post-processing, such as hot-isostatic pressing (HIP), on heterogeneity.

- Weld integrity and weldability, including pre- and post-weld heat treatments: additional data and codes and standards development are needed.

4. Summary and Conclusion

In this report, the staff has identified and assessed the material-generic differences for LPBF process and product performance as well as the material-specific differences for 316L stainless steel compared to conventional manufacturing. The staff has also identified gaps in existing codes and standards that should be addressed to support LPBF use in nuclear applications.

Table 1 –Technical Information – LPBF Generic

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking of Significance		Key Technical Information
		Importance	Knowledge / Manageability	
LPBF Machine Process Control (Software and File Control & Machine Calibration)	Machine process control includes the software controlling the scan strategy of the LPBF machine and the machine calibration to reliably fabricate components.	**Medium** Machine process control could have a moderate impact on final product performance.	Machine process control is very manageable with quality assurance (QA) including appropriate calibration.	• Control of LPBF file preparation is needed to ensure process control. Improper file control can significantly impact final product properties and performance and affect fabrication replication. • Machine calibration is vital for fabrication replication, particularly contamination minimization when recycling powder, ensuring correct laser power and beam shape, and atmospheric quality control in addition to geometric tolerances.
Powder Quality (Contamination Management, Powder Characterization, Sieving System)	Powder quality covers the important characteristics of the powder, such as composition and size distribution, and how it is managed in the production process prior to the build process (e.g., sieving, reuse, storage, contamination).	**High** Powder quality can have a significant impact on the final product performance.	Powder quality can be challenging to manage and the effects on final product performance are material specific. Powder quality is an area of active research to understand what the critical powder characteristics are for a given alloy and their impacts on product performance.	• Powder contamination is a critical issue that may adversely affect material properties and process by introducing oxides and changing chemical composition. • Powder should always be used after sieving, because unsieved powder may not be representative of composition as elemental composition and phases may not be uniformly distributed across the powder size range. • Powder re-use acceptance/rejection depends on routinely sampling and characterizing powder after sieving. The LPBF system, sieving system and maintenance of inert environment are all important factors that influence the amount of powder re-use that can be done safely. • For example, in 316L Si and Mn content in the powder can create oxides that have adverse effects on SCC growth rates. Consideration should be given on oxide content in powder acceptance (virgin and recycled) criteria.
LPBF Build Process Management and Control (Environmental Sensor Data, In-	Build process management and control includes monitoring parameters during fabrication using environmental	**Medium** Build interruptions and loss of process control can adversely impact product performance by	This issue is manageable with QA and the use of in situ monitoring and environmental sensor data.	• Build interruptions (planned and unplanned) can have a very significant impact on quality of the component and should be avoided. • In situ monitoring without feedback control can be used to identify issues in the build process in real time and may be used alone or in conjunction with other approaches to demonstrate process control.

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Situ Monitoring and Feedback, Planned and Unplanned Interruptions)	sensors, in-situ monitoring, and evaluating the effects of build interruptions.	creating defects, altering local material microstructure and properties, and creating warping and distortion due to changing the thermal distribution by cooling.	Regarding the use of in situ monitoring with feedback control designed to correct defects automatically during the build process, knowledge is relatively limited and still maturing.	• In situ monitoring with feedback control is still a developing area of research and should be carefully managed and strongly demonstrated if proposed for use during production. • While artificial intelligence (AI) is commonly used to flag defects for human review; lack of AI-flagged defects should not be interpreted as no existing defects. • One limitation of all build chamber surface monitoring methods is that only the top surface is observed.
Witness Specimens (Witness Specimens)	Witness specimens are test specimens that are fabricated concurrently with end-use components and used to provide confirmation of build quality and product performance.	**Medium** Witness specimens offer one approach to demonstrating process control by measuring properties from parts built coincidentally with service product.	Witness specimens are well-established for use to provide empirical evidence of incomplete spreading, delamination, or other events that may result in component rejection. However, the use of witness specimens for optimization and generating quantitative data for qualification is less well-established and could involve demonstration for the material and geometry of the final product.	• The most highly representative test specimens are obtained from end use component geometries o Geometry impacts, particularly thickness, on witness specimen microstructure and properties should be considered and addressed • Optimal witness specimen parameters (geometry, size, location, spatial orientation, and frequency) depends highly on the end use component geometry and the goal of the witness testing approach (e.g. monitoring build issues as part of process control or generating representative material properties data as part of process qualification). • When sectioning end-use geometries is not feasible, functional evaluations of end-use geometries such as burst tests are recommended in conjunction with simplified witness specimen geometries.
Post - Processing	Post-processing includes methods used after the initial	**High** Post-processing should make material	Post-processing heat treatments are commonly done for	• Post-processing heat treatments without HIP generally are designed to provide two benefits: stress relief and/or

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	product build, such as hot isostatic pressing and heat treatments, to improve material properties and performance by increasing density and reducing porosity.	properties and performance more homogeneous and similar to conventional forged materials and may significantly impact considerations related to the other LPBF-specific topics identified in lower rows.	LPBF and conventional materials and are fairly well-understood. Hot-isostatic pressing (HIP) is also a well-established method, but less commonly used for conventional materials where porosity is not a significant issue.	annealing, but likely have little impact on porosity or flaws. o Stress relief heat treatments will primarily reduce residual stresses from the as-built part without otherwise affecting the microstructure or properties. o Annealing heat treatments should greatly reduce or eliminate residual stress as well as coarsen the microstructure (to improve toughness) and reduce heterogeneity in microstructure and properties. • HIP may be beneficial for reducing residual stress, porosity, heterogeneity, and internal cracks, while also coarsening the microstructure (to improve toughness). • For all post-processing approaches, material-specific demonstration is important to identify adequate heat treatment or HIP parameters to achieve desired improvements in microstructure, properties, heterogeneity, porosity and fabrication flaws. • Post-processing may significantly impact considerations related to the other LPBF-specific topics identified in lower rows.
Local Geometry Impacts on Product Properties and Performance (LPBF Design Considerations, Geometry-Scan Strategy Interactions)	The geometry of the component and the heat transfer characteristics from the product build directly affect local microstructure (e.g., grain size and orientation), which can affect material properties and performance, including SCC susceptibility.	**High** Local geometry impacts can have a significant impact on product performance if not managed or addressed.	Local geometry impacts are highly dependent on the material and geometry of the final product. They can be managed through post-processing and sampling / witness specimens to measure the impacts.	• The role of geometry on local microstructure and properties is one of the key differences between LPBF produced components and conventionally produced ones. • Local geometry significantly impacts thermal profiles during fabrication, which affects the local microstructure and properties. o For example, a thin section with relatively rapid cooling rates will likely have a much finer microstructure than a thicker section with a slower cooling rate due to more surrounding material being melted. o As a result, local material properties such as strength, ductility and toughness will be affected by the variation in microstructure as a function of geometry. • Witness specimens can be used to assess local geometry impacts but should be carefully demonstrated to be applicable to the end-use geometry.

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				• Post-processing and/or scan strategy refinement have the potential to minimize the local geometry impacts, however, they can vary significantly based on the geometry and materials used • Varying processing parameters to be nonconstant and nonlinear is potentially another method to compensate for the effect of geometry and minimize local geometry impacts. This is a less mature approach and could benefit from additional research and demonstration.
Heterogeneity and Anisotropy in Properties (Material Property Sampling Methodology and Heterogeneity)	Heterogeneity and anisotropy generally manifest as different properties in the build direction relative to the other two directions due to the nature of the layer-by-layer build process. This impacts the microstructure and fabrication defect structure and generally creates poorer properties between build layers.	**High** Heterogeneity and anisotropy in LPBF fabricated components are a significant difference from conventional materials, which are largely isotropic, and can have a significant impact on product performance if not addressed in the design and fabrication process.	This effect is generally well-understood but requires specific measures to manage, whether through an appropriate sampling methodology or post-processing to help minimize this effect.	• Heterogeneity generally manifests with different properties in the build direction relative to the other two directions due to the nature of the layer-by-layer build process. This impacts the microstructure and fabrication defect structure and generally creates poorer properties between build layers. • Post-processing with appropriate parameters would be expected to make material properties and performance more homogeneous and similar to conventional forged materials. • For example, in as-fabricated and stress-relieved 316L, the variation in microstructure due to geometry also causes fatigue and SCC cracks to preferentially travel in the build direction should they initiate.
Residual Stress (Residual Stress – Warping, Cracking, and Delamination)	Residual stresses form during the LPBF build process and can lead to warping, cracking, and delamination if not properly managed.	**Medium** Residual stress and associated defects can have an impact on product performance.	There is significant knowledge on residual stress, including how to manage it through post-processing or NDE.	• High residual stress may result in warping, cracking, and delamination; however, these events typically can be visually detected. • In addition, residual stress can make the product susceptible to future degradation such as SCC or fatigue from the presence of high tensile residual stress on the surface. • Post-processing with appropriate parameters would be expected to relieve residual stress.

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Porosity (Porosity Measurement)	Porosity includes the size, distribution, and total volume of voids and pores in the LPBF component.	**High** Porosity can have a significant impact on product performance. By the nature of LPBF, the porosity may have smaller size and higher density than forged materials.	There is knowledge on how to manage porosity both in the build process and through post-processing.	• Porosity is known to adversely affect fatigue life, SCC, and IASCC, though the precise quantitative impact depends on the material and porosity characteristics (pore frequency, pore size, pore morphology, and total void fraction). • Machine parameters and scan strategy refinement have the potential to address porosity concerns; however, they may vary significantly based on the geometry and materials used. • For post-processing, HIP with appropriate parameters has been demonstrated to reduce porosity and produce properties more similar to conventionally forged materials.

Note 1: Discussion of the corresponding ORNL gaps can be found in Section 3.4 of the ORNL TLR (ADAMS Accession No. ML20351A217).

Table 2 –Technical Information – LPBF 316L Material-Specific

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking of Significance		Key Technical Information
		Importance	Knowledge / Manageability	
Tensile Properties (Tensile Properties)	Tensile properties	**Low** Failure due to tensile overload is not a common failure mode in nuclear components and no more likely in LPBF materials due to their similar or superior tensile properties.	316L LPBF materials have generally sufficient data showing similar or superior tensile properties compared to similar forged materials.	• High porosity would likely degrade tensile performance but would have a greater impact on other material properties.
Initial Fracture Toughness (Fracture Toughness)	Initial fracture toughness refers to the material's starting fracture toughness upon entering service after fabrication.	**High** Low initial fracture toughness can lead to brittle component failure if not adequately managed.	There is limited data on fracture toughness for 316L LPBF materials. Post-processing should improve fracture toughness and minimize any difference.	• Limited data on 316L LPBF materials have shown significantly lower initial fracture toughness depending on post-processing than similar forged materials. • Data in representative environments is important to demonstrate that fracture toughness will be adequate to meet component design assumptions. • Post-processing with appropriate parameters would be expected to improve fracture toughness.
Thermal Aging (Aging and Irradiation Degradation)	Thermal aging refers to the reduction in fracture toughness after significant time at elevated temperature, which is a known aging mechanism for stainless steels containing significant levels of ferrite.	**High** Thermal aging can lead to brittle component failure if not adequately managed.	NRC is not aware of any significant data on thermal aging behavior of 316L LPBF materials. However, this issue can be managed by assuming a very conservative toughness value for design and flaw evaluation purposes until sufficient data can be generated.	• Data in representative environments is important to demonstrate that fracture toughness does not degrade excessively due to thermal aging and will be adequate to meet component design assumptions. • Post-processing with appropriate parameters would be expected to make material properties and performance more similar to conventional forged materials.

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SCC (SCC and IASCC)	SCC refers to stress corrosion crack initiation and growth of susceptible materials under roughly constant stress operating conditions due to the corrosive environment.	**High** SCC can lead to component failure if not adequately managed.	Very limited data exists on SCC behavior of 316L LPBF materials, which is a known degradation mode in LWRs.	• Data in representative environments is important to demonstrate that changes in material performance due to SCC will not be degraded to a greater degree in LPBF materials than forged materials. • Post-processing with appropriate parameters would be expected to make material properties and performance more similar to conventional forged materials.
Fatigue (Fatigue)	Fatigue refers to the initiation and propagation of cracks due to cyclic loading with or without environmental effects playing a significant role in the process.	**Medium** While fatigue can be a concern and lead to component failure, it is generally addressed conservatively through design standards and has not generally led to many safety-significant failures or flaws.	Limited data is available in the literature on the fatigue life of a LPBF materials compared to conventionally manufactured materials.	• Surface roughness is known to be a greater issue with LPBF materials and can reduce fatigue life. • Fatigue properties are strongly dependent on post-processing heat treatment and component porosity. • Data in representative environments is important to support fatigue calculations including environmentally-assisted fatigue (EAF) in LPBF materials.
Irradiation Effects (SCC and IASCC, Aging and Irradiation Degradation)	Irradiation effects refers to the impact of neutron irradiation on various aspects of material properties and performance, including, but not limited to, loss of fracture toughness, IASCC, and void swelling.	**High** Irradiation effects are a highly relevant issue to address for irradiated reactor internals components in LWRs, which can lead to premature component failures.	Very limited data exists on irradiation effects, particularly neutron irradiation, on the behavior of 316L LPBF materials.	• Data in representative environments is important to demonstrate that irradiation effects will not be significantly greater in LPBF materials than forged materials. • Post-processing with appropriate parameters would be expected to make material properties and performance more similar to conventional forged materials.
Weld Integrity	Weld integrity refers to the properties and performance of the	**High** Welds can be a location of degradation and may behave	NRC is not aware of any significant data on weld integrity for of 316L LPBF materials.	• Data in representative environments is important to demonstrate that welds with LPBF base

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	weld and surrounding heat-affected zone.	significantly differently with LPBF materials.		materials will perform similarly to those with conventionally manufactured base materials.
Weldability / Joining (Weldability)	Weldability refers to the ability to successfully weld a material to another component without unacceptable defects.	**Medium** Weldability is a concern for the licensee but should not greatly impact component performance as long as satisfactory welds passing Code requirements can be made.	NRC is not aware of any significant data on weldability of 316L LPBF materials.	• Limited data shows a narrower weld parameter range may be appropriate for LPBF 316L.

Note 1: Discussion of the corresponding ORNL gaps can be found in Section 3.4 of the ORNL TLR (ADAMS Accession No. ML20351A217).