NRC Technical Assessment of Additive Manufacturing—Laser-Directed Energy Deposition

1. Introduction and Purpose

This document provides a U.S. Nuclear Regulatory Commission (NRC) technical assessment of the impact on component performance of the identified differences between additive manufacturing—laser-directed energy deposition (L-DED) and traditional manufacturing methods and the aspects of L-DED 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 a technical letter report (TLR) entitled, "Review of Advanced Manufacturing Techniques and Qualification Processes for Light Water Reactors—Laser-Directed Energy Deposition Additive Manufacturing" (Agencywide Documents Access & Management System (ADAMS) Accession No. ML21292A187) (hereafter referred to as the "ORNL TLR"). This assessment, combined with the ORNL TLR, highlights key technical information related to L-DED-fabricated components in nuclear power plants and fulfills the deliverable for L-DED under Subtask 1A of the "Action Plan for Advanced Manufacturing Technologies (AMTs), Revision 1," dated June 23, 2020 (ADAMS Accession No. ML19333B973).

2. NRC Identification and Assessment of Differences

This section describes the differences between an L-DED-fabricated component and a traditionally manufactured component, assesses the impact that the identified difference has on component performance, and identifies specific technical considerations related to L-DED-fabricated components. The overall impact to plant safety (e.g., safety significance) is a function of component performance and the specific component application, such as its intended safety function. This report does not include the impact on plant safety, as such an assessment would not be possible without considering a specific component application.

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

- important aspect: part of the AMT fabrication process or component performance that needs to be considered and carefully controlled during manufacturing (e.g., powder quality for the laser powder directed energy deposition [LP-DED] process)
- gap: part of the AMT fabrication process or component performance that is not well known or understood due to limited information and data

Two tables show the results of this technical assessment. Table 1 includes the material-generic differences for the L-DED process and component performance compared to traditional manufacturing. Table 2 includes additional material-specific differences for 316L stainless steel, which is the alloy relevant to L-DED-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 stainless steel, 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 L-DED. In general, any nuclear L-DED-fabricated component needs to have material-specific data for the proposed processing and post-processing parameters to ensure adequate component performance in its environment, including various properties (e.g., fracture toughness, tensile strength) and aging mechanisms (e.g., thermal aging, irradiation effects, and stress-corrosion cracking (SCC)). It is important to note that the feedstock (i.e., powder vs. wire) may impact the differences listed in the tables. Tables 1 and 2 note the impact that the feedstock has on a specific difference, as appropriate.

The following columns in Tables 1 and 2 identify and provide technical information on the L-DED process and component performance:

- **Difference:**
  - **Corresponding ORNL Gaps:** Identification of corresponding gaps from Section 3.4 of the ORNL TLR.
- **Definition:** Brief description of the difference with the L-DED process.
- **NRC Ranking:**
  - **Importance:** Impact on final component performance considering the likelihood of occurrence or magnitude of degradation in conjunction with the ease of detection or ability to mitigate.
    - 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.
- **Key Technical Information:** Technical information for the consideration of L-DED-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 L-DED as well as a detailed analysis of standards identified as highly relevant to nuclear applications. Significantly fewer standards are available for L-DED than for laser powder bed fusion (LPBF). One standard, American Welding Society (AWS) D20.1M, “Specification for Fabrication of Metal Components using Additive Manufacturing,” is generic to both LPBF and L-DED and may serve as a reasonable starting point for the consideration and development of codes and standards for L-DED for nuclear applications.

In addition, Table 15 from the ORNL TLR identifies several LPBF-specific standards that have no L-DED equivalents to date. These LPBF standards cover a range of important topics that should also be addressed for L-DED, including the following:

- design (LPBF specific: International Standards Organization (ISO)/American Society for Testing and Materials (ASTM) 52911-1:2019, “Additive manufacturing—Design—Part 1: Laser-based powder bed fusion of metals”)
- 316L stainless steel composition and tensile specifications (LPBF specific: ASTM F3184-16, “Standard Specification for Additive Manufacturing Stainless Steel Allow (UNS S31603) with Powder Bed Fusion”)

- process control (LPBF specific: MSFC-SPEC-3717, “Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes”; ASTM/ISO 52904:2019, “Additive manufacturing—Process characteristics and performance—Practice for metal powder bed fusion process to meet critical applications”)
- material property evaluation specifications (LPBF specific: MSFC-STD-3716, “Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals”)
- thermal post-processing (LPBF specific: ASTM F3301-18a, “Standard for Additive Manufacturing—Post Processing Methods—Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion”)

In general, the ORNL TLR recommendations emphasize that “properties and microstructure cannot be extricated from the geometry and scan strategy.” Therefore, the codes and standards approach for L-DED should focus on establishing a consistent process for component qualification that recognizes that geometry affects material properties and performance and allows the process to vary the geometry while still maintaining qualification. The use of in-process data combined with destructive sampling and modeling and simulation tools may be one approach that could enable the qualification process to be robust and aligned with the unique aspects of L-DED and other AM technologies.

4. Summary and Conclusion

In Tables 1 and 2 of this report, the staff has identified and assessed the material-generic differences for the L-DED process and component performance as well as the material-specific differences for 316L stainless steel compared to conventional manufacturing. The staff also discussed gaps in existing codes and standards that should be addressed to support L-DED use in nuclear applications.

Table 1 Technical Information—L-DED Generic

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking		Key Technical Information
		Importance	Knowledge/ Manageability	
L-DED Machine Process Control (Software and File Control, L-DED Machine Calibration)	Machine process control includes the software controlling the scan strategy of the L-DED machine and the machine calibration to reliably fabricate components.	**Medium** Machine process control could impact final component performance, but it is expected to be managed through appropriate quality assurance (QA)provisions.	Machine process control is very manageable with QA including appropriate calibration.	• Control of L-DED files is needed to ensure process control. Improper file control can significantly impact final component properties and performance and affect fabrication replication. Cybersecurity, database traceability, management of software updates, and similar items are highly important to ensuring end-use component quality. • Machine calibration is vital for fabrication replication, particularly ensuring correct feedstock deposition parameters, laser power, laser spot size, travel speed, and atmospheric quality control in addition to geometric tolerances. For LP-DED, this includes contamination minimization if recycling powder.
Powder Feedstock Quality (Contamination Management for LP-DED, Feedstock Characterization, Powder Reuse Management)	Powder quality covers the important characteristics of the powder, such as composition and size distribution, and how it is managed in the production process before the build process (e.g., sieving, reuse, storage, contamination).	**High** Powder quality can have a significant impact on the final component performance and knowledge/ manageability challenges.	Powder quality can be challenging to manage, and the effects on final component performance are material specific. Powder quality is an area of active research to understand the critical powder characteristics for a given alloy and their impacts on component performance. Powder also has more variables to control, and industry has less experience with it as compared to wire feedstock.	• Detailed powder characterization and control, preventing powder contamination, and maintenance of an inert gas environment are important factors in ensuring powder quality and reducing powder variability. • Powder contamination is a critical issue that may adversely affect material properties and process by introducing oxides and changing chemical composition. • Thorough cleanliness activities, dedication of LP-DED machines to specific alloys, and periodic replacement of feedstock conveying tubes and components can address powder contamination. • LP-DED can achieve high powder utilization exceeding 90 percent in some cases, which makes powder reuse less essential than in LPBF. • Powder reuse can provide substantial cost benefits but can introduce significant variability in powder composition. Powder characterization and the establishment of associated acceptance criteria may be warranted to reuse powder, especially for safety-significant components.

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking		Key Technical Information
		Importance	Knowledge/ Manageability	
Wire Feedstock Quality (Feedstock Characterization)	Wire quality covers the important characteristics, such as wire composition and diameter and how it is managed in the production process before the build process (e.g., storage).	**Medium** Wire quality can have a significant impact on the performance of the final component, but wire generally involves fewer variables and uncertainties than powder.	The ability to ensure the conformance of welding consumables to applicable standards is well established for industrial welding applications, with a lengthy history of established quality control.	• Laser wire directed energy deposition (LW-DED) applications almost always use welding wire feedstock certified by the manufacturer to conform to AWS or ISO standards for the specific alloy and wire product in question. • There is a long-established history of ensuring welding consumables conform to applicable standards for industrial welding applications. • Wire chemistry and processing path must be tightly controlled. • Contamination concerns are well understood and are less of a concern than for powder feedstock.
L-DED Build Process Management and Control (L-DED Environmental Sensor Data, In Situ Monitoring and Feedback, Planned and Unplanned Build Interruptions, Data Management)	Build process management and control includes monitoring parameters during fabrication using environmental sensors, in situ monitoring, and evaluating the effects of build interruptions.	**Medium** Build interruptions and loss of process control can adversely impact component performance by creating defects, altering local material microstructure and properties, and creating warping and distortion due to changing the thermal distribution by cooling.	This issue is manageable with QA and the use of in situ monitoring and environmental sensor data. Knowledge is relatively limited and still maturing on the use of in situ monitoring with feedback control designed to correct defects automatically during the build process.	• Build interruptions (planned and unplanned) can have a very significant impact on component quality 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 in conjunction with other approaches to demonstrate process control. • In situ monitoring with feedback control is still a developing area of research and should be carefully managed and its effectiveness definitively demonstrated if proposed for use during production. • Management, storage, retrieval, and analysis of the data generated during the L-DED process are critical for accelerating process optimization, although guidance for the proper identification, handling, and evaluation of this information is still under development.
Witness Specimens	Witness specimens or witness coupons are test specimens that are fabricated concurrently with e	**Medium** Witness specimens offer one approach to demonstrating process control by	Witness specimens may be useful for identifying build issues such as delamination or other	• The most highly representative test specimens are obtained from end-use component geometries. ○ Geometry impacts, particularly thickness, on witness specimen microstructure and properties should be considered and addressed.

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking		Key Technical Information
		Importance	Knowledge/ Manageability	
	nd-use components and used to confirm build quality and component performance.	measuring properties from parts built coincidentally with the service component.	events that may result in component rejection. However, the use of witness specimens for optimizing and generating quantitative data for qualification is less well established and could involve demonstration that the specimen is representative of the final component.	• Optimal witness specimen parameters (geometry, size, location, spatial orientation, and frequency) depend 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 the relationship between the acceptability of the end-use geometries (e.g., burst tests, inspections) and the use of simplified witness specimen geometries would need to be demonstrated.
Thermal Post-processing	Thermal post-processing includes methods used after the initial component build that involve elevated temperatures, such as hot isostatic pressing (HIP) and heat treatments, to improve material properties and performance by increasing density and reducing porosity.	**High** Thermal post-processing should make material properties and performance more homogeneous and similar to those of conventional forged materials and may significantly impact considerations related to the other L-DED-specific topics identified in lower rows. Conversely, component performance may	Post-processing heat treatments are commonly done for L-DED and conventional materials and are fairly well understood. HIP is also a well-established method, but it is less commonly used for conventional materials where porosity is not a significant issue.	• Post-processing heat treatments without HIP generally are designed to provide two benefits, stress relief or annealing (or both), but they likely have little impact on porosity or flaws. ○ Stress-relief heat treatments will primarily reduce residual stresses from the as-built part without otherwise affecting the microstructure or properties. ○ 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 thermal 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. • Thermal post-processing may significantly impact considerations related to the other L-DED-specific

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking		Key Technical Information
		Importance	Knowledge/ Manageability	
		be degraded if thermal post-processing is not used.		topics identified in lower rows (e.g., porosity, residual stress, initial fracture toughness).

Local Geometry Impacts on Component Properties and Performance
 	
(L-DED Design Considerations, Geometry-Scan Strategy Interactions, Inspection of Fabricated Components)
	The geometry of the component and the heat transfer characteristics from the component 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 component performance if not managed or addressed.	Local geometry impacts are highly dependent on the material and geometry of the final component. 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 L-DED-produced components and conventionally produced ones.
				• Local geometry significantly impacts thermal profiles during fabrication, which affects the local microstructure and properties.
				  ○ 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 because more surrounding material is melted.
				  ○ As a result, the variation in microstructure as a function of geometry will affect local material properties such as strength, ductility, and toughness.
				• Post-processing and scan strategy refinement have the potential to minimize the local geometry impacts; however, the effects on properties and performance can vary significantly based on the geometry and materials used.
				• If used, witness specimens representing the thinnest section are needed to bound the material properties of the component.
				• The advantages of L-DED to fabricate components with as-built internal features can make the inspection of the component features more difficult.

Heterogeneity and Anisotropy in Properties (Material Property Sampling	Heterogeneity and anisotropy generally manifest as different properties in the build direction	**High** Heterogeneity and anisotropy in L-DED-fabricated components differ significantly from	This effect is generally well understood but requires specific measures to manage, whether	• 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.

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking		Key Technical Information
		Importance	Knowledge/ Manageability	
Methodology, Heterogeneity)	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.	those in conventional materials, which are largely isotropic, and can have a significant impact on component performance if not addressed in the design, fabrication, or post-fabrication process.	through an appropriate sampling methodology (e.g., witness specimens) or thermal post-processing, to help minimize this effect.	• Thermal post-processing with appropriate parameters would be expected to make material properties and performance more homogeneous and similar to those of conventionally forged materials. • For example, in as-fabricated and stress-relieved 316L stainless steel, the variation in microstructure due to geometry causes preferential crack growth directions for fatigue cracks.
Residual Stress (Residual Stress Warping, Cracking, and Delamination)	Residual stresses form during the L-DED build process and can lead to warping, cracking, and delamination if not properly managed.	**Medium** Residual stress and associated defects can negatively impact component performance.	There is significant knowledge related to managing the potential negative impacts of residual stress, including through optimizing the build process, post-processing, or inspection.	• L-DED components typically experience significant as-fabricated residual stress. • High residual stress may result in warping, cracking, and delamination; however, these events typically can be detected visually. • In addition, residual stress can make the component susceptible to future degradation such as SCC or fatigue from the presence of high tensile residual stress on the surface. • Thermal post-processing with appropriate parameters would be expected to relieve residual stress.
Porosity (Porosity Measurement)	Porosity includes the size, distribution, and total volume of voids and pores in the L-DED component.	**High** Unacceptable levels of porosity can have a significant impact on component performance. By the nature of L-DED, the porosity may have smaller size and higher density	Techniques to manage porosity in the build process are known, but porosity can be challenging to mitigate through thermal post-processing.	• Porosity is known to adversely affect fatigue life, SCC, and irradiation-assisted stress-corrosion cracking (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.

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking		Key Technical Information
		Importance	Knowledge/ Manageability	
		than in forged materials.		• Porosity is more prevalent in LP-DED than LW-DED due to the internal porosity and trapped gas in powder feedstock that does not exist in wire feedstock. • For post-processing, HIP with appropriate parameters has been demonstrated to reduce porosity and produce properties more similar to those of conventionally forged materials.
Surface Finish (Surface Roughness)	Surface finish (or surface roughness) refers to the measure of the texture of the part surface. Processing techniques that are conducted to improve surface finish include machining, shot peening, and chemical treatment.	**High** Surface finish can have a significant impact on component performance, particularly through increased susceptibility to fatigue and SCC initiation.	L-DED components can be finished using traditional post-processing techniques.	• Surface roughness is generally greater in as-built L-DED parts than in similar forged materials. ○ The layer-by-layer nature of LP-DED, combined with the tendency to weld unmelted powder particles to the component surfaces, produces a rough outer surface in LP-DED. ○ LW-DED typically results in a bead-like surface due to the layer-by-layer deposition but does not give the added roughness of attached particles. • Higher surface roughness can lead to reduced fatigue life and lower SCC and corrosion resistance. • Surface finish can be improved by post-processing such as subtractive machining or other surface treatments. • For components with complicated geometries, hybrid manufacturing approaches (iterating between additive and subtractive steps) may be necessary to reach all surfaces for post-processing.

Note 1: Section 3.4 of the ORNL TLR discusses the corresponding ORNL gaps.

Table 2 Technical Information—316L L-DED Stainless Steel 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 it is no more likely in L-DED materials due to their similar or superior tensile properties.	316L L-DED stainless steel materials have generally sufficient data showing similar or superior tensile properties compared to those of 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.	Limited data are available on fracture toughness for 316L L-DED stainless steel materials. Post-processing should improve fracture toughness and minimize any difference.	• Limited data on 316L L-DED stainless steel materials have shown significantly lower initial fracture toughness, depending on post-processing, than for similar forged materials. This may be due to porosity or other defects that may be reduced with optimized processing parameters and thermal post-processing. ○ However, 316L L-DED stainless steel is still expected to have adequate initial toughness. • Data in representative environments are important to demonstrate that fracture toughness will be adequate to meet component design assumptions. • Thermal post-processing with appropriate parameters would be expected to improve fracture toughness.
Thermal Aging	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	**High** Thermal aging can lead to brittle component failure if not adequately managed.	The NRC is not aware of any significant data on thermal aging behavior of 316L L-DED stainless steel materials.	• Data in representative environments are important to demonstrate that fracture toughness does not degrade excessively due to thermal aging and will be adequate to meet component design assumptions. • Thermal post-processing with appropriate parameters would be expected to make material properties and performance more similar to those of conventional forged materials.

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking of Significance		Key Technical Information
		Importance	Knowledge/ Manageability	
	significant levels of ferrite.			
SCC and Corrosion Resistance (SCC and IASCC, Corrosion Resistance)	SCC refers to stress-corrosion crack initiation and growth of susceptible materials under roughly constant stress operating conditions due to the corrosive environment. Corrosion refers to other corrosion processes that may be active in the environment.	**High** SCC can lead to component failure if not adequately managed. Local material characteristics (i.e., grain boundary chemistry and microstructure) may amplify differences with conventional materials not apparent in other tests (e.g., tensile).	Very limited data exist on SCC behavior of 316L L-DED stainless steel materials, although SCC is a known degradation mode in light-water reactors.	• Data in representative environments are important to demonstrate that material performance due to SCC will not be degraded to a greater degree in L-DED materials than in forged materials. • Post-processing with appropriate parameters would be expected to make material properties and performance more similar to those of conventional forged materials. • In 316L stainless steel, the silicon content in the powder can create oxides that have adverse effects on SCC growth rates. Acceptance criteria for powder (virgin and recycled) should consider oxide content.
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, other post-processing steps such as surface finishing, residual stress reduction, and HIP heat treatments can be used to improve fatigue susceptibility in many applications.	Limited data are available in the literature on the fatigue life of L-DED materials compared to conventionally manufactured materials.	• Without adequate post-processing, surface roughness is known to be a greater issue with L-DED materials and can reduce fatigue life. • Fatigue properties also depend on post-processing heat treatment and component porosity. • Limited data suggest high-cycle fatigue life may be reduced compared to that of conventional 316L stainless steel, while low-cycle fatigue life is comparable to that of conventional 316L stainless steel. • Stress-relieved (without annealing heat treatment) 316L L-DED stainless steel shows anisotropic fatigue strength and preferential crack growth directions due to the columnar microstructure. • Data in representative environments are important to support fatigue calculations,

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking of Significance		Key Technical Information
		Importance	Knowledge/ Manageability	
				including for environmentally assisted fatigue, in L-DED materials.
Irradiation Effects (SCC and IASCC, Irradiation-Assisted Degradation)	Irradiation effects refer 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 highly relevant to address for irradiated reactor internals components in light-water reactors, which can lead to premature component failures. Local material characteristics (i.e., grain boundary chemistry and microstructure) may amplify differences with conventional materials not apparent in other tests (e.g., tensile).	Very limited data exist on irradiation effects, particularly neutron irradiation, on the behavior of 316L L-DED stainless steel materials.	• Data in representative environments are important to demonstrate that irradiation effects will not be significantly greater in L-DED materials than in forged materials. • Post-processing with appropriate parameters would be expected to make material properties and performance more similar to those of conventional forged materials. • Current studies point to reduced irradiation-induced defects in L-DED components compared to those produced with conventional manufacturing. However, the understanding is very limited, and research is ongoing. Additional research is likely needed to understand performance differences.
High-Temperature, Time-Dependent Aging Effects (e.g., Creep and Creep-Fatigue)	High-temperature aging effects refer to any time-dependent aging mechanisms relevant to elevated temperatures (as discussed in American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 5), including creep and creep-fatigue.	**High** High-temperature, time-dependent aging effects are of high importance to component integrity for the elevated operating temperatures expected for many advanced reactor designs.	Very limited data exist on high-temperature, time-dependent aging effects for 316L stainless steel L-DED materials.	• For high-temperature operating environments (as discussed in ASME Boiler and Pressure Vessel Code, Section III, Division 5), data in representative environments are important to demonstrate that high-temperature, time-dependent aging effects in L-DED materials will be equivalent to or acceptable when compared to those in forged materials. • Post-processing with appropriate parameters would be expected to make material properties and performance more similar to those of conventional forged materials.

Difference (Corresponding ORNL Gaps)[1]	Definition	NRC Ranking of Significance		Key Technical Information
		Importance	Knowledge/ Manageability	
Weld Integrity	Weld integrity refers to the properties and performance of the weld and surrounding heat-affected zone.	**High** Welds can be a location of degradation and may behave significantly differently with L-DED materials.	The NRC is not aware of any significant data on weld integrity for 316L L-DED stainless steel materials.	• Data in representative environments are important to demonstrate that welds with L-DED base 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 but should not greatly impact component performance as long as satisfactory welds passing ASME Boiler and Pressure Vessel Code requirements can be made.	The NRC is not aware of any significant data on the weldability of 316L L-DED stainless steel materials. Existing welding standards to demonstrate weldability and accept final manufactured welds are expected to remain applicable for L-DED components.	• Very limited information has been published on the results of using traditional joining methods on L-DED components. • Higher oxygen content, residual stress, and microstructural segregation may affect the optimal parameters for welding on 316L L-DED stainless steel compared to on conventional 316L stainless steel. • Weldability should be demonstrated for L-DED materials, but the existing welding standards and demonstration processes should be sufficient.

Note 1: Section 3.4 of the ORNL TLR discusses the corresponding ORNL gaps.