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STANDARDS RESEARCH

Advanced Manufacturing for Small Modular Reactor Applications

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Authors

Oluwasegun (Emmanuel) Adesola, MSc., EIT, March Consulting Associates Inc.

Glen Crawford, B. Eng, March Consulting Associates Inc.

Lesley McGilp, P.Eng, MBA

Project Advisory Panel

Kevin Lee, CNSC

Lucian Ivan, CNL

Stephen Veldhuis, McMaster University

Andre Pelletier, OCNI

Jim Brown, BWXT

Richard Barnes, ANRIC Enterprises

Ron Oberth, RonOberth Consulting Inc.

Dragica Jeremic Nikolic, CSA Group

Larisa Logan, CSA Group

Robert Reipas, CSA Group (Project Manager)

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Abbreviations

AFCEN	French Association for Design, Construction, and Operation of Nuclear Equipment
AI	Artificial Intelligence
AM	Additive Manufacturing
AMMT	Advanced Materials and Manufacturing Technologies
AMSC	Additive Manufacturing Standardization Collaborative
AMT	Advanced Manufacturing Technique
ANSI	American National Standards Institute
ARQANE	Actions for Realization and Qualification in Nuclear
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATF	Accident Tolerant Fuel
ATLAS	Advanced Technology for Large Scale Hot Isostatic Pressing
AWS	American Welding Standard
BPVC	Boiler and Pressure Vessel Code
CANDU	Canada Deuterium Uranium
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (French Alternative Energies and Atomic Energy Commission)
CNL	Canadian National Laboratory
CNSC	Canadian Nuclear Safety Commission
CS	Cold Spray
CSAM	Cold Spray – Additive Manufacturing
DED	Direct Energy Deposition
DSA	Deterministic safety analysis
EASI-SMR	Ensuring Safety Innovations for SMRs
EB	Electron Beam
EBW	Electron Beam Welding
EPRI	Electric Power Research Institu
FAST	Future Advanced Structural Integrity
GMAAM	Gas Metal Arc Additive Manufacturing
GMA-DED	Gas Metal Arc Direct Energy Deposition
HAZ	Heat Affected Zone
HT	Heat Treatment
IAEA	International Atomic Energy Agency
IEEE	Institute of Electrical and Electronics Engineers

ISO	International Organization for Standardization
ITER	International Thermonuclear Experimental Reactor
LAS	Low Alloy Steels
LB	Laser Beam
LPBF	Laser Powder Bed Fusion
LWR	Light Water Reactor
MIC	Modular In-Chamber
MMR	Micro Modular Reactor
Nuclear AMRC	Nuclear Advanced Manufacturing Research Centre, UK
NASA	National Aeronautics and Space Administration
NDE	Non-Destructive Examination
NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
NRCAN	Natural Resources Cana
NUCOBAM	Nuclear Components Based on Additive Manufacturing
OCNI	Organization of Canadian Nuclear Industries
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
PBF	Powder Bed Fusion
PM-HIP	Powder Metallurgy – Hot Isostatic Pressing
R&D	Research and Development
RCC-M	Design and Construction Rules for Mechanical Components of Pressurized Water Reactor (AFCEN)
REGDOC	Regulatory Document
RPV	Reactor Pressure Vessel
SAE	Society of Automotive Engineers
SDO	Standards Development Organizations
SMR	Small Modular Reactor
SS	Stainless Steel
TCR	Transformational Challenge Reactor
TLR	Technical Letter Report
TSEBW	Thick-Section Electron Beam Welding
TWI	The Welding Institute Ltd, UK
US DOE	United States Department of Energy
US NRC	United States Nuclear Regulatory Commission
WAAM	Wire Arc Additive Manufacturing

Executive Summary

This research report assesses the role and readiness of advanced manufacturing technologies (AMTs) for application in Canada's nuclear industry, including for small modular reactors (SMRs). Its objective is to support the safe, cost-effective, and strategic adoption of AMTs by identifying key opportunities, reviewing the availability and applicability of existing standards, and highlighting both technical and systemic challenges to their adoption in the Canadian nuclear context. The assessment was achieved through a literature review, interviews with key interested parties, and a detailed standards review.

The study focused on five AMTs with current or emerging relevance to nuclear applications: cold spray, powder metallurgy-hot isostatic pressing, electron beam welding, laser-powder bed fusion, and directed energy deposition. Each technology was examined based on its maturity, current applications in other sectors, and potential uses in nuclear component manufacture, repair, and maintenance. Case studies and ongoing initiatives in Canada and internationally were also reviewed to illustrate progress and emerging best practices.

The review of relevant standards covered both Canadian and international frameworks, including CSA nuclear standards and AMT-specific international standards. Several CSA nuclear standards relevant to AMT use were identified, along with key AMT-specific standards and guidance documents that can be leveraged in nuclear contexts. However, gaps remain in both technical provisions and nuclear-specific requirements within existing AMT standards. The report also highlights ongoing efforts by standards development organizations and interested parties to advance AMT standardization for nuclear applications.

Through literature review and engagement with interested parties, the report identifies barriers to AMT adoption in the Canadian nuclear industry that may be mitigated, in part, by standardization. These include limited industry awareness, evolving quality system requirements unique to AMTs, and regulatory considerations.

To support broader AMT adoption, the report recommends the following for consideration:

- Developing Canadian AMT-specific standards and implementation guidelines
- Addressing AMT-specific considerations in relevant CSA nuclear standards
- Advancing targeted research and development to support AMT standards development

These efforts will require coordination among governments, utilities, regulators, suppliers, and other organizations.

Overall, while full-scale adoption of AMTs in the nuclear sector will take time, early and incremental steps are both feasible and recommended. With focused leadership and strategic collaboration, Canada can position itself as a leader in the safe, timely, and cost-effective deployment of AMTs in the nuclear sector, enhancing domestic supply chain resilience and long-term global competitiveness.



"A global resurgence in nuclear energy is underway, driven by urgent needs to decarbonize energy systems, strengthen energy security, and support economic growth."

1 Introduction

1.1 Background Information

A global resurgence in nuclear energy is underway, driven by urgent needs to decarbonize energy systems, strengthen energy security, and support economic growth. This renewed interest is not only revitalizing existing nuclear infrastructure but also accelerating the development of next-generation advanced reactor technologies and small modular reactors (SMRs).

Advanced reactors refer to a broad class of innovative nuclear designs that go beyond the capabilities of today's conventional light-water reactors (LWRs). These reactors incorporate innovative technologies, such as passive safety features, alternative fuel or coolant types (e.g., liquid metal, gas, molten salt), and higher operating temperatures [1]. Within this broader category, SMRs stand out for their smaller size, typically producing less than 300 MWe [2]. SMRs are intended to be factory-built in modules, then shipped and assembled on-site, offering a solution that reduces construction times, financing risks, and deployment barriers. Their size and flexibility make them well-suited for remote communities, industrial facilities, and regions with smaller grids or limited infrastructure.

As interest in advanced reactors and SMRs grows, so does the need to overcome key manufacturing challenges, not only for new builds but also for sustaining existing reactor fleets. Traditional manufacturing techniques can present challenges in meeting modern nuclear demands, including high-production costs, limited design flexibility, extended lead times, and difficulties in producing components with complex geometries. These challenges are magnified in advanced reactor and SMR designs, many of which are expected to operate under more demanding operating conditions, such as highly corrosive, high-temperature, and high-irradiation environments compared to traditional reactors [3]. Such conditions demand rapid advancement in both advanced materials and manufacturing processes. This is where advanced manufacturing offers potential.

Advanced manufacturing refers to production approaches that integrate innovative technologies to improve the efficiency, flexibility, and precision of manufacturing processes. It typically involves either producing existing products through new methods or applying well-established methods in novel ways [4]. Advanced manufacturing technologies (AMTs) have been adopted in many sectors, including aerospace, automotive, defence, and healthcare, to meet complex engineering demands. While definitions vary across these sectors, advanced manufacturing with respect to the nuclear industry has been defined as:

"Techniques and material processing methods that have not been utilized in manufacturing components for the nuclear industry and have yet to be formally standardized by the nuclear industry (e.g., through nuclear codes and standards or other processes resulting in nuclear regulatory approval/endorsement)" – United States Nuclear Regulatory Commission (US NRC) [5], [6].

AMTs offer several advantages over traditional manufacturing approaches [7]:

- Cost and Time Savings: Reduced production time and material waste, leading to faster turnaround and lower overall manufacturing costs.
- Enhanced Component Performance: Ability to produce complex, high-performance components with improved material properties.
- Design Flexibility: Enables innovative part designs with fewer constraints, including integrated components and optimized geometries that streamline assembly and functionality.
- Improved Quality and Reliability: Delivers precise, repeatable builds with fewer welds and joints, reducing failure risks and enhancing overall component integrity.
- Sustainability: Minimizes material waste and energy use, supports part repair instead of full replacement, and contributes to a lower environmental footprint.

Given these benefits, AMTs have value for emerging SMR deployments and for existing nuclear reactors, where aging components and supply chain gaps require modern solutions such as reverse engineering and "3D printing" of replacement components for obsolete parts. However, despite their promise, the adoption of AMTs in the nuclear industry has been gradual compared with other sectors. Contributing factors include low new-build activity, which offered limited opportunities for AMTs to penetrate established nuclear markets, and the adherence to known, safety-proven approaches, driven by stringent regulation and licensing requirements [7]. In a sector where safety and reliability are paramount, introducing new technologies demands a cautious approach.

To support the safe and effective adoption of AMTs in the nuclear sector, they must be supported by rigorous qualification and regulatory frameworks. This includes clear guidance throughout the manufacturing lifecycle, from design and process controls to part inspection and long-term performance assessment.

Currently, standards for AMTs remain limited and fragmented. International efforts are underway through organizations such as the American Society of Mechanical Engineers (ASME), the French Association for Design, Construction, and Operation of Nuclear Equipment (AFCEN), the International Organization for Standardization/American Society for Testing and Materials (ISO/ASTM), and the International Atomic Energy Agency (IAEA). However, additional updates to Canada's nuclear regulatory and standards framework may be necessary to fully address the technical considerations associated with AMTs and advanced reactor technologies. Doing so will be key to unlocking the full potential of AMTs for both near-term SMR deployment and the broader modernization of nuclear manufacturing, particularly in Canada.

1.2 Report Objectives

The key objectives of this research report are to:

- Provide an overview of relevant AMTs, their stages of technology maturity, and their anticipated applications within the Canadian nuclear industry
- Review and benchmark Canadian and international initiatives and standards relevant to the use of AMTs
- Assess the applicability of existing Canadian and international nuclear standards related to AMTs
- Identify challenges and opportunities in existing Canadian standards for the use of AMTs and develop recommendations to address these issues, including specifically for incorporating advanced manufacturing-specific considerations into requirements and descriptions for special processes

The overarching objective is to identify opportunities for developing new technical standards or adapting existing standards used in other sectors. These efforts aim to support the safe, timely, and cost-effective deployment of AMTs by Canada's nuclear supply chain, thereby contributing to the successful rollout of SMRs and the broader modernization of nuclear manufacturing in Canada.

1.3 AMT Scope

Since advanced manufacturing broadly encompasses activities that integrate information, automation, software, sensing, networking, and interoperability to innovate manufacturing processes, some AMTs integrate physical manufacturing techniques with digital technologies like artificial intelligence (AI) and the Internet of Things to create a more efficient and interconnected manufacturing ecosystem [4], [7]. Digital solutions, whether connected to AMTs or independent of them, are driving a significant change and opportunity in the nuclear sector. This study acknowledges the importance of digital technologies and their interconnections with physical AMTs (briefly discussed in Appendix G) but focuses primarily on "physical AMTs" directly relevant to the fabrication, repair, and enhancement of nuclear components, particularly in pressure and non-pressure boundary applications. Physical AMTs are hereafter referred to as AMTs.

2 Methodology

A literature review and targeted engagement with industry interested parties were conducted to develop a comprehensive overview of the AMTs under consideration for nuclear applications, along with ongoing AMT initiatives.

2.1 Literature Review

The literature review focused on publicly available sources from technical, regulatory, industry, and research domains. Key sources included:

1. Technical letter reports (TLRs) for various AMTs developed under the US NRC AMT Program, primarily prepared by United States Department of Energy (DOE) national laboratories
2. Presentations and proceedings from past conferences and events such as the Canadian Nuclear Society Disruptive, Innovative, and Emerging Technologies, Nuclear Components Based on Additive Manufacturing (NUCOBAM) Final Meeting, and US NRC AMT workshops
3. Scientific journal articles and research and development (R&D) publications from leading research institutions (e.g., Electric Power Research Institute, Oak Ridge National Laboratory (ORNL), Nuclear Advanced Manufacturing Research Centre), focusing on AMT applications and readiness
4. News releases, position papers, and industry updates from organizations such as the Nuclear Energy Institute (NEI), IAEA, Organization of Canadian Nuclear Industries, and nuclear technology vendors (e.g., Westinghouse, Rolls-Royce, Framatome, EDF)

Findings from the literature review informed the selection of five AMTs (outlined in Section 3.1), which were evaluated based on the four key aspects, detailed in Section 3.2:

1. Technology Overview: Core principles, key features, and benefits of the AMT
2. Technology Maturity and Current Applications: Maturity level and applications across non-nuclear sectors
3. Potential Nuclear Applications: Potential benefits in nuclear manufacturing, including progress updates from R&D initiatives and target materials/components
4. Nuclear-Specific Initiatives: Industry initiatives specific to nuclear applications of the AMT

2.2 Standards Review

2.2.1 Canadian Standards Review

The Canadian standards review for this study builds on a preliminary standards assessment conducted by a CSA task force, which considered seven key topic areas: design requirements, process qualification, material requirements, qualification of additive manufacturing (AM)-produced components, acceptance criteria, inspection requirements, and aging management.

The review involved an initial environmental scan for Canadian AMT-specific standards. This was followed by a review of all of the existing CSA nuclear standards [8], which include:

- CSA N285 series: CANDU nuclear power plant pressure-retaining systems and components
- CSA N286: Management systems
- CSA N287 series: Concrete containment structures
- CSA N288 series: Environmental management
- CSA N289 series: Seismic design
- CSA N290 series: Reactor control systems, safety systems, and instrumentation
- CSA N291: Safety-related structures
- CSA N292 series: Radioactive waste management
- CSA N293: Fire protection
- CSA N299 series: Quality assurance program requirements for the supply of items and services for nuclear power plants

The standards included within the above nuclear series amount to a total of approximately 70 individual standards, encompassing technical, quality assurance (QA), and management system standards. While these standards were not developed specifically for AMTs, the review focused on their applicability to AMTs, identifying the following:

- Standards whose content might either restrict or accommodate AMT adoption and application
- Topics in the standards that intersect with AMT considerations, such as materials, design, qualification, aging, QA, and quality control (e.g., inspection requirements)
- Plant equipment or components covered by the standards that could potentially be manufactured using AMTs
- Areas where potential changes to the standards may be required to accommodate AMTs

2.2.2 International Standards Review

Unlike the Canadian standards review, which identified intersections between AMT considerations and existing Canadian nuclear standards, the international review focused on international standards developed specifically for AMTs, to assess their applicability to nuclear applications. Relevant international AMT standards were identified from a literature review and an environmental scan of available AMT standards across different sectors, incorporating insights from industry roadmaps, TLRs and draft AMT guidelines from the US NRC AMT Program, and findings from relevant industry events and technical reports.

We evaluated each standard against a set of criteria (outlined in Table 1) relevant to nuclear AMT component qualification and production. These criteria were developed based on common elements in existing guidance, regulatory requirements, and industry best practices. Further details on the criteria and their application are summarized in Section 4.3.

Table 1: Criteria for standards evaluation

1. Scope	7. Qualification Testing
2. Personnel Qualification	8. Production Execution
3. Design Considerations	9. Post-processing Requirements
4. Feedstock Material Control	10. Part Inspection and Testing
5. AM Process Qualification	11. Nuclear-Specific Considerations
6. Equipment Qualification	12. Documentation and Traceability



To provide a structured and comparative assessment of identified relevant standards, appendices D, E, and F present detailed comparative analysis tables (tables D1, E2, and F2). These tables outline the extent to which each standard addresses the criteria in Table 1 and are colour shade-coded using the classification keys below for a high-level assessment:

- Not Addressed: No specifications provided in the standard for a given criterion (light grey)
- Partially Addressed: Some specifications provided for a given criterion, or references to other applicable standards (grey)
- Addressed: Provides detailed specifications for a given criterion (blue)

2.3 Interested Party Engagements

To complement the literature and standards review, interviews were conducted with key interested parties across nuclear and non-nuclear industries. A total of 13 individuals participated, representing a range of roles across:

- Nuclear technology vendors
- Nuclear suppliers
- Nuclear regulator
- Nuclear operator
- Advanced manufacturing technical experts

A total of seven one-on-one interviews were held to gather insights on:

- The most relevant AMTs for Canadian reactor deployments
- Barriers to AMT adoption in nuclear
- Gaps in existing standards and AMT qualification pathways
- Regulatory concerns with AMT adoption

These discussions informed the identification of priority areas, gaps, and recommendations presented in the report. The data collected during the interviews is used in an aggregated and anonymized format throughout the report to protect participant privacy.

3 Advanced Manufacturing Techniques (AMTs)

3.1 AMTs for Nuclear Applications

As demonstrated in other industries, AMTs promise significant efficiency gains and present a transformative opportunity for the nuclear sector. However, a critical step in their adoption is validating that these processes and their components meet the rigorous quality and performance requirements set by the industry and regulatory authorities. Many AMTs are still undergoing technical validation, and

the standards needed to define and qualify both the processes and the resulting components remain incomplete across most applications. Existing AMT standards may not fully apply to nuclear applications, underscoring the urgent need to develop robust AMT codes and standards. This need has prompted multiple industry initiatives supporting the safe integration of AMTs in nuclear applications, some of which are highlighted in subsection 3.1.1.

One such initiative, by the NEI in 2019, produced a "roadmap for regulatory acceptance of advanced manufacturing methods in the nuclear energy industry," identifying 16 AMTs of greater interest to the nuclear industry, described in Appendix A [5]. These techniques represent a broad range of innovative approaches that could transform nuclear manufacturing, each with unique characteristics and advantages. However, not all are immediately applicable or suitable for nuclear applications.

Based on recent developments and ongoing initiatives related to AMTs in the nuclear sector (see section 3.1.1), the focus on AMTs has narrowed to a smaller subset of techniques outlined in Table 2. This refinement appears driven by evolving industry interests and priorities, practical applicability to nuclear requirements, and other factors [9], [10]. It is important to note that labelling a technology as "advanced" does not necessarily equate to added value—cost-effectiveness and deployment timelines remain key considerations [10].

This study focuses on the five AMTs in Table 2, selected based on:

- Alignment with current industry interests
- Demonstrated interest from nuclear vendors
- Ability to address critical manufacturing challenges
- Technology readiness levels and existing applications
- Material demands associated with advanced reactors and SMRs
- Effort required to achieve nuclear qualifications [3], [7], [9]

These factors were informed by a comprehensive review of relevant literature, insights from recent industry conferences and events, and discussions with key industry players, including the project advisory panel. Table 2 also summarizes the drivers behind each technology's selection.

While these AMTs represent the most immediate deployment opportunities, other AMTs identified in earlier studies may also have future applications in nuclear component fabrication. For example, laser welding is relevant to nuclear applications but is not discussed in this report.

3.1.1 Advanced Manufacturing Initiatives in the Nuclear Industry

In response to increased interest in advanced manufacturing, several actions have been initiated across the nuclear sector. For instance:

- Nuclear regulatory bodies and government agencies worldwide have established several advanced manufacturing programs [9], [12], [13], [14].
- Various research labs and interested organizations are overseeing multiple ongoing R&D projects on AMTs [15], [16], [17], [18].
- Standards development organizations (SDOs) are launching specialized committees and working groups focused on developing standards for these techniques [19], [20].

These efforts are supported by significant public and private investment and reflect a global push to advance nuclear manufacturing capabilities.

While AMT initiatives are ongoing worldwide, available information indicates that most R&D activity is concentrated in Europe and North America. A review of current initiatives highlights key focus areas: closing gaps in AMT qualification and standardization, demonstrating technologies for fabricating components at various safety levels, supporting regulatory frameworks, developing strategic roadmaps and harmonization initiatives, and assessing nuclear supply chain readiness.

Table 2: AMTs selected for detailed analysis for nuclear applications

Process type	AMT	Drivers for adoption [7]
Surface modification/ coating	Cold spray (CS)	▪ Improved surface properties of nuclear components ▪ In-service repairs
Near-net shape manufacturing	Powder metallurgy – hot isostatic pressing (PM-HIP)	▪ Reduced lead time: elimination of welds, no tooling development required ▪ Reduced cost: reduced material wastage, reduced machining costs ▪ Improved material quality: homogenous, isotropic components ▪ Non-destructive examination (NDE) improvement: easy inspection of homogeneous components
Joining technique	Electron beam welding (EBW)	▪ Reduced welding cost and time ▪ Thick-section welding (sections typically greater than 1 in or 25 mm thickness [11]) ▪ Highly repeatable quality welds ▪ Minimal heat-affected zone (HAZ)
AM	Laser-powder bed fusion (L-PBF)	▪ Reduced lead time: rapid prototyping, reduced inventory, obsolete and replacement components, urgent parts (plant outage demands) ▪ Design flexibility: complex parts, advanced materials, in-situ process monitoring, parts with unique microstructures ▪ Reduced costs: decreased part count, reduced environmental footprint
	Direct energy deposition (DED)	
	Cold spray – additive manufacturing (CSAM)	

Note: While CS can be considered an AM technique because it adds materials layer by layer, in this report, a detailed review of the technology is provided in the context of "surface modification/coating technique," where its applications are more mature and most R&D activities for nuclear applications are focused.

Although international efforts span a broad range of AMTs, literature and interested party input suggest that Canada's nuclear sector primarily concentrates on AM techniques. L-PBF and DED techniques are the most familiar and widely explored in the Canadian context. For example, the Organization of Canadian Nuclear Industries (OCNI) released a roadmap for advanced manufacturing in nuclear in 2021 [21], underscoring AM as a potential solution to Canada Deuterium Uranium (CANDU) reactor obsolescence and a means to reduce fabrication costs for SMR components. Other Canadian AMT initiatives have likewise centred on additive techniques.

This report seeks to broaden awareness across the Canadian nuclear sector by highlighting the diversity of AMTs beyond AM. This section outlines some major programs and initiatives advancing AMT adoption. Table 3 provides a high-level summary of global AMT initiatives and references sections of this report that provides additional details on individual AMTs. Section 3.2, along with detailed sections on specific AMTs, discusses progress on AMT-specific initiatives and related insights.

Table 3: AMT initiatives for nuclear applications

Project/initiative	Active years	Sponsors/ collaborators	AMT	Report section providing details
General				
Advanced Manufacturing and Materials Working Group [22]	Since 2023	Generation IV Forum	General	Appendix B
UK Department of Business, Energy and Industrial Strategy's Nuclear Innovation Programme – Advanced Manufacturing and Materials [23]	Since 2017	Multiple collaborators	General	Appendix B
Advanced Materials and Manufacturing Technologies (AMMT) Program [12]	Since 2022	US DOE	General	Appendix B
US NRC AMT Program [9]	Since 2017	US NRC	L-PBF, DED, EBW, PM-HIP, CS	Appendix B
America Makes and American National Standards Institute (ANSI) Additive Manufacturing Standardization Collaborative (AMSC) [24]	Since 2016	America Makes and ANSI	AM	Appendix B
ASME (Multiple Advanced Manufacturing Initiatives) [25]	Ongoing	ASME	General	Appendix B
Cooperation on Reactor Design Evaluation and Licensing – Mechanical Codes and Standards Task Force [26]	Since 2011	World Nuclear Association	General	Appendix B
Small Modular Reactor Vessel Manufacture and Fabrication [27] [28]	Since 2017	US DOE, Electric Power Research Institute (EPRI), NuScale, and Nuclear Advanced Manufacturing Research Centre, UK (AMRC)	PM-HIP and EBW	3.2.2.4
Project FAST (Future Advanced Structural Integrity) [29]	2019-2021	Rolls-Royce	PM-HIP	3.2.2.4
Program on Technology Innovation: Modular In-Chamber EBW [16]	Ongoing	EPRI, Nuclear AMRC	EBW	3.2.3.4
NUCOBAM [14]	2021-2024	EURATOM project	L-PBF	3.2.4.1.4
Ensuring Safety Innovations for SMR (EASI-SMR) [30]	2024-2028	EURATOM project	L-PBF and DED-laser beam (LB)	3.2.4.1.4

Project/initiative	Active years	Sponsors/ collaborators	AMT	Report section providing details
Actions for Realization and Qualification in Nuclear (ARQANE) Project [31], [32]	2021-2024	EDF, CEA, Framatome, and others	L-PBF and DED	3.2.4.1.4
Enabling SMRs Program—Supporting the Canadian Nuclear Industry with Guidelines, Strategies and Standards for SMR and Micro Modular Reactor (MMR) Deployment [33]	Ongoing	Natural Resources Canada (NRCan) and Canadian National Laboratory	L-PBF and DED	3.2.4.1.4
Transformational Challenge Reactor (TCR) Program [18], [34]	Since 2019	US DOE, ORNL, Idaho National Laboratory, Argonne National Laboratory	AM	3.2.4.1.4
Roadmaps				
Roadmap for Regulatory Acceptance of Advanced Manufacturing Methods in the Nuclear Energy Industry [5]	2019	NEI	General	N/A
Additive Manufacturing Roadmap for the Nuclear Power Industry: Metal Alloy AM Technologies [35]	2021	EPRI	AM	N/A
Advanced Manufacturing Methods Roadmap for the Nuclear Industry [36]	2021	EPRI	General	N/A
Advanced Manufacturing Roadmap for the Canadian Nuclear Industry [21]	2021	OCNI-Kinectrics-KSB	AM	N/A
Advanced Materials and Manufacturing Technologies Roadmap [3]	2022	US DOE, Office of Nuclear Energy	General	N/A
Standardization Roadmap for Additive Manufacturing (v3; 2023) [24]	2023	America Makes and ANSI	AM	N/A
Supply chain study				
Advanced Manufacturing for Small Modular Reactors: Implications for the Saskatchewan Supply Chain [7]	2024	NGen, Saskatchewan Industrial and Mining Suppliers Association, March	General	Appendix B

3.2 AMTs Overview

3.2.1 Cold Spray (CS)

3.2.1.1 Technology Overview

CS is a solid-state material deposition process that uses a high-velocity gas jet (up to 1200 m/s) to accelerate powder particles toward a target material [37], [38]. Powder particles bond to the surface through high-velocity impact that induces plastic deformation and localized adiabatic heating, forming a dense, solid-state layer [37]. Nitrogen and helium are commonly used as carrier gases [37].

Unlike conventional thermal spray techniques, CS relies solely on kinetic energy for material deposition, avoiding high-temperature particle heating [37], [39]. This helps preserve the feedstock's original properties and minimize issues like oxidation and phase transformations during deposition [39]. This makes CS particularly suitable for temperature-sensitive applications.

Two configurations of CS exist—high pressure (HPCS) and low pressure (LPCS)—with HPCS preferred for nuclear applications due to its ability to achieve the kinetic energy needed for high-quality deposition of steel and other high-strength alloys, such as Inconel [37], [40].

CS offers versatility and scalability, supporting a wide range of process parameters and equipment configurations. It also accommodates diverse material choices for component designers, as it is compatible with diverse metal alloys and allows the fusion of dissimilar metals [41], [42]. CS is effective for dimensional restoration and applying wear- or corrosion-resistant coatings [39], [43]. CS can also produce dense deposits, with no theoretical limit to the thicknesses achievable for most materials [40]. The technique can be applied with a hand-held apparatus or robotic arm, offering portability and flexibility. Mobile CS systems also enable in-situ repair or coating operations.

3.2.1.2 Technology Maturity and Current Applications

Developed in Russia in the mid-1980s, CS has evolved from a laboratory innovation to a commercially viable process adopted worldwide [44]. R&D efforts, such as those led by the US Army Research Laboratory Cold Spray Center, initially targeted non-structural military applications like corrosion- and wear-resistant coatings [40], [44]. Applications have since expanded into aerospace, automotive, medicine, and energy sectors, addressing both structural and non-structural needs [45]. Key applications of CS across industries include:

- Surface coating and repair: Extensively used for protective coatings and enhancing wear and corrosion resistance. CS is ideal for repairing large, complex surfaces that require precise material deposition [45].
- Remanufacturing and dimensional restoration: Restores worn or damaged parts by adding material selectively, reducing waste, and extending service life. For instance, the US Department of Defence reported over $250M in cost savings in 2015 from 15 approved CS repairs that would have otherwise required component replacements [46].
- AM: An emerging use of CS combines with AM build complex 3D components layer by layer, leveraging CS's precision and low-temperature operation [39].

While most work in other industries uses substrates and powder feedstock materials different from those typically encountered in nuclear applications (e.g., aluminum and magnesium alloys in aerospace), insights from applications can be transferred to nuclear, including competencies and practices related to process control and parameters, qualification methodologies, and testing standards [40].

3.2.1.3 Potential Nuclear Industry Applications

The success of CS in other industries has prompted interest in its use for nuclear energy systems. Research suggests CS in nuclear applications ranges from improving the reliability and safety of existing reactor fleets to enabling innovative designs in advanced reactors and SMRs [47], [48]. However, CS applications in the nuclear sector remain in early R&D stages, with near-term opportunities focused on non-structural coatings [40], [47], [49]. Currently, no structural applications for CS are anticipated in nuclear plants, as these applications are not yet



well-established and will require standards that define how load-bearing CS depositions are to be tested and their properties validated [40].

Examples of ongoing R&D include:

- Accident-Tolerant Fuel (ATF) Cladding Coatings: R&D efforts show cold-sprayed chromium coatings effectively protect zirconium alloy from oxidation under simulated loss-of-coolant accident conditions [47], [50], [51]. Programs such as the US DOE ATF initiative [52] and research by nuclear reactor vendors have developed and tested CS-coated fuel cladding designs. For example, Westinghouse, through its EnCore® Fuel Program, has developed ATF fuel assemblies with cold-sprayed Cr-coated cladding. These assemblies have been inserted for testing in multiple nuclear power plants (NPPs), including Byron Unit 2, Doel Unit 4, and Vogtle Unit 2, to support fuel qualification [53].
- CS Coatings for Reactor Components: Studies have demonstrated in-situ restoration of eroded Inconel 600 bellows in a nuclear plant using cold-sprayed Ni/Al_2O_3 composite coatings [47], [54]. Cold-sprayed microporous coatings have also been applied to the outer surface of LWR pressure vessels to enhance heat removal when the reactor pressure vessel (RPV) is forcibly submerged in coolant water during severe accident conditions, a procedure implemented in certain LWR designs [55].
- CS Coatings for Used Fuel Storage and Repository: Research explores CS coatings for mitigating and repairing chloride-induced stress corrosion cracking in stainless steel (SS) canisters used in interim storage systems [56], copper coatings on spent fuel canisters [57], and restoration of nuclear waste storage tank components (e.g., at the Hanford waste site) [58].
- CS Near-Net Shape Manufacturing for Advanced Reactors: CS is under evaluation for fabricating oxide dispersion-strengthened steel cladding tubes, which are suitable for high-temperature and high-radiation environments in advanced reactors and SMRs [48], [59].

For both operating reactors and SMRs, CS presents opportunities for localized component repair, in-field maintenance, and functional coatings that can enhance durability and extend the lifespan of reactor components.

3.2.1.4 Nuclear Industry Application Initiatives

No active initiatives have been identified for developing CS standards for nuclear applications. However, collaborative efforts such as the annual Cold Spray Action Team conference [60], led by the US Army Research Laboratory, provides a global platform for industry stakeholders to share data, experiences, and research findings. This

presents opportunities to promote collaborative R&D, and the best practices shared at this conference can help establish the groundwork for future CS standards for nuclear applications.

3.2.2 Powder Metallurgy–Hot Isostatic Pressing (PM-HIP)

3.2.2.1 Technology Overview

PM-HIP is an AMT that combines powder metallurgy with high-temperature and high-pressure processing to produce near-net-shape components with superior material properties. The PM-HIP process consists of (i) producing high-quality metal powder of the required specification, typically via inert gas atomization, (ii) designing and fabricating the can (a container used to encapsulate the powder; typically made of mild or SS) to produce the desired component shape, (iii) filling the empty can with metal powder, (iv) degassing and sealing the can, (v) compacting the can to densify the metal powder by HIP by subjecting it to extreme isostatic pressure (>100 MPa), and high temperatures (>1000°C) under vacuum conditions, eliminating internal voids and achieving theoretical densities of 95–100 %, and (vi) removal of the can either by machining or via acid pickling [26], [61].

Step (ii) is the most challenging part of the process, as design calculations must account for volume shrinkage during HIP, which is why cans are sometimes designed oversized. After can removal, PM-HIP-produced components will require a combination of surface finishing and post-processing operations [61].

PM-HIP offers several advantages over conventional manufacturing methods. Its near-net shape capability significantly reduces material waste and machining costs, making it a cost-effective and resource-efficient option. This AMT also offers an efficient alternative route for long-lead-time components produced via conventional methods, like forging and casting. The process eliminates the need for welds in many components, which helps reduce stress points. Components produced using PM-HIP feature isotropic properties and uniform microstructures, which tend to improve material properties like strength, fatigue, creep, and ductility [61], [62]. The homogenous nature of PM-HIP material makes such products readily inspectable along all three primary directions, which is attractive for nuclear applications [63]. Additionally, PM-HIP enables the use of advanced alloys like nickel- and cobalt-base alloys, which are often challenging to process with traditional manufacturing techniques like forging. This makes PM-HIP particularly suitable for applications that demand advanced materials and high performance [61], [64].

3.2.2.2 Technology Maturity and Current Applications

PM-HIP is one of the more mature technologies among the AMTs reviewed in this study. HIP emerged in the 1960s as a popular method for consolidating metal powders into solid components [61]. Over the years, its applications have expanded to include: diffusion bonding of dissimilar metals and alloys; elimination of porosity in casts and additively manufactured metals and alloys; and production of ceramic and composite products [26].

In sectors such as offshore oil and gas extraction, PM-HIP has been employed for over two decades to manufacture large components, including manifolds, valves, tees, and wyes. These components are similar in size to those used in nuclear service. They operate under harsh conditions, including high corrosion and intense pressures at deep ocean depths [63], [65]. The automotive and aerospace industries also extensively use PM-HIP parts, although many of these components are smaller in size than those being considered for nuclear applications. While PM-HIP offers variations in component sizes, the scale is limited by available HIP equipment and modelling and simulation capabilities for estimating volumetric shrinkage during metal powder consolidation. Shrinkage can be up to 30% [63].

PM-HIP can be used to process materials relevant to the nuclear sector, such as SS and nickel-based alloys [61]. Mature standards have been developed for PM-HIP applications in other industries (see section 4.5.2), which offer the potential to support the adoption of this AMT in nuclear settings.

3.2.2.3 Potential Nuclear Applications

Nuclear applications of PM-HIP have a long history. Early efforts in the 1950s in the United States explored its use for bonding zirconium cladding to uranium dioxide fuel rods for corrosion resistance [66]. Later, research by Rolls-Royce in the late 1980s demonstrated that PM-HIP could produce large NPP components like valve bodies and tee sections made of 304L and 316L type SS, matching or surpassing the mechanical properties of conventionally manufactured components [61]. PM-HIP was also investigated by international teams from Europe, Japan, and the United States for fabricating components for the International Thermonuclear Experimental Reactor (ITER) fusion experiment using 316L(N)-IG (ITER Grade) SS [61], [65].

While early research focused primarily on 316 SS, recent developments have expanded to low-alloy steels (LASs), such as type A508, a crucial material for manufacturing RPVs. This shift aligns with industry goals to use PM-HIP for large Class 1 nuclear safety components such as RPVs, reactor vessel heads, and steam plenum chambers, and their access ports [26], [61].

As global nuclear reactor deployments are projected to increase before 2050, demand for large components like RPV forgings is expected to exceed current limited manufacturing capacity [67]. PM-HIP presents an alternative solution, enabling the production of large, near-net-shape, defect-free components with shorter construction timelines and reduced costs compared to traditional processes. PM-HIP is expected to be used extensively over the next few decades to produce pressure-retaining components for SMR and advanced reactor applications [63].

Another promising application of HIP in the nuclear industry is immobilizing radioactive waste products and encapsulating spent fuel. Research by the UK National Decommissioning Authority and National Nuclear Laboratory [68], [69], [70], and organizations like Geo Roc [71] in the UK demonstrates that HIP can produce dense, physically robust nuclear wastes with significant volume reductions.

3.2.2.4 Nuclear Industry Application Initiatives

Rolls-Royce – Project FAST

Partners: TWI Limited (UK), The Manufacturing Technology Centre

Rolls-Royce has been at the forefront of PM-HIP development for several decades [61], [72]. One of its recent projects, Project FAST, is part of the UK Nuclear Innovation Programme, Advanced Manufacturing and Materials Phase 2A [73]. It aims to develop a novel method of manufacturing nuclear RPVs.

Key technologies being developed for this specific application are:

- Hot isostatic pressing of LAS vessel sections
- Thick-section electron beam welding (TSEBW) of vessel sections
- Heat treatment process modelling
- Physical process development

This project produced a physical demonstrator, named the small vessel demonstrator, and manufactured the world's first completed HIP and TSEBW-produced pressure vessel using LAS 508 Gr. 4N steel [29]. Findings from this demonstration project are being used to support an ASME nuclear code case submission for this type of application [74]. Code cases provide rules that permit the use of materials and alternative methods of construction/fabrication that are not yet covered by existing code requirements.

Outside of Project FAST, Rolls-Royce is also involved in developing TITAN. TITAN is a ~4.6 m diameter large-scale vessel and one of two "large HIP" initiatives under consideration to extend the size limitations of HIP components beyond 3.0 m diameter [75].

EDF – Framatome [26], [76]

A development program led by EDF Group and Framatome focused on characterizing A508, 304L, and 316L SSs processed using HIP and comparing their properties to forged steel.

As part of this initiative, specialized HIP simulation software was developed to model container deformation during the HIP cycle (shrinkage) and

predict the metallurgical state post-HIP [76]. The program demonstrated that PM-HIP could be effectively used to manufacture critical nuclear components such as pipework, pump impellers, and bimetallic junctions. Notably, a full-scale primary pipe in 304L SS was successfully manufactured, showcasing the viability of PM-HIP for producing large, complex components with precise geometries and reliable properties [26], [76].

EPRI

EPRI has been involved in multiple projects under different initiatives supporting the development and qualification of PM-HIP for nuclear applications. Key collaborations include:

- **EPRI and Carpenter Technologies**

  Produced valve bodies from 316L SS and Grade 91 steel. The goal was to use information regarding the processing and mechanical properties of the PM-HIP-produced components for an ASME code case. Early works on 316 SS led to the publication of ASME Boiler and Pressure Vessel Code (BPVC) Sec III Code Case N-834 [77] in 2013.

- **US DOE SMR Project on SMR Manufacture and Fabrication [78]**

  Partners: EPRI + Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC, UK) + NuScale Power

  Investigated combining PM-HIP and EBW for large structural 2/3 scale component assemblies of an SMR vessel. Estimated a potential cost savings of 40%, with a reduced time frame of less than 12 months using LAS A508. Major components include the upper and lower reactor heads, steam plenum, and steam plenum access covers, which are representative of those for the NuScale Power RPV [63]. Because a 2/3 scale head is too large for the largest PM-HIP unit in the United States, two half-head sections were produced and then joined by EBW [61], [63].

- **Project Advanced Technology for Large-Scale (ATLAS) HIP**

  Project ATLAS is the other "large HIP" initiative alongside Project TITAN. This project involves developing a large-scale HIP vessel—4.05 m diameter, with 80 tons (US) load capacity [75]. EPRI is working with the industry to bring ATLAS forward to enable the production of very large HIP components.

3.2.3 Electron Beam Welding

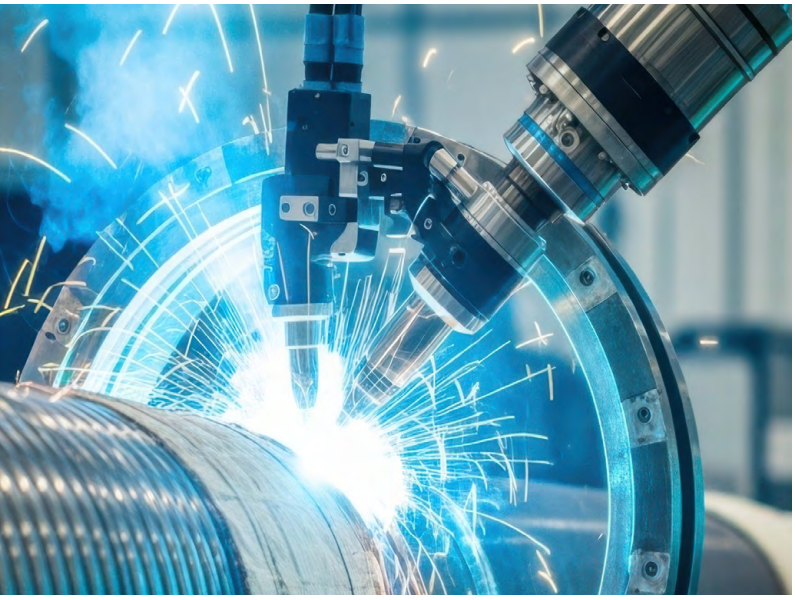
3.2.3.1 Technology Overview

EBW is a fusion welding process that uses heat from a high-velocity beam to melt and join two materials directly. The electron beam is focused on the workpiece by magnetic fields. The kinetic energy of the beam is converted to heat upon impact, melting the workpiece and creating a joint [79]. The entire process is performed in a vacuum to prevent gases from scattering the beam. This can be achieved by placing the entire workpiece in a vacuum chamber or by using a local vacuum on sections to be welded [80]. This approach minimizes oxidation and impurities. Additionally, EBW is heavily automated and computer-controlled. Specialized fixtures and computer numerical control tables facilitate precise movement and positioning of workpieces within the vacuum environment [79].

EBW is a single-pass, fast (up to 200 mm/s) welding technique that does not require filler material. However, precise machining and joint fit-ups are required [81]. EBW offers improved joint access and can weld dissimilar metals and material thicknesses from <0.5 mm to ~300 mm [82]. It offers precise weld penetration with repeatable accuracy. Welds maintain up to 95% of the base material's strength [79]. Its high thermal efficiency produces a small HAZ, minimizing distortion and material shrinkage while allowing welding near heat-sensitive components [79], [80].

3.2.3.2 Technology Maturity and Current Applications

EBW is a mature welding technique developed in the 1950s. Due to high equipment cost, vacuum, and facility requirements, applications are mostly limited to high-production and high-risk industries where precision, deep penetration, and minimal distortion are critical. EBW is typically used in the automotive industry for transmission components,



"Nuclear interest in EBW has spanned several decades, focusing recently on thick-section vessel components."

gears, and turbochargers, and in aerospace for jet engine components and turbine blades [83]. Its ability to produce deep, high-integrity welds with minimal HAZ makes it suitable for safety-critical parts in the nuclear industry. Importantly, numerous welding standards address EBW applications across multiple industries (see section 4.5.3).

3.2.3.3 Potential Nuclear Applications

Nuclear interest in EBW has spanned several decades, focusing recently on thick-section vessel components [80]. Research emphasizes deep, large-girth welds for pressure vessels, particularly using LASs like LAS A508 [29], [80], [84]. Successful demonstrations show EBW can create defect-free, high-quality RPV girth welds, saving cost and time. Most R&D has occurred in the UK (The Welding Institute (TWI) and Nuclear AMRC) and the United States (EPRI).

Current initiatives aim to develop EBW systems for SMR pressure vessels. Historically, large vacuums were required, limiting component size and increasing costs. For example, a traditional in-chamber vacuum dedicated to welding SMR RPV circumferential welds (~40 ft/12.19 m long) costs about $20M [80]. To address this challenge, the industry has been actively developing two alternative approaches: local vacuum and modular in-chamber EBW (MIC-EBW).

The local vacuum process eliminates the need for a full vacuum chamber by employing a localized sealing interface around the weld area [80]. A reduced-pressure EBW system was developed by Cambridge Vacuum Engineering, TWI, and other partners [85]. This system has been successfully applied in large-scale projects, including the Dogger Bank wind farm in the UK to weld a wind turbine monopile foundation. This application proved to be at least 25 times faster than current methods while using 90% less energy, costing 88% less, and producing 97% less CO_2 emissions than submerged arc welding methods [86], [87]. It is also currently being investigated under the EBManPower program for use in modular reactors (described further in section 3.2.3.4) [88].

The MIC-EBW approach, currently developed by Nuclear AMRC UK and EPRI under a US DOE project, employs a modular vacuum chamber that is scalable to accommodate varying component sizes and welding elevations [16]. By attaching an electron beam gun to the side of one of the modules, MIC-EBW enables efficient welding of large nuclear components while overcoming traditional limitations associated with fixed vacuum chambers. Examples of welds that could be performed with the MIC-EBW system include the assembly of RPVs, pressurizers, or steam generators [16], [89].

Recent research also explores EBW of PM-HIP materials, aligning with industry efforts to manufacture nuclear components using PM-HIP [80]. EBW presents a promising solution for welding large PM-HIP components that must be fabricated in parts together with minimal distortion and high integrity.

Ongoing research is exploring the post-weld heat treatment of electron beam (EB) welds to homogenize the weld and base metal microstructures [80]. Since EBW does not require filler material, post-weld heat treatment methods for EB welds are being investigated to restore the weld fusion zone to near-base metal properties. This change could potentially eliminate the need for in-service inspection of girth welds and further enhance the efficiency and reliability of welded nuclear components [27]. This concept needs further development, and regulatory approval will be required to forgo current requirements for in-service inspection of RPV welds [80].

3.2.3.4 Nuclear Initiatives

EBManPower Project

Collaborators: TWI Ltd, Cammell Laird, Aquasium Technology, supported by grant funding from InnovateUK.

The EBManPower Project [88] aimed to commercialize EBW fabrication for the power generation market [85]. It involved the industrial development of a new type of localized vacuum EBW technology, the Ebflow system, for RPV manufacture [88]. This project developed equipment and methods shown in the fabrication of the UK's first full-size MMR vessel segment [88]. EBManPower demonstrated a cost-effective and rapid manufacturing solution of thick-section vessels for nuclear and other power industries.

Rolls-Royce—Project FAST (Future Advanced Structural Integrity)

This initiative is discussed under nuclear initiatives for PM-HIP (see section 3.2.2.4). It includes local vacuum thick-section EBW of PM-HIPed RPVs [89].

Nuclear AMRC UK

This group is investigating the modularization of EBW equipment, including the RPEB system for large-component fabrication. Additionally, Nuclear AMRC support integrating EBW into the R6 (UK) and API 579-1/ASME FFS-1 fitness-for-service procedures, ensuring the technology meets structural integrity and safety assessment standards [80]. Welds on SA508 Grade 3 and 4N LAS have been evaluated as part of this work. Nuclear AMRC is also collaborating with EPRI on developing a MIC-EBW system under a US DOE-funded project [16].

EPRI

EPRI has been involved in multiple projects under different initiatives supporting the development and qualification of EBW for nuclear applications, including:

- **US DOE SMR Project on SMR Manufacture and Fabrication**

  Partners: EPRI + Nuclear AMRC, UK + NuScale Power

  This project was discussed under nuclear initiatives for PM-HIP in section 3.2.2.4 and aims to demonstrate the production of 2/3-scale NuScale SMR RPV vessel sections in less than 12 months, with a 90% reduction in welding time and over 40% cost reduction. The time and cost estimates are based on a combination of PM-HIP, EBW, and diode laser cladding [84]. This in-chamber EBW project demonstrated that EBW could be applied to thick-section circumferential welds [89]. In 47 minutes, the team joined two shells with a diameter of 70 in (1.77 m) and a wall thickness of 3 in (76 mm), a process that could take up to two weeks using conventional welding techniques [16].

- **US DOE Project on Establishing Modular In-Chamber (MIC)-EBW Capability in the United States**

  Partners: EPRI + NuScale + Doosan + BWXT Nuclear + AMRC + PTR-Precision Technologies + Bridger Welding Engineering + Rusach International

  This is a follow-on effort to the DOE/EPRI/Nuclear AMRC project mentioned previously. This project aims to develop and establish MIC-EBW capabilities for SMR manufacturing at a leading US fabricator. The MIC-EBW facility will be set up at BWXT Nuclear's facility in Barberton, Ohio [16]. A key goal is to cut welding arc time by as much as 90% compared to traditional welding methods. Project activities include producing a 10 ft (3.05 m) diameter, 4.375 inches (110 mm) thick LAS weld in under 90 minutes [89]. Although it is being demonstrated on NuScale Power's RPV design, the system can be applied to various other components, including pressurizers, steam generators, vessels, and large valves [89]. If successfully demonstrated, the MIC-EBW capability could result in cost savings in excess of 50% over a dedicated in-chamber system [16].

EPRI is also evaluating the feasibility of thick-section girth welds for LAS A508 Grade 3 Class 1 and 2 using

different material combinations, such as forging-to-forging, forging-to-PM-HIP, and PM-HIP-to-PM-HIP welds [80]. As part of the thick-section EBW development for SA508 LAS, EPRI is also exploring a comprehensive solution heat treatment process for SA508 Grade 3 steels. This process aims to eliminate weld indications while achieving enhanced mechanical properties, ultimately leading to the elimination of in-service weld inspections [80].

3.2.4 Additive Manufacturing

AM, commonly known as 3D printing, is a layer-by-layer fabrication process that builds components directly from digital models. Unlike subtractive manufacturing methods, which remove excess material to shape a part, AM adds material only where needed, creating complex geometries, minimizing material waste, and enhancing design flexibility [90].

The AM process typically begins with a 3D model created using computer-aided design software or reverse engineering techniques, such as 3D scanning of an existing object. This model is then digitally "sliced" into thin layers using specialized software and sent to a 3D printer. Next, material, such as plastics, resins, ceramics, and metals, is deposited, fused, or solidified layer by layer to construct the final object [90].

AM technologies have evolved from rapid prototyping with polymers to producing high-performance metal components for various industries, including aerospace, automotive, and medical. Companies like SpaceX, Boeing, Airbus, and GE Aviation leverage AM for mission-critical applications, demonstrating its transformative potential in modern manufacturing [91], [92]. By reducing part counts, enabling the use of advanced materials, and incorporating in-situ process monitoring, AM provides greater design flexibility while minimizing costs [21], [90]. It can also play a role in reducing lead times for urgent plant outage demands, producing obsolete or replacement components, and decreasing reliance on large inventories [21], [35].

While metal AM techniques such as L-PBF and DED have been selected for review and presented in subsequent sections, it is important to note that AM encompasses a broad range of techniques, covering both metal and non-metal applications. There is also growing interest in AM of advanced materials like carbon fibre-reinforced composites, which can be produced using other AM techniques such as fused deposition moulding and selective laser melting [93]. These other techniques could also play a significant role in manufacturing components of varying safety levels for nuclear applications, further expanding AM's impact across the industry.

3.2.4.1 Laser-Powder Bed Fusion

3.2.4.1.1 Technology Overview

L-PBF is an AM technique that employs a high-power laser to selectively melt and fuse layers of fine metal powder, enabling the creation of highly precise and intricate 3D components. The process involves spreading a thin layer of powder across a build platform, which is then selectively melted by the laser based on a sliced 3D model. Once a layer is completed, the build platform is lowered, and a new layer of powder is applied and fused to the previous one. This cycle continues until the part is fully formed. The L-PBF process is conducted in an inert gas environment, typically argon or nitrogen, to prevent oxidation [94].

L-PBF is particularly suited for fabricating small to medium-sized components (less than 50 lbs and approximately 23 kg) with intricate geometries and high surface quality [95]. The process often requires support structures to stabilize overhanging features, manage thermal stresses, etc., which are later removed during post-processing. Key advantages of L-PBF include [94]:

- Material efficiency – Unused powder can be recycled, minimizing waste
- High precision – Layer thicknesses as fine as 20 microns enable superior surface finishes
- Cost reduction – Decreased part count and minimized waste led to lower manufacturing costs
- Design flexibility – Complex geometries, unique microstructures, and in-situ process monitoring improve component functionality
- Reduced lead times and costs – Supports rapid prototyping, urgent part replacements, and on-demand production of obsolete components

3.2.4.1.2 Technology Maturity and Current Applications

L-PBF has gained significant traction across various industries due to its unique advantages. Among several metal AM techniques, L-PBF is the most extensively studied, particularly in sectors that demand high-performance metal parts such as aerospace, automotive, and biomedical engineering. For example, SpaceX has been using direct metal laser sintering, a proprietary synonym for L-PBF, to produce critical rocket engine components [92]. These additively manufactured parts have replaced cast components in human-rated flight systems, proving their reliability and performance under extreme operating conditions: They withstand cryogenic temperatures at excessive pressures and high vibration [92], [96].

L-PBF has been extensively used for titanium and nickel-based alloys, SS, and aluminum [94]. For nuclear applications, however, 316L SS has been the primary focus, given its widespread use in nuclear environments [97]. Despite its advantages, broader adoption in the NPP sector faces challenges related to anisotropic material properties, porosity, process control limitations, and reproducibility [97]. However, experience from industrial sectors with established L-PBF applications provides valuable insights that can accelerate its qualification and implementation in nuclear settings.

While process standardization efforts are ongoing, early studies indicate that L-PBF-produced components can meet or even exceed the mechanical performance of conventionally manufactured parts [97], [98]. SDOs and research institutions worldwide are actively working on qualification frameworks, but further research is required to address microstructural properties, residual stress behaviour, irradiation effects, and weldability for long-term nuclear performance [97]. Initiatives like those discussed in section 3.2.4.1.4 are driving efforts to address these gaps and develop qualification methodologies and pre-qualification guidelines for L-PBF components in nuclear applications. A technical review of the L-PBF technique and qualification processes for LWRs was published by ORNL [97]. The Standardization Roadmap prepared by the America Makes & ANSI AMSC [24] also provides further information on the technical and standardization gaps for the L-PBF technique.

3.2.4.1.3 Potential Nuclear Applications

Interest in L-PBF within the nuclear sector has grown due to its potential to streamline manufacturing, reduce lead times, and enable design innovations that traditional methods cannot achieve. Its ability to produce intricate, high-precision components makes it particularly attractive for both existing nuclear plants and advanced reactors, including SMRs and Gen IV systems.

For current nuclear fleets, L-PBF could be used for complex reactor internals, fuel assemblies, control rod drive internals, and obsolete and hard-to-source replacement parts. It addresses supply chain challenges and extending plant life. Its capability to fabricate optimized cooling channels can enhance heat exchanger and steam generator performance [99].

In advanced reactors and SMRs, L-PBF enables the fabrication of compact, high-performance components that support modular designs and enhanced safety features. Its compatibility with high-temperature and corrosion-resistant materials like nickel alloys makes it suitable for advanced heat exchangers, cooling channels, and structural supports in Gen IV systems [99].

3.2.4.1.4 Nuclear Initiatives

Nuclear Components Based on Additive Manufacturing

NUCOBAM was a four-year EU-funded project that concluded in 2024, bringing together 13 organizations from six European countries to advance the qualification of 316L L-PBF components for nuclear applications [14]. The project's primary objective was to develop a structured qualification methodology document for additively manufactured nuclear components to be proposed for standardization and communicated to nuclear design code committees, ASME, and RCC-M, based on its findings [100].

For some background context, the RCC-M [101] is a code for mechanical components designed and manufactured for pressurized water reactors published by AFCEN [102]. In its 2020 edition, the RCC-M code introduced Clause M116 – Specific use of a non-referenced manufacturing process [26]. This clause permits the use of manufacturing processes



not explicitly referenced by the RCC-M, provided that the manufacturer submits the following items to the contractor for approval: (a) a procurement specification, (b) a first part qualification, and (c) a document package justifying the use of the material and a qualification procedure [100].

The EU wanted to develop a project to structure and gather the technical documentation required for AM standardization (ref: requirement "c" in M116), by evaluating end-to-end requirements, from the theoretical qualification process through parts manufacturing to testing. On the ASME side, the proposed qualification methodology document links the chapters in NUCOBAM's developed project methodology to ASME document PTB-13-2021 [100], [103].

To verify L-PBF's viability for nuclear applications, NUCOBAM focused on demonstrating process stability, repeatability, and reproducibility—three key aspects required for regulatory acceptance. The project also evaluated the in-service behaviour of L-PBF-manufactured components, assessing their mechanical properties, irradiation resistance, and long-term durability in nuclear environments. While irradiation testing is still ongoing, several technical publications referencing data from NUCOBAM tests indicate that 316 L-PBF material could be a suitable candidate for the production of NPP reactor core parts [100], [104], [105].

Ensuring Safety Innovations for SMRs (EASI-SMR) Project

EASI-SMR is a four-year program that commenced in 2024, led by EDF [30]. The program is largely inspired by the European SMR pre-partnership R&D research (now the European Industrial Alliance on SMRs) and will address the safety challenges associated with major light water-SMR innovations. One of the key areas of focus includes AM to improve the compactness of modularization of nuclear steam supply system internals. The program will qualify and validate L-PBF and DED-LB techniques for producing mock-ups of SMR components using Alloy 800 and Inconel 625. Two SMR concepts—NUWARD (developed by EDF) and LDR-50 (developed by VTT)—were selected for investigation. A large mock-up (1 to 2 m) of a tube-type steam generator design will be fabricated with Inconel 625, while a smaller compact steam generator mock-up with narrow channels will be fabricated by L-PBF with Inconel 625 and Alloy 800. The intention is to subject these mock-ups to destructive and non-destructive characterization and develop a methodology report for pre-qualifying additively manufactured heat exchangers based on experimental results. These efforts are intended to contribute to the work of the ASME and AFCEN committees.

EDF-Framatome AM Initiatives

EDF and Framatome have been at the forefront of AM adoption in the nuclear sector. They are major contributors to different AMT initiatives for nuclear applications, including NUCOBAM [106]. Their ongoing efforts focus on standardizing AM components that comply with RCC-M codes and ensuring equivalence with traditionally forged materials. By 2025, Framatome aims to introduce RCC-M M116-compliant 316L SS and Inconel 718 AM components from L-PBF, Wire Arc Additive Manufacturing (WAAM), and PM-HIP, further advancing AM integration into nuclear supply chains [107]. Framatome has begun serial production of AM parts from L-PBF and DED-WAAM, and aims to develop specific qualification guidelines for these techniques in the RCC-M 2026 edition [107], [108].

Actions for Realization and Qualification in Nuclear Project

The ARQANE project was a major collaborative initiative led by EDF and included key industry players like CEA, Framatome, ORANO, and many others [31], [32]. The project aimed at demonstrating and validating the industrial maturity of metal AM for the nuclear sector. It focused on two AMTs: L-PBF and Arc-Wire/Laser-Wire AM [32]. The ARQANE project targets three core areas:

- Technical: Develop, qualify, and validate metal AM processes tailored for nuclear applications, using real, critical components and establishing unified technical reference systems.
- Economic: Reduce manufacturing lead times and costs through rapid design iteration, material efficiency, and promote agile, localized production, especially among SMEs in the nuclear supply chain.
- Environmental: Minimize the environmental impact by reducing material use, energy consumption, and chemical processing, while enhancing recyclability and supporting the decarbonization of major sectors through clean nuclear energy.

TCR Program, United States

The TCR program, led by ORNL, aims to demonstrate the use of AM and AI in nuclear reactor development [109]. The program will manufacture and operationally test a microreactor using L-PBF, particularly for 316L SS components. It aims to validate AI-driven AM design, material performance, and irradiation resistance, contributing to future AM qualification frameworks. Multiple reports have been published under this program [110].

Canadian L-PBF Qualification Efforts

Kinectrics, the Nuclear Innovation Institute, Bruce Power, and Burloak Technologies collaborated to develop a standard qualification framework for L-PBF-manufactured nuclear components. Their primary focus was on pressure boundary integrity assessments, starting with an L-PBF-fabricated hydraulic manifold, a part of an inspection tool used in a NPP. This part was a good candidate due to its difficulty in manufacturing via traditional methods; it had complex geometry and complex machining. The project was a prototype, and the component was not installed in any NPP, as it wasn't a like-for-like replacement. Overall, the final results after mechanical and pressure testing of the fabricated manifold were satisfactory [17].

Project Supporting the Canadian Nuclear Industry with Guidelines, Strategies, and Standards for SMR and MMR Deployment

This project is funded under NRCan's Enabling SMR program and will run for three years until 2027 [33]. The Canadian National Laboratory (CNL) has been tasked with developing guidelines for implementing AMTs within the Canadian nuclear framework of codes and standards. Industry engagement with CNL representatives revealed that the AMTs of focus for this project include L-PBF and DED. They mentioned the project will manufacture a reactor-grade component that is SMR-agnostic and non-pressure boundary, build it, test it, and use the lessons learned to guide the development of these standards. The project will also create guidelines for performing fuel qualification within the Canadian regulatory context, aiming to minimize SMR waste creation and optimize SMR waste management [33].

3.2.4.2 Direct Energy Deposition

3.2.4.2.1 Technology Overview

DED is an AM process that uses a focused energy source, such as a laser, EB, or plasma arc, to melt and deposit material onto a substrate. The feedstock

material, either powder or wire, is continuously fed through a nozzle and melted as it is deposited. This enables precise, layer-by-layer material addition. Unlike L-PBF, which is limited by the build chamber size, DED offers multi-axis nozzle movement (5+ axis motion). This allows for complex, large-scale builds (up to approximately 500 lb) with high flexibility [95], [111].

DED is essentially a robotically controlled welding process. While it can produce complete parts, it is most commonly used to repair, modify, or add material to existing components. This offers a cost-effective solution for extending the service life of high-value components.

Although the term DED is often used generically, it refers to a family of related AM techniques that share a common process architecture—a point heat source forming a melt pool while the feedstock material is continuously fed into it. Examples of DED variants include laser-DED (L-DED), electron beam-DED, WAAM (or DED-WAAM), gas metal arc additive manufacturing (GMAAM or gas metal arc (GMA-DED)), and many others [111], [112].

DED offers several key advantages, particularly for repairing and remanufacturing applications, including [111], [112]:

- High deposition speeds, making it significantly faster than PBF for larger builds.
- Capability for large build volumes, enabling the repair and fabrication of large components.
- Hybrid manufacturing integration, allowing seamless combination with computer numerical control machining for enhanced precision.
- Material versatility, supporting a wide range of metals, including SSs, superalloys, and titanium.
- Multi-material builds, enabling the fabrication of functionally graded materials with localized material properties.

DED also presents challenges compared to L-PBF, including:

- Rougher surface finish, requiring post-processing for applications needing fine detail.
- Coarser microstructures, which may necessitate heat treatment to refine material properties.
- Lower geometric accuracy, making it less suitable for components with intricate features unless secondary machining is applied.

3.2.4.2.2 Technology Maturity and Current Applications

DED is one of the two most commonly used AM technologies for metallic materials, alongside PBF. Industries that demand high-performance, large-scale metal components, particularly in aerospace, defence, energy, and heavy industrial manufacturing, have successfully implemented it.

In aerospace, DED is widely used for turbine blade repair and large structural aircraft components, significantly reducing material waste and extending component service life [112]. Automotive and tooling industries also leverage DED for mould repair, die refurbishment, and hybrid manufacturing. DED also supports the energy sector by repairing and fabricating high-value power plant components, such as turbine blades and discs, substantially lowering operational costs [112], [113].

Among the various DED processes, WAAM has been widely used for decades in weld metal buildup applications, particularly in power generation, oil and gas, and aerospace industries. WAAM effectively repairs nozzles, lugs, reinforcement pads, transition pieces, and rotating equipment components, especially under high stresses and cyclic loading [114].

While DED can process a wide range of materials, the nuclear industry has primarily focused on 316L SS, given its established performance in NPP environments and its well-documented behaviour under irradiation [111]. Ongoing research by ASME and EPRI evaluates GMA-DED for pressure boundary components, assessing its viability as an alternative to traditional manufacturing routes [115]. Further information on the technical and standardization gaps for DED has been detailed by others [111], [24].

3.2.4.2.3 Potential Nuclear Applications

DED adoption in nuclear manufacturing remains limited compared to L-PBF. One of its key advantages for nuclear applications is the ability to deposit material directly onto existing components. This could make it ideal for repairing and refurbishing existing reactor components. Potential DED applications in nuclear environments include, for example, fabricating pipe attachments, small-to-medium-size nozzles, valves, penetration tubes (e.g., for control rod drive mechanism, stub tubes), flanges, turbine blades and discs, and reactor internals [99].

3.2.4.2.4 Nuclear Initiatives

Fewer nuclear-focused initiatives are dedicated specifically to DED compared to L-PBF. In recent years, the US DOE AMMT program has studied both L-PBF and DED techniques, exploring their potential for fabricating next-generation reactor components. The EASI-SMR project (section 3.2.4.1.4), assesses both PBF and LP-DED methods to improve the modularity and compactness of SMR steam supply system internals.

Although not entirely nuclear-focused, the following ASME research projects are relevant to DED's broader industrial adoption and potential integration into nuclear manufacturing [115]:

- ASME LLC-Research Project 0198 – Evaluates the extension of Arc DED into time-dependent regimes for ASME BPVC applications. Awarded in May 2024, the project supports weld metal data generation for time-dependent applications of B91 steel (and other) materials, helping establish a foundation for long-term AM component performance in high-temperature applications [115].
- ASME, EPRI, and Lincoln Electric Collaboration – Evaluates GMA-DED with wire feedstock for manufacturing pressure equipment. The findings support the development of an ASME code case for DED in applications not governed by time-dependent degradation (e.g., creep). This helps to establish the groundwork for standardizing DED-fabricated pressure boundary components under the ASME BPVC sections I and VIII [115].

4 Standards Review for AMT Applications in the Nuclear Industry

4.1 Standards and Related Documents Requirements

Developed through a consensus development process, "standards establish accepted practices, technical requirements and terminologies for many different fields" [116]. They often include:

- Design requirements – Define how a component or system should be engineered and specified, including material, dimensions, tolerances, QA, safety margins, and performance requirements. In this report, "design standards" refers to documents that primarily address design requirements.
- Material requirements – Specify the required chemical, mechanical, and physical properties of feedstock materials used in manufacturing or finished products. In this report, "material standards" refers to documents that primarily address material requirements.
- Process requirements – Outline acceptable methods, procedures, and parameters for manufacturing operations such as welding, heat treatment, or AM. In this report, "process standards" refers to documents that primarily address process requirements.
- Inspection and testing requirements – Provide methods and criteria for verifying that a material, component, or system meets defined requirements, including mechanical property testing, destructive and non-destructive evaluation, feedstock characterization, and testing. In this report, "testing standards" refers to documents that primarily address inspection and testing requirements.
- QA requirements – Outline process controls and verification steps to identify and prevent non-conformances, ensuring that each product meets specified requirements. In this report, "QA standards" refers to documents that primarily address QA requirements.

Technical specifications may be developed by a qualified subject matter expert, such as a customer, to provide supplier(s) with technical requirements for a particular material, component, process, or deliverable. Technical specifications may reference applicable standards.

Internal company documents, sometimes called internal procedures and guidelines, define proprietary or site-specific manufacturing methods, quality checks, and approval processes. They are often used to fill gaps where standards and technical specifications do not yet exist. Internal documents may include internal audit criteria, maintenance practices, or detailed AMT procedures developed through R&D.

4.2 Overview of Standards and Regulatory Context

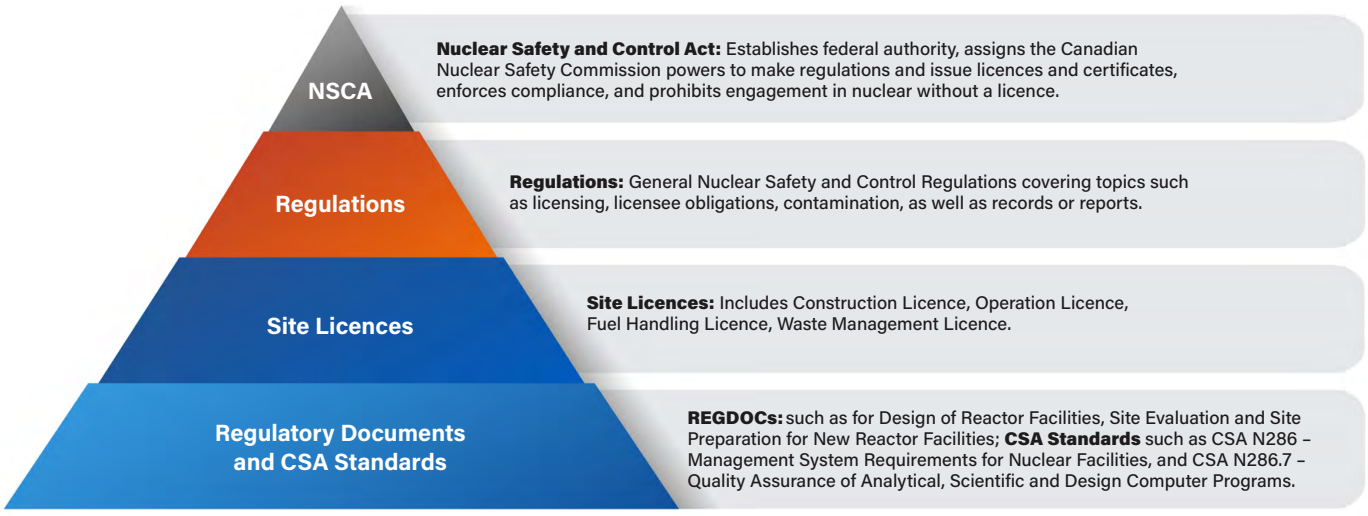
AMTs used in the nuclear sector must comply with a robust regulatory and their referenced standards framework. In Canada, the nuclear regime operates within a hierarchical system that begins with federal legislation and cascades down through regulations, licensing requirements, and standards. This structure ensures a consistent and transparent approach to managing nuclear safety, regulatory compliance, and quality. Figure 1 illustrates this hierarchy.

As the regulatory authority for nuclear energy in Canada, the Canadian Nuclear Safety Commission (CNSC) develops regulatory requirements, licence conditions, and evaluates and enforces compliance at nuclear facilities in Canada. The independent commission reviews and issues licences and approvals. The CNSC prepares regulation guidance documents (REGDOCs), which address regulatory requirements for activities throughout the lifecycle of a NPP facility, from licensing to decommissioning.

CNSC's regulatory framework references voluntary standards, including CSA nuclear standards, which provide standardized guidance for nuclear-related activities. These standards also assist in the development of materials submitted for licence applications and are referenced in the ongoing oversight of nuclear operations, including in licence conditions handbooks.

CSA nuclear standards are widely used across the Canadian nuclear industry and cover a broad range of topics. These standards contain many requirements

Figure 1: Nuclear reactor regulatory framework in Canada. Reproduced with permission from March Consulting Associates Inc. © 2024 [7]



relevant to the fabrication and maintenance of systems, structures, and components—activities that involve both the nuclear supply chain and nuclear operators. For procurements, the owner/operator typically references applicable standards in their technical specifications, which are then imposed on suppliers for the procurement of equipment or services for their facility.

These CSA nuclear standards also reference and require the application of many non-nuclear-specific standards, including other CSA standards or standards developed by organizations such as ASTM, Society of Automotive Engineers (SAE), and Institute of Electrical and Electronics Engineers (IEEE). Examples include CSA W47.1 [117] for welding qualifications, CSA-A23.3 [118] for the design of concrete reinforcement, and American Society of Civil Engineers (ASCE)/Structural Engineering Institute (SEI) 4-98 [119] for seismic criteria for structures.

An owner/operator usually references these non-nuclear-specific standards to develop technical requirements for a supply contract or includes them directly in the contract to assign the relevant requirements to the supplier. In some cases, CSA nuclear standards do not reference a specific standard for a particular need. In these circumstances, after consultation with regulatory bodies and independent experts in advanced manufacturing, industry professionals, including owner/operators and suppliers, apply standards from other industries that are most relevant. In Canada, this could include provincially mandatory standards, such as those for platforms, walkways, or crane design.

4.3 Qualification Criteria for AMT Nuclear Applications

Before evaluating the adequacy of current standards, it is essential to understand the qualification requirements for AMT applications. While the foundational structure of QA and qualification shares similarities with traditional manufacturing, AMTs introduce new variables and unique challenges that require specialized considerations.

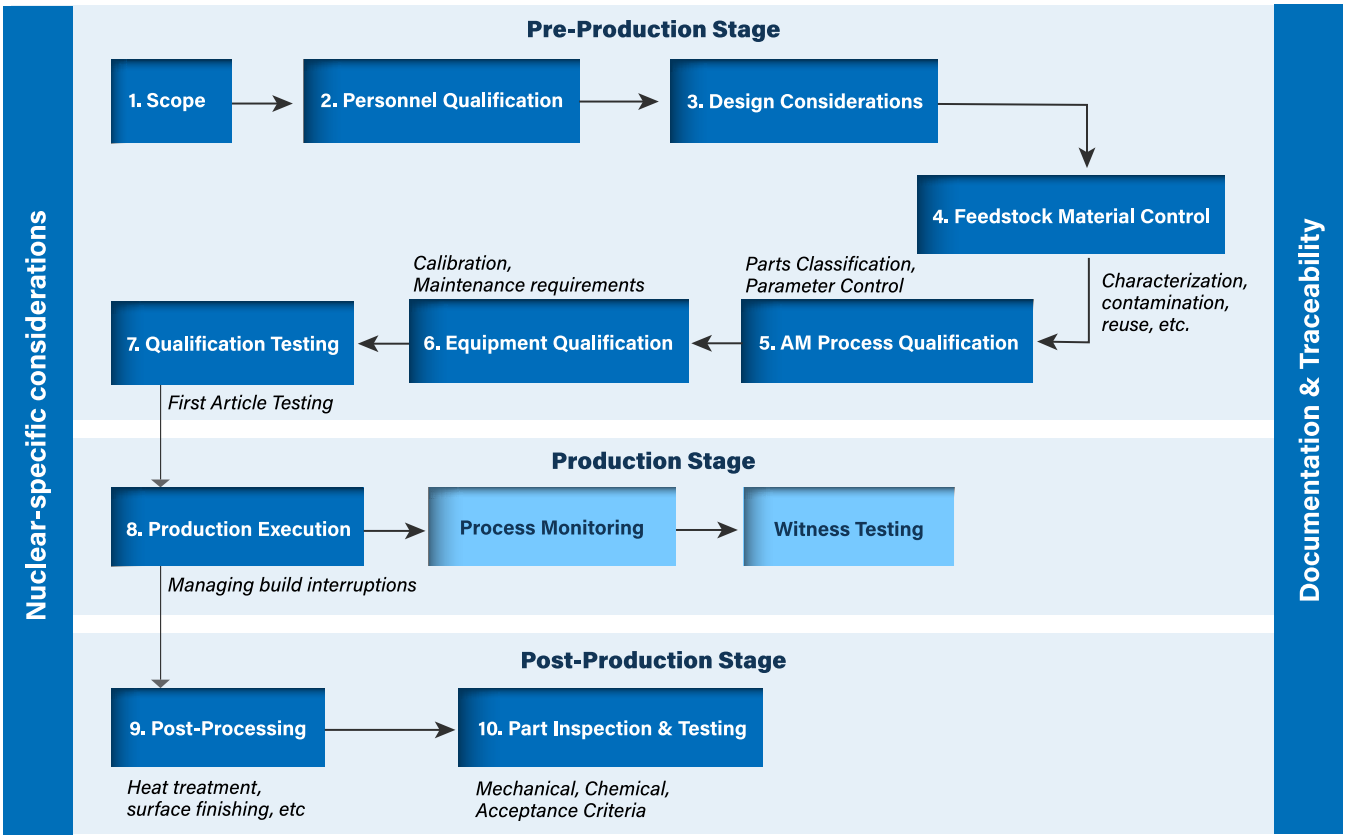
For example, feedstock material control (particularly for powder- or wire-based systems) is significantly more critical due to variants in particle size, morphology, and other factors that are less critical in wrought or cast materials. AMT processes are highly sensitive to parameters such as scan speed, deposition angle, and layer height. They also rely on tightly controlled build environments, such as vacuum, inert gas atmospheres, which are not typically required in traditional methods. Furthermore, post-processing and inspection routines must be adapted to account for AMT-specific defects, including porosity, lack of fusion, or anisotropy in material properties.

These differences make it essential to adopt a more tailored qualification framework to support the repeatability, reliability, and safety of components produced using AMTs, especially for safety-critical sectors like nuclear. As noted by an interviewee, this is the only way AMTs can move from prototypes to serial production. Figure 2 presents key elements of such a framework for AMT qualification.

The qualification criteria in Figure 2 span the full lifecycle of AMT part production—from early design requirements and material controls to in-process monitoring, post-processing specifications, and final inspection and testing. These criteria were established through a comprehensive review of current AMT standards [103], [120], draft regulatory guidance such as US NRC [121], [122], comparative studies of qualification methodologies developed in initiatives like NUCOBAM [100], and insights from recent industry engagement.

These criteria align with best practices increasingly recognized across the AMT community and reflect growing consensus on critical areas, such as feedstock qualification, process control, and first-article inspection. Together, they support the development of a repeatable production cycle for AMT components. An AM expert in the heavy industrial sector noted that AM standards have advanced significantly over the past five years ago, leading to a general consensus on requirements for feedstock qualification, process qualification, and first-article testing.

Figure 2: AMT qualification criteria for nuclear applications



The qualification criteria and examples of relevant types of standards that would typically contain or define the associated requirements are summarized in Table 4.

Nuclear-specific considerations and documentation cut across all production stages and are crucial to the qualification of AMTs for nuclear applications.

4.4 Canadian Standards Review

An environmental scan and literature review revealed that no established commercially available Canadian technical standards specifically address AMTs. CSA publishes a series of nuclear standards on various topics, within which AMTs could or should be considered.

Among the reviewed CSA nuclear standards, the following QA and design standards, in full or in part, were identified as potentially relevant to AMT use:

- CSA N285 Series – requirements for CANDU nuclear power plant pressure-retaining systems and components
- CSA N286 - requirements for management systems
- CSA N299 – QA program requirements for the supply of items and services for nuclear power plants
- CSA N287 Series – requirements for concrete containment structures
- CSA N289 Series – seismic design requirements
- CSA N290 Series – reactor control systems, safety systems, and instrumentation requirements, and
- CSA N291 – safety-related structures requirements

These CSA nuclear standards do not currently contain any specific references to AMTs. However, some requirements could potentially limit or facilitate AMT implementation. The following

Table 4: Qualification criteria, descriptions, and examples of relevant standards

Qualification criteria	Description	Examples of relevant standards
Qualification scope definition	Defines purpose, application, and boundary conditions of the qualification activity; ensures the qualification activity; ensures testing and documentation are traceable.	QA standards, process standards, design standards, etc.
Personnel qualification	Validates skills of designers, operators, and technicians specific to AMT systems.	QA standards, process standards
Design considerations	Accounts for geometry, material, service conditions, design for testing.	Design standards, material standards, process standards
Feedstock material control	Ensures feedstock consistency and quality, covering characterization, composition, reuse requirements, procurement, storage, and handling.	Material standards, testing standards, process standards
AM process qualification	Confirms process parameters produce consistent, defect-free parts; defines AM manufacturing plan and parts classification.	Process standards, testing standards, material standards, QA standards
Equipment qualification	Verifies AM machines and environments meet required standards (such as for machine calibration, maintenance frequency).	Process standards, testing standards, QA standards, etc.
Qualification testing	Tests samples or first articles to confirm specifications; ensures readiness for full-scale production [123].	Testing standards, process standards, material standards, QA standards
Production execution	Implements protocols for building parts, including managing deviations, monitoring quality, and witness testing.	Process standards, QA standards
Post-processing	Covers heat treatment, part finishing, removal of support structures, and machining.	Testing standards, material standards
Part inspection and testing	Ensures final parts meet acceptance criteria using NDE, mechanical, and microstructural tests.	Testing standards, material standards
Nuclear-specific considerations	Addresses safety, aging, and regulatory requirements for nuclear applications.	CSA nuclear standards
Documentation and traceability	Maintains records of materials, processes, and inspections for compliance and audits.	QA standards, process standards, testing standards

subsections describe specific standards in each CSA nuclear standards series that may be relevant to AMT applications. For each standard, we discuss its scope in terms of AMT applications and the requirements that could address AMTs. Tables C1–C4 in Appendix C provide an overview of each reviewed CSA nuclear standard presented below.

4.4.1 CSA N285 Series

CSA N285.0 [124] addresses pressure-retaining equipment in coordination with CSA B51 [125]. It outlines design, manufacturing, inspection, examination, and testing requirements for nuclear pressure boundary systems, components, and supports that could be relevant to AMTs. CSA N285.0 references ASME BPVC Sec III [126], which specifies requirements for processes such as welding. These include personnel and facility qualifications and certifications, equipment and process control and monitoring, and examination and testing. ASME is working to address similar considerations for specific AMTs, either directly or by reference to external standards, as detailed in the following sections discussing international AMT standards [20]. It is anticipated that ASME's efforts will cover most pressure boundary applications for AMTs in Canada through the existing reference in CSA N285.0.

Other standards in the CSA N285 series—CSA N285.4 [127], CSA N285.5 [128] and CSA N285.7 [129]—address inspection of equipment covered by CSA N285.0. These inspection-related standards do not address degradation mechanisms that may be unique to AMTs or the related inspection or examination processes that may be required to perform these assessments.

4.4.2 CSA N286 and CSA N299 Series

Both CSA N286 and CSA N299 pertain to quality, so they are discussed together.

CSA N286 [130] addresses management system requirements for nuclear facilities, including supply chain requirements that could apply to AMT-produced components. It broadly defines nuclear facilities management system requirements but does not provide detailed guidance on how to meet them.

CSA N299 series provides detailed QA requirements for procured items and services for NPPs. These standards outline processes to address quality requirements thoroughly but do not discuss fabrication methods or AMT use specifically.

CSA N299.1, CSA N299.2, and CSA N299.3 include requirements for special processes. In CSA N299.1 [131], Clause 7.14 outlines the need to define personnel qualifications, process procedures, documentation, and equipment for special processes. It also requires recording this information according to applicable codes and standards. This clause guides quality expectations needed for AMT use, including identifying, performing, and documenting special production and inspection processes.

Many requirements that ensure AMTs are performed with sufficient accuracy, consistency, and competency relate to QA activities. Other technical requirements may not directly relate to quality. Since quality requirements often appear in technical standards for AMTs, referencing AMT standards in CSA N286 or CSA N299 could efficiently clarify AMT-specific QA requirements. The existing wording on special processes could be evaluated to determine if it is sufficient.

4.4.3 CSA N287 Series

CSA N287.1 [132] gives general requirements for concrete containment structures. It addresses steel liners, embedded parts, and anchors, which could be manufactured using AMTs. The standard does not reference product forms that AMTs may provide, where additional material, design, or age-related inspection considerations could apply.

CSA N287.2 [133] specifies material requirements for concrete containment structures and lists allowable material specifications, but does not address materials from AMT processes.

CSA N287.3 [134] provides design requirements for metallic embedded parts and liners for containment structures, but does not cover AMT-specific considerations.

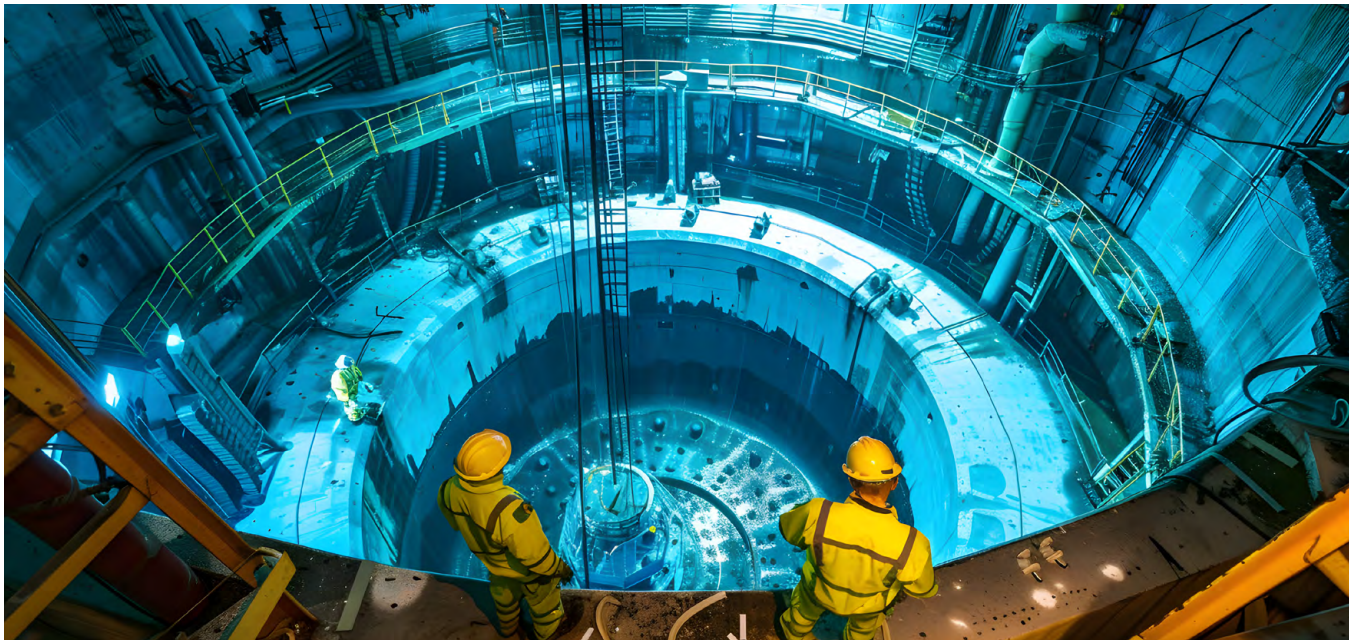
CSA N287.4 [135] includes fabrication requirements for metallic parts for containment structures, including welding and heat treatment, but does not address AMT-unique requirements.

CSA N287.5 [136] covers initial examination and testing, and CSA N287.6 covers in-service examination. However, neither addresses inspection of AMT products, though weld inspections for welded parts are included.

CSA N287.8 [137] addresses aging management of concrete containment structures, which could include metallic AMT parts. However, the standard does not provide criteria for AMT-specific aging examination.

4.4.4 CSA N289 Series

CSA N289.1 [138] provides general requirements for evaluating seismic hazards of equipment and components such as containment structures, supports, or components in nuclear power, which could be manufactured using an AMT process. It does not restrict seismic design for products from AMT processes that may exhibit new failure mechanisms or lack testing or in-service seismic failure experience. It also does not consider possible AMT-unique aging mechanisms that could affect a seismic analysis.



CSA N289.1 [138], which references CSAN289.3 [139], provides general seismic analysis and design methods but does not specify requirements for seismic for potential AMT-related failures.

4.4.5 CSA N290 Series

CSA N290.0 [140], CSA N290.1 [141], and N290.3 [142] address nuclear plant safety systems, including containment and components that could be fabricated using AMTs. Additions may be required to address considerations for AMTs, including AMT-specific aging and failure modes and material qualification. Limited operating experience for AMT-produced items may require additional reliability analysis.

CSA N290.8 [143] defines technical specification requirements for nuclear plant components, including mechanical, electrical, and control components that could be AMT-produced. The standard also defines design requirements that must be included in technical specifications for procurement of safety system components for NPPs. These requirements might be applicable to SMRs. The submission of special process procedures is covered in the standard without specifically indicating AMT processes.

CSA N290.13 [144] addresses environmental qualification, and CSA N290.20 [145] addresses aging, including product forms that could be produced using AMT processes. Neither specifically addresses AMT-unique considerations.

4.4.6 CSA N291

CSA N291:19 [146] addresses non-pressure boundary safety-related structures and their components, including brackets and their attachments. It lists allowable materials and references other specifications. While it allows specification of other materials with satisfactory tests, it contains no requirements specific to AMTs. The standard addresses degradation mechanisms and inspection for embedded parts but does not consider AMT-unique failure mechanisms.

4.5 International AMT Standards Review for Nuclear Application

This section presents key findings from an environmental scan and literature review of existing AMT standards, focusing on their applicability to nuclear sector needs. International standards cover different stages of the AMT production lifecycle. While many standards support front-end activities, such as design and feedstock control, this review focused on standards related to material processing, process qualification, material property testing, and nuclear-specific AMT specifications. The analysis targeted standards that could be adapted to support the qualification and acceptance of AMT-fabricated components for nuclear applications.

4.5.1 CS Standards

The CS process involves numerous interdependent variables, such as gas temperature and pressure, powder properties, and particle velocity. Achieving repeatable and reliable results across applications requires a step-by-step standardization approach, encompassing everything from powder manufacturing to post-processing. Without established qualification protocols and consistent practices, ensuring uniformity in CS applications becomes challenging, particularly in high-stakes industries like nuclear energy.

Few international standards are available for CS, but some CS-specific standards developed by the military are now applied across various industries:

- MIL-DTL-32495A – Powders for cold spray deposition [147]
- MIL-STD-3021 – Materials deposition, cold spray [148]

4.5.1.1 Review Summary of Selected Relevant CS Standards

Table D1 in Appendix D summarizes the contributions of these MIL standards to CS process qualification. MIL-STD-3021 [148] provides a structured framework for developing manufacturing process controls, ensuring consistency in CS operations. MIL-DTL-32495A [147] specifies procurement requirements for CS powders, detailing acceptable powder compositions and properties. Together, these standards guide supplier and operator qualification, qualification documentation, and part inspection and testing.

These standards generally reference ASTM standards for detailed qualification and testing, as CS-specific testing standards are not widely available. Ozdemir *et al.* [149] provide an overview of qualification and testing standards for CS. Current military standards [147], [148] focus mainly on non-structural coatings, leaving a gap in standardization for structural CS applications. Developing CS-specific standards for structural applications and post-processing protocols, such as NDE and property testing to assess long-term performance, will be critical. Comprehensive guidelines for qualifying CS-manufactured components would accelerate adoption of this promising technique.

4.5.1.2 Current Progress in CS Standards Development

A literature survey revealed limited activity in developing new CS standards. Notably, SAE recently published SAE AMS7057 [150], *Cold spray additive manufacturing (CSAM) process,* which establishes process controls for repeatable manufacturing of metallic and metal-non-metal blend components.

4.5.2 PM-HIP Codes and Standards

Many aspects of the PM-HIP process have been standardized, as reviewed by Hoelzer [61]. A range of ASTM and ASME codes and standards apply to different stages of PM-HIP component fabrication.

Several ASTM standards support the front end of the PM-HIP process, particularly powder characterization. These include ASTM B215-20 [151], which specifies practices for sampling metal powders, and ASTM B214-22 [152], which defines methods for determining particle size and size distribution via sieve analysis. A review [61] conducted for the U.S. NRC determined that existing powder characterization standards are sufficient to support nuclear PM-HIP applications. Holzer's review [61] also identified three mandatory ASTM PM-HIP standards relevant for NPP components:

- ASTM A988 – Standard specification for hot isostatically-pressed SS flanges, fittings, valves, and parts for high-temperature service [153]
- ASTM A989 – Standard specification for hot isostatically-pressed alloy steel flanges, fittings, valves, and parts for high-temperature service [154]
- ASTM B834 – Standard specification for pressure consolidated powder metallurgy Fe-Ni-Cr-Mo (UNS N08367), Ni-Cr-Mo-Nb (UNS N06625), Ni-Cr-Fe Alloys (UNS N06600 and N06690), and Ni-Cr-Fe-Nb-Mo (UNS N07718) alloy pipe flanges, fittings, valves, and parts [155]

Notably, no ASTM PM-HIP specifications cover low-alloy pressure vessel steels such as A508.

On the ASME side, PM-HIP was only acknowledged within the ASME BPVC code through code cases (see Table E1 in Appendix E). In 2021, ASME BPVC

Section II [156] endorsed approximately 30 HIP materials specified in ASTM standards (SA988/SA988M, SA989/SA989M, and SB834/SB834M) for the first time [75], [157]. This inclusion covers several austenitic SSs, ferritic steels, and Ni-based alloys for pressure-retaining applications [75].

Additionally, guidance for approval process of new materials was provided for qualifying and accepting PM-HIP under BPVC Section II, Part D, Mandatory Appendix 5 [158]. This guidance permits PM-HIP to be used for manufacturing components similarly to forged, cast, or wrought product forms, as long as the material can be qualified [157].

Materials accepted to be utilized in pressure-retaining applications under ASME BPVC Section II, must also be recognized by Section I [159], Section III [126], or Section VIII [160] [75].

Initially, PM-HIP of 316L SS, a commonly used material in NPPs, was recognized only under ASME BPV-III Code Case N-834 [77]. Section III recently recognized 316L SS under Mandatory Appendix XXVIII [161] [75], providing a blueprint for other PM-HIP materials in a nuclear facility and high-temperature reactor systems covered under Section III, Division 1 or Division 5, respectively. ASME's near-term target includes developing a PM-HIP code case for 316H SS for high-temperature reactor systems, using an approach similar to the BPV-III Code Case N-834 [77], [162]. Additional alloys anticipated in Section III over the next few years include SA508 LAS and several Ni-based alloys (600, 617, 625, 690 and 800H) [75].

4.5.2.1 Review Summary of Selected Relevant PM-HIP Standards

Table E2 in Appendix E summarizes relevant PM-HIP standards. ASTM specifications [153], [154], [155] provide fundamental requirements for material processing, including feedstock specifications and chemical composition of HIP-manufactured components. They also define detailed density, mechanical, and microstructural testing requirements. However, they offer limited guidance on supplier and personal qualification, and minimal direction for equipment or process qualification.

ASME BPV-III Code Case N-834 [77] governs PM-HIP-processed 316L SS for nuclear applications. It builds on ASTM A988/A988M by specifying key process variables, such as powder storage, feedstock particle size, test specimen protrusion length, and supplementary testing. If acid pickling is used to remove the can from the finished component, surfaces exposed to process fluids must be machined or ground to a specified depth. N-834 also sets a neutron dose limit of 1×10^{17} n/cm^2 within the component's design life.

It is important to note that while the reviewed ASTM and ASME standards do not address some AMT qualification requirements, other published standards exist. For example, ASTM A1080/A1080M-24 [163] provides quality control requirements for the HIP of steel, SS, and other related alloy castings, including equipment qualification, process parameter controls, and monitoring. ASTM A1080/A1080M also references key documents such as SAE AMS2750H [164], which outline detailed specifications for equipment and sensor calibration, temperature control, and autoclave (a pressure-containing vessel used in the HIP process) qualification.

Generally, ASME PBV-III Code Case N-834 [77] and Mandatory Appendix XXVIII to ASME BPVC Sec III [161] provide pathways for PM-HIP use in nuclear components. NRC approved N-834 for Class 1 components in NRC Regulatory Guide 1.84 [61], [165]. Other code cases, such as BPV-VIII Code Case N-2840-1 [166], extend PM-HIP provisions to ASME BPVC Section VIII components [61]. These documents can support PM-HIP qualification and regulatory acceptance in the regulatory sector.

4.5.2.2 Current Progress in PM-HIP Standards Development

Although integration of PM-HIP into ASME BPVC has progressed, further work is needed to expand its applicability to a wider range of nuclear-grade materials, such as LAS A508. As outlined in section 3.2.2.4, ongoing initiatives aim to develop new ASTM specifications and corresponding ASME code cases to establish PM-HIP as a qualified fabrication

route for critical nuclear components [74], [78]. In particular, current efforts led by EPRI and others to qualify PM-HIP processes for A508 LAS, targeted for use in RPV applications, are expected to form the technical basis for an ASTM specification, which in turn could underpin a future ASME code case [61].

4.5.3 EBW Standards

4.5.3.1 Review Summary of Selected Relevant Beam Welding Standards

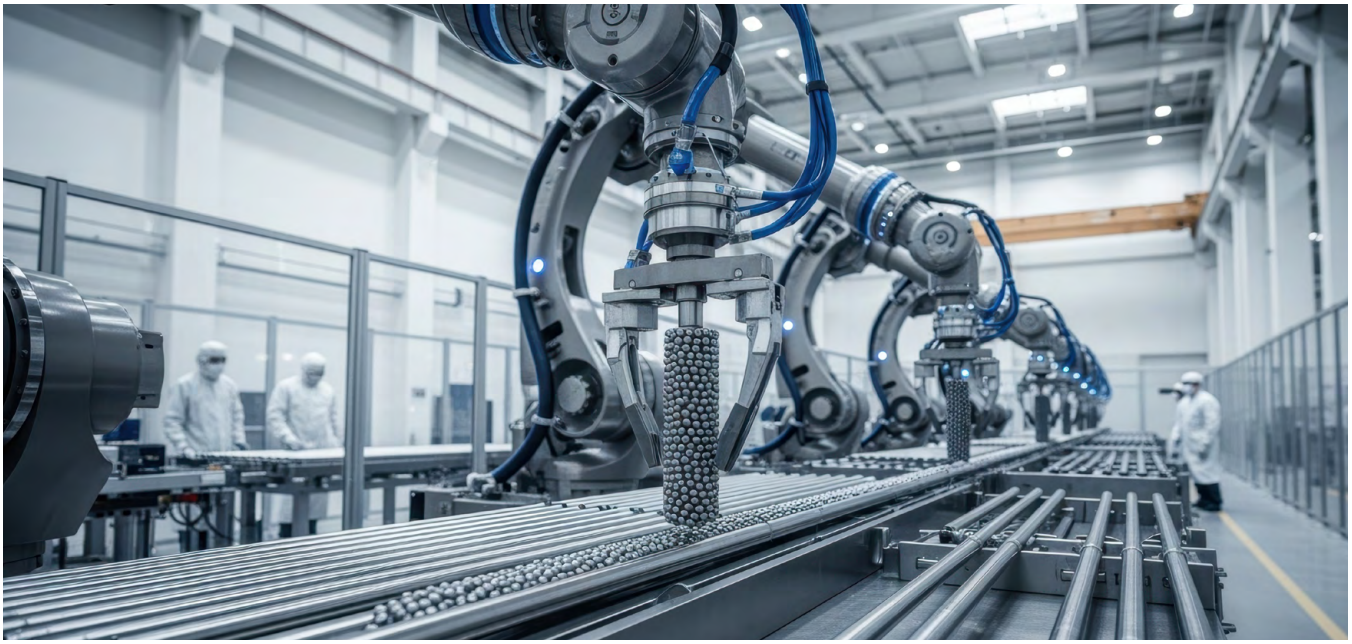
EBW is a well-established technology with existing standards supporting its commercial deployment across various industries, including nuclear. As such, this study did not review any specific EBW standard. Table 5 presents a range of welding codes and standards governing EBW applications.

4.5.3.2 Current Progress in Electron Beam Welding (EBW) Standards Development

Low standards development activities for EBW were observed in the literature. Although updates to existing requirements may be needed, considering the ongoing development of different variants of EBW systems, such as the MIC-EBW.

Table 5: Examples of standards supporting EBW applications [80], [167], [168]

Designation	Title
ANSI Z49.1 [169]	Safety in welding, cutting, and allied processes
AWS C7.1M [170]	Recommended practices for electron beam welding and allied processes
AWS A3.0M [171]	Standard welding terms and definitions including terms for AM, adhesive bonding, brazing, soldering, thermal cutting, thermal spraying, and non-destructive examination
AWS B1.10 [172]	Guide for the non-destructive examination of welds
AWS B2.1 [173]	Specification for welding procedure and performance qualification
AWS C7.3 [174]	Process specification for electron beam welding
ASME BPVC Section III [126]	Rules for construction of nuclear facility components
ASME BPVC Section V [175]	Non-destructive examination
ASME BPVC Section IX [176]	Qualification standard for welding, brazing, and fusing procedures; welders; brazers; and welding, brazing, and fusing operators
ASME BPVC Section XI [177]	Rules for in-service inspection of NPP components
ISO 14744-1 [178]	Welding – Acceptance inspection of electron beam welding machines Part 1: Principles and acceptance conditions
ISO/TR 17671-7 [179]	Recommendations for welding of metallic materials – Part 7: Electron beam welding
ISO 15609-3 [180]	Specification and qualification of welding procedures for metallic materials – welding procedure specification – Part 3: Electron beam welding
ISO 15614-11 [181]	Specification and qualification of welding procedures for metallic materials – welding procedure test – Part 11: Electron and laser beam welding
ISO 13919-1 [182]	Electron and laser-beam welded joints – Requirements and recommendations on quality levels for imperfections – Part 1: Steel, nickel, titanium and their alloys
ISO 22826 [183]	Destructive tests on welds in metallic materials – Hardness testing of narrow joints welded by laser and electron beam (Vickers and Knoop hardness tests)
SAE AMS2681B [184]	Welding, Electron beam
SAE AMS2680D [185]	Electron beam welding for fatigue critical applications



4.5.4 Additive Manufacturing Codes and Standards

Various SDOs are working to establish standards and specifications for AM processes. While standards indirectly supporting L-PBF, such as those for powder measurement and laser calibration, are already in place, standards for DED remain largely under development. Those focusing specifically on the L-PBF process have been developed, whereas available DED standards are typically included within broader AM standards that cover multiple AM techniques.

Because many DED standards also apply to L-PBF, both are reviewed together to avoid repetition and provide a comprehensive discussion. The Standardization Roadmap for Additive Manufacturing [24] provides an industry-wide assessment of AM standards. It identifies existing standards, ongoing developments, and key standardization gaps. It also offers recommendations for future research and harmonization. This document reviews AM standardization efforts across various industries such as aerospace, automotive, medical, and nuclear.

Table F1 in Appendix F lists relevant AM standards for different life cycle stages. The following standards and documents were identified as relevant to AM applications in the nuclear sector and selected for detailed review:

- ISO/ASTM 52904 – Process characteristics and performance of metal powder bed fusion for critical applications [186]
- ASTM F3184 – Specification for AM SS (UNS S31603) via powder bed fusion [187]
- NASA MSFC-STD-3716 – Standard for additively manufactured spaceflight hardware by L-PBF in metals [188]
- NASA MSFC-SPEC-3717 – Specifications for control and qualification of L-PBF metallurgical processes [189]
- NASA-STD-6030 – AM requirements for spaceflight systems [120]
- NASA-STD-6033 – AM requirements for equipment and facility control [190]
- AWS D20.1/D20.1M – Specification for metal component fabrication using AM [191]
- ASME PTB-13 – Criteria for pressure-retaining metallic components using AM [103]

4.5.4.1 Review Summary of Selected Relevant AM Standards

Table F2 in Appendix F summarizes the reviewed AM standards.

Most AM standards rely on existing specifications for conventionally manufactured components rather than defining AM-specific requirements. Standards such as ASTM F3184 [187] and ISO/ASTM 52904 [186] primarily reference conventional ISO and ASTM material standards instead of prescribing detailed technical requirements specific to AM manufacturing. These ASTM standards also lack guidance on personnel and equipment qualification, leaving aspects such as process qualification, part condition, finish, and inspection criteria to be defined through customer–supplier agreements. This lack of specificity limits their applicability to high-reliability applications like NNPs.

In contrast, AWS D20.1M [191] and National Aeronautics and Space Administration (NASA) standards [120], [188], [189], [190] provide detailed frameworks for machine, process, and component inspection qualification. They classify parts by failure consequence, structural demand, and other critical factors, enabling a graded approach to AM process qualification. These standards establish requirements for AM build interruptions and witness testing to ensure process control and validation. MSFC-STD-3716 [182], and NASA-STD-6030 [120], [188] introduce statistical methods to quantify sources of variability, such as anisotropy and feedstock variability, and to establish design values for AM processes, which are particularly relevant to high-precision applications. The inclusion of best-practice commentary in NASA standards further supports nuclear-specific AM standardization [120], [188], [189], [190].

ASME PTB-13 [103] takes a performance-based approach to qualifying pressure-retaining metallic components. It requires manufacturers to complete enough qualification builds to demonstrate, with 95% confidence, that 99% of produced material meets ASME material specifications. This criteria sets detailed qualification requirements, demanding testing for new machines and materials while allowing reduced qualification for previously characterized systems. The document specifies detailed requirements for test specimen design, mechanical testing, microstructural evaluation, and NDE. It also allows hybrid construction combining AM and non-AM (welded or brazed) components, provided the construction complies with the applicable ASME code or standard [103].

ASME PTB-13 is a criteria document, not a standard. It provides guidance on the essential elements that standards constructing metallic pressure-retaining AM equipment should include [25]. It serves as a reference document for developing AM code cases or additions to existing codes and standards [25]. In practice, manufacturers use these criteria with an existing ASME construction code or standard [103].

A recurring limitation across AM standards is the lack of provisions for active feedback control mechanisms, which could enhance process stability and real-time defect mitigation. Another difference among the standards is the variation in feedstock powder reuse requirements: ISO/ASTM 52904 [186]) specifies chemical conformance requirements, while NASA AM standards [120], [188] restrict powder reuse cycle if it has an adverse effect on performance (e.g., NASA AM standards [120], [188]).

Overall, AWS D20.1M [191], the NASA standards [120], [188], [189], [190], and ASME PTB-13 [103] offer more detailed frameworks for developing AM standardization in nuclear applications. Each standard addresses complementary areas that can collectively fill existing gaps.

4.5.4.2 Current Progress in AM Standard Development

Several SDOs continue to develop new standards and revise existing ones as AM technologies mature. For instance:

ISO/TC 261, ISO's technical committee (TC) for AM technologies, is developing new standards and technical reports to advance AM adoption [19]. Currently, ISO/TC 261 has 21 standards and/or projects under development addressing design guidelines for NDE, powder flow properties, data capture for PBF machine logs, among others. See [192] for further information.

SAE's AMS AM Metals Committee [193] is developing additional AM standards, including:

- SAE WIPARP7068, *In-situ process monitoring considerations for metal fusion additive manufacturing*. A recommended practice for in-situ process

monitoring across all fusion-based metal AM machines, applicable to PBF and wire- or powder-fed DED technologies [194].

- SAE AMS7032A, *Machine qualification for fusion-based metal additive manufacturing.* An update to SAE AMS7032 and defines a series of requirements that results in a specific AM machine qualified to produce material in compliance with an aerospace materials specification [195].

ASTM International's TC F42 on AM technologies continues to develop standards under multiple subcommittees focusing on design, materials, processes, and test methodologies [196]. ASTM International's Additive Manufacturing Centre of Excellence [197] also conducts strategic R&D to advance AM standards, publishing guidance on topics such as in-situ monitoring readiness and data management in AM operations [198].

The **AWS D20 Committee** is revising AWS D20.1 exclusively for processes using powder feedstock in either PBF or DED. A new standard, AWS D20.2, will address DED processes using wire feedstock [24].

ASME TCs' are also developing BPVC code cases for nuclear components. Ongoing work includes a draft code case for L-PBF 316L SS for use with BPVC Section III, Division 5, leveraging ASTM F3184 [199]. In 2023, ASME approved code case BPVCC N-3072 [200] for producing SS valve parts using AM PBF [115].

For DED applications, ASME committees have:

- Added qualification rules for GMA-DED in Article VI in the 2023 edition of ASME BPVC Section IX [115], [201]
- Drafted a code case for constructing pressure equipment using DED with wire feedstock [115], [202]
- Formed a task group to develop code cases or an alternative approach for the use of AM in ASME B16 [115]
- Begun developing a DED criteria document similar to PTB-13 for L-PBF [25]

Finally, the **Japanese Society of Mechanical Engineers** task group on AM drafting a code case for implementing AM technologies in nuclear component construction. Its concept, based on ASME PTB-13 [103], targets L-PBF and L-DED processes using Type 316L SS material [203].

5 AMT Standardization Gaps and Adoption Challenges for Nuclear Industry

5.1 Gaps in Existing Standards

5.1.1 Gaps in International AMT Standards for Nuclear Applications

Across all AMTs reviewed in this study, several key challenges to standardization were identified. The following summarizes the common gap themes.

- **Availability and inconsistencies among AMT standards**

Some AMTs, such as EBW processes, are supported by well-established standards, while others, like AM, are still evolving. Despite the availability of standards covering various stages of the production lifecycle—from design and feedstock control to process control and final part inspection—these standards are often fragmented. Users therefore rely on multiple standards developed for different industry sectors, which can lead to conflicting requirements for a particular AMT. For example, the variability in powder reuse criteria for some AM techniques with powder feedstock. AWS D20.1M [191] explicitly recommends against using powder reuse cycles as a metric for rejecting recycled powder, whereas the NASA AM standards [120], [188] suggest using the number of reuse cycles as a metric if it has a quantitatively adverse effect on performance.

Suppliers interviewed noted that they reconcile differences across multiple standards using a risk-informed approach based on part type, failure consequence, and customer's needs. However, this patchwork approach can create challenges in consistency.

Other AMTs, particularly CS, are covered by only a limited number of published standards. In the absence of standards, many organizations that extensively use AMTs have developed internal procedures for process control, QA, inspection, and performance validation. But much of this knowledge remains siloed within individual organizations.

Inconsistencies in terminology across standards, such as the interchangeable use of "recycle" and "reuse," further highlight the need for standardized definitions.

- **Gaps in Nuclear Applicability of AMT Standards**

Many existing AMT standards were initially developed for early-adopting industries such as aerospace and automotive. As a result, most feedstock control, process qualification, and material property testing standards focus on commonly used materials in these sectors (e.g., aluminum, magnesium, titanium alloys, and SSs). While some overlap exists with materials used in nuclear applications (e.g., 316L SS), technical standards and specifications covering advanced materials, including composites and alloys for SMRs and advanced reactor designs, are still under development or unavailable.

As identified through the literature review and supported by interviews, several nuclear-specific considerations re frequently missing in AMT standards. These include:

- Acceptable defect thresholds for radiation exposure
- Process control requirements for safety-class components
- Design acceptance criteria based on nuclear codes
- Requirements for traceability, documentation, and QA aligned with nuclear regulatory expectations

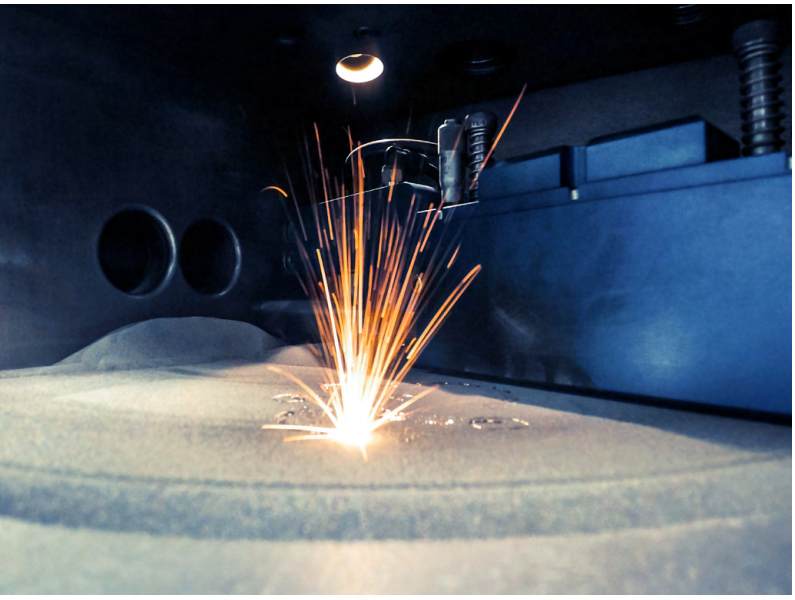
Without these adaptations, existing AMT standards face limitations in their adoption for direct use in producing and qualifying components for nuclear service.

Some standards (e.g., ISO/ASTM 52904 [186]) leave key requirements, including material property acceptance criteria, to be defined by customer–supplier agreements. This flexibility reflects sector-specific priorities: some industries focus on geometric tolerance, while others prioritize throughput or fatigue properties. However, for nuclear applications, such flexibility can create uncertainty and inconsistency, as safety-critical applications require clear, prescriptive acceptance criteria rather than case-by-case agreements.

Interview feedback reinforced these limitations. One SMR vendor reported they have had to fund extensive R&D to characterize an advanced alloy for reactor core use, citing the absence of relevant material specification standards to support their licensing submissions. This example illustrates the gap in materials specifications for nuclear-grade AMT and their potential regulatory implications. Although many ASTM and AISI material specifications exist for common materials, further development is needed to create material specifications for newer, advanced materials expected to operate under higher temperatures, radiation, or corrosive environments in some advanced SMR designs and applications.

In addition, many current AMT standards primarily cover short-term material testing and baseline mechanical properties (e.g., tensile strength, hardness, and dimensional tolerances). However, nuclear components require assurance of long-term performance. Existing material standards often lack guidance for nuclear-relevant criteria such as creep and fatigue resistance, and neutron irradiation tolerance. This absence of such critical data and testing protocols limits their applicability in the nuclear sector.

Some standards also lack pertinent testing specifications, instead referencing generic testing standards. Conventional destructive and non-destructive testing methods may not adequately AMT-specific variability (e.g., porosity and anisotropy) found in certain AMTs like AM technologies. Therefore, material standards specific to AMTs are needed before AMT-produced components can be accurately and properly defined. AMT-specific testing specifications should also be developed, requiring extensive research into potential AMT-specific failure mechanisms and variability effects.



"Several interviewed industry experts viewed some process qualification requirements as overly rigid, limiting their use in nuclear applications."

Finally, several interviewed industry experts viewed some process qualification requirements as overly rigid, limiting their use in nuclear applications. While some technical standards use graded process qualification approaches based on part classification (e.g., consequences of failure, structural demands), others do not. Many require locked-in, unalterable processes after qualification, meaning even minor parameter adjustments can trigger complete requalification—an expensive and time-consuming process. While such rigidity is appropriate for safety-critical components, it may be unnecessarily burdensome and cost-prohibitive for non-safety-critical components and can stifle innovation, especially for technologies that benefit from real-time process control or adaptive parameter tuning, such as metal AM. Current existing standards do not typically accommodate such flexibility (see Appendix G for more details).

5.1.2 Gaps in AMT Standards Addressing Needs of Canadian Nuclear Industry

While international technical standards cover certain AMTs requirements, none currently address the specific needs of the Canadian nuclear industry. However, the CNL-NRCan project [33], detailed in section 3.2.4.1, is expected to generate Canadian guidelines for mostly AM applications in the nuclear industry.

A review of CSA nuclear standards identified several areas where existing documents may not fully address the requirements or considerations introduced by AMT-based manufacturing.

CSA N286 sets out the overall management system requirements for NNPs, while **CSA N299**—often invoked for nuclear procurements—outlines quality requirements for the supply chain. However, the requirements in their current editions are not tailored to AMTs, particularly regarding design, special processes, and procurement.

CSA N285.0 bridges the gap between established ASME pressure boundary requirements and Canadian nuclear industry needs. While it benefits from ASME's ongoing efforts to incorporate AMT considerations, certain gaps remain unaddressed, such as provisions for inspectability of AMT-produced parts, degradation mechanisms unique to AMTs, and AMT-specific inspection processes.

Other CSA reviewed (tables C1–C6 in Appendix C) may also lack requirements related to aging or failure mechanisms, inspection or NDE, environmental qualification, and guidance for AMT considerations.

5.1.3 Gaps Related to Specific AMTs

5.1.3.1 Gaps in CS Standards

Several key gaps identified in CS standards include:

- Limited Public Standards: Only three publicly available CS standards [147], [148], [150] (discussed in section 4.5.1) were identified and visible ongoing standardization efforts remain scarce. Coordinated initiatives are needed to address this gap as CS gains traction in nuclear and other critical industries.

- Application Limitations: Existing military specifications focus mainly on non-structural coatings, leaving structural CS applications unaddressed.
- Limited Testing Standards for CSAM Applications: Current military specifications reference inspection and testing standards for CS coatings but not for CSAM applications or structural applications. CSAM-specific post-processing specifications and testing standards to assess the long-term performance of produced parts under service conditions. In particular, NDE testing methods for assessing bond strength, especially in thicker CS depositions, remain underdeveloped and represent an area where further R&D is needed [40].
- Inadequate Process Guidance: The reviewed MIL process standard [148] provides general deposition requirements but lacks detailed process controls. Given CS's inherent variability and its sensitivity to factors such as such as feedstock properties, gas pressure, temperature, nozzle design, and deposition angle, more comprehensive and tailored process standards and specifications are needed. These could include application-specific guidance to ensure consistency, reliability, and suitability for critical use within the nuclear sector.
- No Nuclear-Specific Standards: No CS standards currently address nuclear-specific applications. Existing military standards may offer a preliminary foundation but are not tailored for this context.

5.1.3.2 Gaps in PM-HIP Standards

Unlike CS, PM-HIP has some nuclear-specific standards available (see section 4.5.2). However, several standardization gaps remain:

- Design Standards: No standard specifically addresses PM-HIP components design. Such a standard may exist but is not widely accessible and is not a major limitation in practice. Design for HIP components typically relies on geometry-specific considerations for the HIP can and estimates of its volumetric shrinkage during consolidation. Generic design guidance exists in technical literature [204], [205], and PM-HIP designers typically depend on iterative computer modelling and simulations, supported by material property data and past trials to achieve the desired final part shape and properties. Regardless, a dedicated design standard is needed to ensure comparability, repeatability, and broader confidence in PM-HIP nuclear applications.
- Feedstock Control: A review of PM-HIP for NPP components [61] determined that existing standards for powder characterization are sufficient to support nuclear applications of PM-HIP. But the report also noted that process standards addressing powder handling and storage should be developed to minimize contamination risks and improve consistency in final component performance.
- Limited Material Coverage: Currently, process standards for PM-HIP applications in nuclear only address a narrow set of materials. For example, only 316L SS is permitted for PM-HIP use under ASME BPVC Section III [126]. Additionally, while ASTM PM-HIP process specifications exist for SSs, alloy steels, and some non-ferrous materials, specifications for LASs, such as A508 grade—of high interest for nuclear RPVs—do not yet exist. Future standards should consider the susceptibility of these alloys to acid during post-processing. For example, provisions should address that can removal for LAS materials should be accomplished through machining rather than acid pickling [61].
- Personnel Certification and Operational Qualification: No reviewed standards address certification of personnel involved in PM-HIP operations. However, feedback from industry engagement indicates that organizations typically rely on internally developed procedures for auditing and verifying personnel experience and qualifications for PM-HIP operations.

5.1.3.3 Gaps in EBW Standards

A review by Faraone *et al.* [80] found no significant gaps in standards for EBW use in nuclear applications. The process is permitted under multiple sections of the ASME BPVC (see Table 5) without restrictions on base material types and is allowable for welding RPV sections. However, ASME BPVC Section III explicitly restricts the welding of instrument tubing to gas-tungsten arc welding. Other limitations may apply to the welding of structural attachments specified in ASME BPVC Section III.

The BPVC Sec. III Code does not specifically restrict EBW for these joints, but EBW implementation is less straightforward because joint design requirements for these attachments typically suit conventional arc welding processes. Modifying joint designs could improve EBW applicability, but the feasibility of such changes depends on whether the cost-benefit advantage of using EBW over conventional welding justifies the required adaptations [80].

5.1.3.4 Gaps in AM Standards

Despite significant progress in developing L-PBF and DED AM standards, notable gaps remain across multiple life cycle stages. This section outlines key AM standardization gaps across six thematic categories: design, feedstock materials, processing, qualification and certification, testing, and gaps specific to nuclear applications.

Design Standard Gaps:

AM's design freedoms introduce complexities not fully addressed in existing AM design standards. Detailed specifications are needed for designing AM components for final part inspection and testing, especially for components with complex internal channels or lattice structures. Designs must ensure these parts can be cleaned, inspected, or stress-relieved afterward.

Existing design standards also lack detailed design considerations for post-processing operations. Most AM parts undergo post-processing steps such as machining, heat treatment, or HIP, which can alter dimensions (e.g., shrinkage, distortion), microstructures, or surface properties. Without detailed specifications that anticipate these changes during design, final AM parts risk non-conformance or costly rework. Standards like ASTM F3530-22 [206] and ISO/ASTM 52910-18 [207] include high-level discussions of design considerations for post-processing; however, more detailed design specifications addressing specific AM processes, materials, and applications are needed [208].

Feedstock Materials Gaps:

Although several standards exist for feedstock control, critical gaps remain in material standards. Limited guidance exists on powder sampling protocols, internal porosity thresholds, and morphological specifications [208].

Process Standards Gaps include:

- Process Control Specifications: Standards are needed to address machine calibration and preventive maintenance for AM processes. Current AM users may not have established best practices or internal procedures and may assume that original equipment manufacturer maintenance procedures are enough for production [208]. Requirements for machine calibration and calibration frequency also vary across standards. Few standards directly address in-process monitoring for AM. While some sensor technologies are mature, data processing and analysis techniques for the measured data (e.g., for flaw identification) remain at lower technology readiness levels (see Appendix G).
- Post-Processing Specifications: Many existing process standards provide limited material coverage for heat treatment (HT) of PBF-built parts. Broader material-specific HT requirements are needed. In addition, differences between laser-based and electron beam-based PBF processes are not sufficiently addressed. Although both processes are considered the same in terms of HT requirements, PBF-EB is performed at higher temperatures and produces more uniform microstructures, potentially requiring less or no stress [208].

  HT requirements for metals made with non-powder AM processes, such as DED using wire feedstock, are currently not addressed in any standards except for titanium-6Al-4V via DED (SAE AMS7004 [209]) [208].

  Similarly, existing HIP standards do not fully address AM material-related issues. The HIP parameters in current AM standards were developed for castings, forgings, and sintered parts. These may not be optimal for AM materials, as their thermal history, as-printed microstructure, and property requirements often differ significantly from those of conventionally manufactured materials [208]. Furthermore, since AM components used in NPPs would need to be joined with other components (AM or conventional), standards addressing welding AM parts are needed [97].

Qualification Gaps:

One challenge to qualification is that much of the knowledge on demonstrating key variables and maintaining process stability in serial production remains proprietary. More publicly available research is needed.

AM part risk classification systems also vary across existing standards. These systems describe the level of risk associated with a part and serve as a metric to gauge appropriate qualification requirements. A standardized approach is needed to define common AM failure modes and a method for determining qualitative failure likelihood or quantitative failure probability for each mode [208].

For non-metallic AM materials such as silicon carbide, which are being evaluated for high-temperature nuclear applications, no process standards support their use [208]. Training and certification requirements for AM operators are also inconsistent across existing standards.

Testing Standards Gaps:

While existing mechanical test methods for traditionally manufactured parts are applicable, new testing standards are needed to address unique AM attributes such as anisotropy, heterogeneous microstructures, and surface effects, especially for functionally graded or multi-material parts. NDE testing standards should address AM-specific defect types. Testing standards for internal feature metrology and in-service inspection, particularly for components exposed to radiation and chemical degradation, are also lacking. Furthermore, NDE acceptance criteria for fracture-critical AM parts remain undefined [208].

Gaps Specific to Nuclear Applications:

At present, there are no nuclear-specific standards for the AM of either metallic or non-metallic components. Gaps remain in long-term performance data under irradiation, high temperature, and corrosive environments typical of nuclear service. In-service inspection protocols have not been established. Additionally, promising innovations, such as embedded sensors within AM components for real-time monitoring, lack standard integration pathways, limiting their adoption in nuclear and similarly regulated sectors [208].

5.2 Challenges in Adopting AMTs and AMT Standards in the Canadian Nuclear Industry

Interested parties across Canada's nuclear industry identified several challenges directly related to standardization and the effective adoption of AMTs within the sector. These challenges fall primarily into three categories: awareness and knowledge gaps, unclear expectations for AMT standards, and integration with existing regulatory and quality frameworks.

- Limited Awareness and Understanding of AMT Standards: A recurring theme across interviews was the limited awareness of AMT standards, how to interpret them, and how they apply in nuclear contexts. While international standards are emerging, key industry players remain unaware of their scope or how to use them effectively. Given the variety of AMTs and their unique characteristics, AMT standards can span a wide array of subjects. For instance, AM standards cover design, feedstock control, process control, qualification, and part inspection and performance. Within these areas, sub-categories, such as powder feedstock characterization and sieving, can add complexity.
- Unclear Expectations for AMT Standards in Nuclear Use: Few nuclear-specific AMT standards exist. Industry engagement revealed no shared understanding of what a nuclear-appropriate AMT standard should include to be considered complete and acceptable. Several interviewees expressed the need for guidance on what AMT qualification content to look for when selecting standards for AMT nuclear applications.
- Uncertainty Around Regulatory and Quality System Integration: Another challenge raised by interviewed experts was uncertainty about how AMT-produced components align with existing nuclear QA and regulatory frameworks.

Several interviewees, particularly from utilities, expressed uncertainty about how AMTs integrate with CSA nuclear standards. Questions arose about how AM parts should be procured, evaluated, and documented under existing QA programs, and what regulatory pathways or precedents exist for adopting AMT-manufactured components in NPPs.

One interviewee noted that while CSA N299 standards provide general QA requirements, they lack specific technical guidance for AMT-produced components. For instance, procurement teams may rely on conventional expectations, such as using certified material test reports from raw feedstock to assess material properties. However, in AM, final part properties can differ significantly from those of the feedstock. Without awareness of these differences, utilities may not request additional QA measures, such as test coupons printed alongside components for verification. This knowledge gap underscores the need for targeted implementation guidance to support effective procurement and qualification of AMT parts within existing standards frameworks.

Interviewees identified such uncertainties as a key source of hesitation and delay in adopting AMT components. Some confusion may stem from limited understanding of nuclear QA standards and their requirements, highlighting the need for continued awareness-raising across the industry on the development and application of technical and quality standards.

6 Recommendations and Considerations

This study identified several gaps in existing Canadian and international standards, as well as practical challenges to the adoption of AMTs and AMT standards in Canada's nuclear sector. To address these issues, a set of targeted recommendations is proposed for consideration. These recommendations focus on three interrelated areas discussed below.

1. Develop Canadian AMT-Specific Standards and Support Their Implementation

The research assessment, based on a literature review and engagement, identifies a clear overall need for developing AMT-specific technical standards or guideline documents to support AMT use in nuclear applications. Interview participants believed it would be particularly beneficial to have Canadian AMT-specific standards or guideline documents that the domestic nuclear industry could reference. These AMT-specific standards could initially be applied in non-safety-related applications, where risk is lower and adoption is more feasible, before being expanded to safety-related applications as experience and confidence grow.

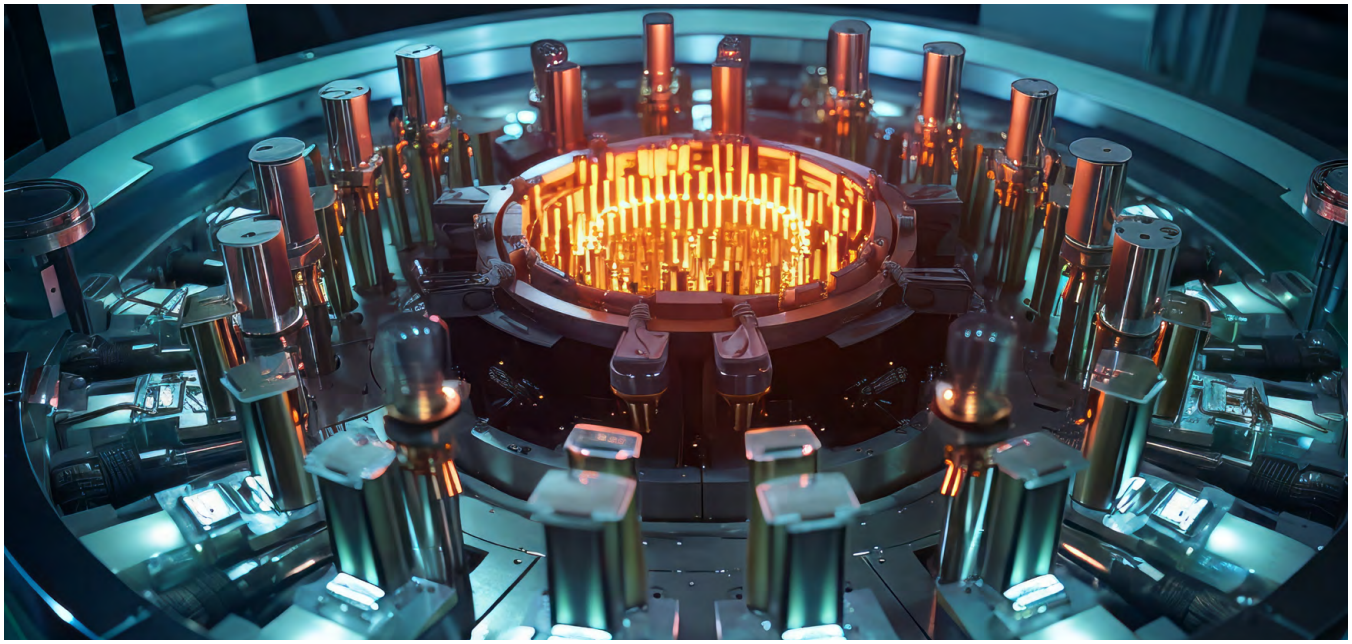
Even when technically robust standards exist, their effectiveness depends on whether users understand how to apply them. Interviewees suggested that the approach of publishing companion materials, such as implementation guides, FAQs, and technical supplements, could be extended to AMT-specific standards. Development of case studies was also strongly recommended as a means of building confidence. Case studies could demonstrate how to adopt and implement AMT standards for specific nuclear-grade components, showcasing lessons learned and best practices from both Canadian and international experiences.

Furthermore, there is a need for training programs focused on how AMTs integrate with existing nuclear QA systems. Targeted training for procurement teams, QA professionals, designers, and regulators would help bridge knowledge gaps, reduce uncertainty, and foster consistent application of AMT standards across the Canadian nuclear supply chain.

2. Update CSA Nuclear Standards to Include AMT-Specific Considerations

While CSA nuclear standards provide a foundation for QA and compliance with licence conditions, many were developed around conventional manufacturing methods and do not reflect the unique characteristics of AMTs. Some of these standards could therefore integrate AMT-specific considerations.

The CSA N299 and CSA N286 series could be revised to include AMT-related provisions for design, special processes and procurement, particularly for SMRs and new reactor technologies. For example, the following modifications of the following CSA N299.1 and N299.2 sections could be considered:



- Design: In Annex C (Guidance on Design), Clause C2.2 (Design Process) could specify AMTs as one of the "pertinent design inputs."
- Procurement: In Clause 7.6.3 (Subcontract Requirements), identifying a product as AMT-manufactured could be added to the information suppliers must list.
- Special processes, in Clause 7.14.2, AMT manufacturing could be considered as a special process subject to the relevant qualification and control requirements.

For CSA N286, it is recommended to consider addition of a section addressing the introduction of new technologies, such as AMTs.

For CSA N285.0, it is recommended to consider adding sections containing requirements for inspection and examination of AMT-specific degradation.

Other CSA nuclear standards could also consider adopting materials produced by AMTs and defining requirements for their unique characteristics, such as aging or failure mechanisms, inspection or non-destructive evaluation requirements, environmental qualification (especially exposure to radiation and neutrons), and limited operating experience data. Examples include:

- CSA N287.1 [132]: Section 4 (General safety system requirements), Clause 4.13.4 on aging could include a note addressing special considerations for new products manufactured using AMTs.
- CSA N289.1 [138]: Clause 5.3.2 (Seismic qualification by analysis) and/or Clause 5.3.6 (Experience-based approach), could include a note cautioning that insufficient data may limit the applicability of traditional seismic design approaches to AMT-manufactured products.
- CSA N287.5 [136]: Clause 10.2 (Inspection) could be expanded to include metal components produced using AMTs and to verify the effectiveness of AMT process qualification procedures.
- CSA N290.13 [144]: Section 5.2.2 (Equipment specifications) and/or Clause 5.2.3 (Qualification Plan) could add a listing of AMT manufacturing as a consideration.

3. Advance R&D to Support AMT Standards Development

Further R&D is needed to enable the development of AMT standards, particularly for nuclear applications. Many of the current gaps in AMT-related standards stem from limited data availability, insufficient understanding of AMT-specific material properties, unclear processing

and post-processing requirements, and the lack of validated AMT-specific testing protocols.

Priority areas for applied R&D of AMT to inform standards include:

- Establishing AMT-specific material property specifications for nuclear-grade materials and advanced materials
- Developing process qualification methodologies
- Advancing NDE techniques tailored to AMT-manufactured components

Additional research is also needed to generate long-term performance data under nuclear operating conditions. Together, these efforts would help define qualification data for AMT use in nuclear environments, material acceptance criteria, and testing protocols aligned with nuclear requirements.

Interviewees also highlighted the importance of making research results publicly accessible. Much of the critical data is siloed within organizations that have independently funded their own research. Public or jointly funded research initiatives were viewed as key to promoting collaboration and ensuring broader access to information, including to standards development committees.

7 Conclusion

This study explores the role of AMTs in Canada's nuclear industry. It identified five AMTs with current or emerging relevance—CS, PM-HIP, EBW, L-PBF, and DED—and recommends three main actions:

1. Creating Canadian AMT-specific standards and guidance documents
2. Integrating AMT considerations into current CSA nuclear standards
3. Advancing R&D to support associated standards development.

Early standardization efforts could focus on lower-risk components. Several AMTs are already mature in standardization efforts across multiple sectors, including limited nuclear industry use cases. For AMTs still evolving in nuclear contexts, well-established precedents in other highly regulated industries such as aerospace, civil aviation, and defence offer valuable standardization roadmaps for the nuclear industry. While nuclear applications require an additional layer of assurance, cross-sector insights can accelerate adoption and build confidence in Canada's nuclear supply chain as it advances AMT adoption.

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Appendix A – Description of Relevant Advanced Manufacturing Methods Initially Identified by Nuclear Energy Institute (NEI)

The following table summarizes advanced manufacturing methods relevant to the nuclear industry.

Table A1: NEI's list of advanced manufacturing methods pertinent to nuclear power plants. Adapted from [5]

Process types	AMT	Brief description
Surface modification/ coating	Chemical vapour deposition (CVD)	A process where gaseous chemical precursors react on a substrate surface to form a solid coating. CVD is used for creating thin films with applications in semiconductor and aerospace industries [210], [211].
	Cold spray	Uses high-velocity gas to accelerate powdered material onto a substrate, which bonds without melting, resulting in a dense coating or build-up of material with minimal thermal distortion [37].
	Laser peening	A process where high-energy laser pulses induce compressive stress on the surface of a material, improving its fatigue resistance, wear resistance, and overall mechanical properties [212].
	Physical vapour deposition (PVD)	A technique where material is vaporized in a vacuum and then condensed onto a surface, forming thin films for coatings with applications in electronics, optics, and protective surfaces [213]
Near-net shape manufacturing	Powder metallurgy – hot isostatic pressing (PM-HIP)	A process where metal powder encapsulated in a container mirroring the shape of the desired part is exposed to high temperature and pressure, to consolidate the powdered metal into a dense, near-net shape component [64].
	Investment casting	A precise manufacturing process where a wax or plastic pattern is coated with a ceramic slurry to create a ceramic mold, which is then heated to remove the pattern and harden the mold. Molten metal is then poured into the mold to form the part [214].
Joining/ cladding	Adaptive feedback welding	A welding process that uses real-time data from sensors to adjust welding parameters, improving the quality and consistency of welds [215].
	Diode laser cladding	A process where a laser system melts material onto a substrate, forming a coating that enhances surface properties like hardness, wear resistance, and corrosion resistance. Typically produces a high-quality clad having extremely low dilution, low porosity, and good surface uniformity [216].
	Electron beam welding with high post-weld heat treatment	Electron beams are used to melt and join materials, followed by post-weld heat treatment to refine the material's microstructure, enhancing its mechanical properties and reducing stress [80].
	Friction stir welding	A solid-state welding process where a rotating non-consumable tool generates heat through friction to join materials without melting them, resulting in strong and defect-free welds. Typically used in modern shipbuilding, trains, and aerospace applications [217].
	Hybrid laser arc welding (HLAW) and hybrid laser-gas metal arc welding (HL-GMAW)	HLAW process combines the principles of laser beam welding and arc welding. This combination uses the laser for high precision and the arc for faster, deeper penetration, resulting in high-quality, strong welds with very narrow heat-affected zones compared to traditional processes [218]. HL-GMAW is a specific type of HLAW where a laser beam is combined specifically with GMAW [219], [220].
	Laser cladding technology (LCT)	A processing technique for adding one material to the surface of another in a controlled manner. Often used in repair of damaged or worn surfaces, improving the surface characteristics such as hardness, wear resistance, or corrosion resistance [210], [221].

Process types	AMT	Brief description
Additive Manufacturing	Powder bed fusion	The powder bed process involves a laser or electron beam selectively fusing powdered material, layer by layer, to create a solid object. Typically used for metals, polymers, and ceramics [97].
	Direct energy deposition (DED)	In DED, focused thermal energy (such as a laser or electron beam) melts and deposits material onto a substrate. DED is often used for repair and coating applications [113]
	Binder jetting	Involves a printhead depositing a liquid binding agent onto a bed of powdered material. The binder fuses the powder particles together, forming a solid object which is later cured [222].

Appendix B – Advanced Manufacturing Technique (AMT) Initiatives in Nuclear Industry

Many organizations are currently undertaking efforts to explore and advance the use of AMTs within nuclear applications. These initiatives span research, standards development, pilot projects, and cross-sector collaborations, both in Canada and internationally. The following provides a summary of some key AMT-related activities identified through literature review and industry engagement.

Generation IV International Forum

The Generation IV International Forum for Advanced Manufacturing and Materials Engineering Working Group (GIF AMME WG) was established in October 2023, continuing the initiatives started by the GIF AMME Task Force (AMME TF) in 2018 [22]. Currently, it includes nine member countries, including the United States, United Kingdom, and Canada. A key objective of the AMME WG is to enhance international, collaborative research and development (R&D) efforts in certifying AMME processes for Generation IV reactor applications. The AMME WG established task groups (TG) in four topic areas:

- TG1 – Survey on advanced manufacturing applications in industry
- TG2 – Sharing, coordination, and demonstration of work on the qualification of advanced manufacturing
- TG3 – Modelling and simulation approaches for the qualification of advanced manufacturing
- TG4 – Experimental approaches for the qualification of advanced manufacturing

Since it was established, the AMME WG members have contributed to several international advanced manufacturing workshops for GEN-IV small modular reactor (SMR) concepts [223].

UK Business, Energy, and Industrial Strategy (BEIS) Nuclear Innovation Programme

The UK's Nuclear Innovation Programme, launched by BEIS, aims to strengthen the country's nuclear sector and position it for future global markets. One of its five key areas, the Advanced Manufacturing and Materials program, is dedicated to building a strong R&D base to support the UK nuclear supply chain and enhance its role in global SMR and advanced reactor deployment [23].

The program has progressed in two phases: Phase 1 (2017–2019) provided initial funding to develop advanced manufacturing technologies, while Phase 2 (2020–present) focuses on advancing these technologies toward demonstration and commercialization [224]. Phase 2 has supported multiple industry-led projects, including Rolls-Royce's Project Future Advanced Structural Integrity (FAST) (see section 3.2.2.4 on PM-HIP) and Sheffield Forgemasters' work on electron beam welding (EBW) for nuclear-grade steels [225].

US Department of Energy (DOE) Office of Nuclear Energy

The US DOE Office of Nuclear Energy established the Advanced Materials and Manufacturing Technologies (AMMT) program in 2022 to accelerate the development, qualification, and deployment of advanced materials and manufacturing to support US leadership in a broad range of nuclear energy applications [12]. This program aims to strengthen the pipeline of new materials that can make the current fleet and new advanced reactors more resilient and economically competitive [3]. Four major goals were set for this program:

- Develop AMMT
- Evaluate materials performance in nuclear environments
- Establish and demonstrate a rapid qualification framework
- Accelerate commercialization through technology demonstration

Since its inception, the AMMT program has integrated programs like the Transformational Challenge Reactor and the Nuclear Materials Discovery and Qualification Initiative, and released an AMMT Roadmap in 2022 [3]. Activities under the AMMT program include conducting basic and applied research, advancing technology development, building data infrastructure, and developing a qualification framework to support AMT implementation in the deployment of advanced reactors.

The US DOE also facilitates other additive manufacturing (AM) technology projects, most of which are specific to a particular technology and are discussed in their corresponding detailed AMT sections of this document.

US Nuclear Regulatory Commission (NRC)

The NRC has been actively engaged in evaluating AMTs to assess their potential impact on nuclear applications requiring regulatory oversight since 2017 through its AMT program [9]. Recognizing the increasing industry stakeholders' adoption of AMTs, the NRC launched a structured approach to understanding, evaluating, and developing regulatory frameworks for AMT implementation. In 2019, the NRC released a Draft NRC AMT Action Plan [6], outlining a systematic approach to addressing AMT-related regulatory considerations. The NRC has also hosted three AMT workshops (2017, 2020, 2023), providing a platform for industry stakeholders to exchange insights on AMT qualification, certification pathways, and recent developments in codes and standards. These workshops play a crucial role in advancing technical understanding and aligning regulatory strategies with industry progress.

The NRC has focused its initial activities on five specific AMTs: cold spray (CS), laser-power bed fusion, direct energy disposition (DED), EBW, and PM-HIP, the same techniques selected for review in this project. As part of its AMT Action Plan, the NRC has developed the following key resources:

- Technical Letter Reports (TLRs): Prepared by NRC contractors (primarily DOE national laboratories) to provide technical background and gap analyses on AMTs.
- Technical Assessments (TAs): These documents present the NRC staff's evaluation of key AMT aspects, focusing on safety and component performance.
- Draft Guideline Documents: Based on insights from TLRs and TAs, these NRC-generated documents outline regulatory guidelines for AMT qualification and use in nuclear applications.

Through these initiatives, the NRC continues to refine its regulatory approach, ensuring that AMT adoption in nuclear applications meets rigorous safety, quality, and performance standards. A more detailed overview of the US NRC's AMT activities can be found in this resource [226].

America Makes and ANSI Additive Manufacturing Standardization (AMSC) Collaborative

The AMSC was established in 2016 as a joint effort between America Makes and American National Standards Institute (ANSI) [24]. The initiative was supported by federal agencies such as the National Institute of Standards and Technology (NIST), the Department of Defense (DoD), and the Federal Aviation Administration (FAA), along with various standards development organizations (SDOs).

Rather than developing standards directly, the AMSC serves as a coordination platform, bringing together original equipment manufacturers, industry leaders, government agencies, academia, and SDOs to create a standardization roadmap for AM adoption. The roadmap has evolved through three versions (2017, 2018, 2023), expanding from an initial focus on metallic AM in aerospace, defence, and medical sectors to now include polymers, electronics, oil and gas, and nuclear applications [24].

American Society of Mechanical Engineers (ASME)

ASME plays a leading role in advancing AMT development through standards, research, technical committees, and cross-sector collaboration. Notably, its Working Group on Advanced Manufacturing under Section III of the Boiler and Pressure Vessel Code develops rules for the physical material properties, and special testing, requirements for fabrication and stamping of items manufactured by AMTs including but not limited to: PM-HIP, DED, powder bed fusion, CS deposition/cladding, and diode laser cladding under the jurisdiction of Section III, Division 1 – Article 2000 [25].

ASME's BPTCS/BNCS Special Committee on Additive Manufacturing also supports AM standardization. It published PTB-13 Criteria [103], outlining essential elements for pressure-retaining equipment using PBF and is currently developing a similar criteria document for DED [25].

Beyond these, ASME supports broader advanced manufacturing initiatives across multiple advanced manufacturing topics as shown in this resource [25]. ASME also engages actively in industry collaboration. Notably, it partners with Electric Power Research Institute on energy-sector innovation and research. These collaborations include joint exploration of AMT applications in nuclear component qualification, code case development, and pilot demonstration campaigns.

World Nuclear Association

The Mechanical Codes and Standards Task Force (MCSTF) is one of the task forces of Cooperation on Reactor Design Evaluation and Licensing (CORDEL) set up by the World Nuclear Association in 2011 to collaborate with regulators, industry, and SDOs to promote the convergence of nuclear mechanical codes and standards and facilitate the international standardization of reactor designs [26]. The MCSTF advocates for the harmonization of various codes and standards development activities. As multiple AMT qualification and standardization initiatives proceed globally, this is essential, particularly for factory-based international deployment of SMRs. The CORDEL group recently released a report in 2022 titled "Advanced Manufacturing of Nuclear Components" [26]. The report presented ongoing and completed advanced manufacturing projects in the nuclear industry and the challenges faced by these projects regarding the application of codes and standards and obtaining regulatory acceptance. The projects presented were carried out in Belgium, France, Russia, the United Kingdom, and the United States and cover a variety of regulatory regimes and codes and standards.

International Atomic Energy Agency (IAEA)

The IAEA has increasingly focused on advanced manufacturing in recent years, as recent high-level reviews to assess the applicability of existing IAEA safety standards to new innovative reactors identified advanced manufacturing methods as one of the gaps and areas warranting additional considerations [227], [228]. To further address these challenges, a specialized working group focusing on manufacturing, construction, commissioning, and operations was formed in Phase 2 of the SMR Regulator's Forum to respond to a concern that the manufacturability of SMRs could pose challenges during regulatory reviews [229]. The IAEA also recently agreed to expand its cooperation with GIF to include advanced manufacturing [230].

In November 2024, the IAEA hosted a Technical Meeting on Advanced Manufacturing and Qualification Programmes for New Materials for Small Modular Reactors and Non-Water-Cooled Reactors: Safety Considerations. This event provided a platform for member states to exchange insights on the safety considerations related to new materials and AMTs for SMRs and non-water-cooled reactors, particularly their qualification for challenging operational environments. Outcomes from this meeting will inform a forthcoming IAEA publication titled "Considerations for Qualification of Advanced Manufacturing and Materials for Components Important to Safety in Small Modular Reactors and Non-Water Cooled Reactors" [227].

Canadian Initiatives

Canadian Advanced Manufacturing in Nuclear Alliance (CAMiNA)

CAMiNA is an industry-led body representing suppliers, utilities, research organizations, universities, and government entities [231]. It oversees progress on the Advanced Manufacturing Roadmap for the Canadian Nuclear Industry, released by the Organization of Canadian Nuclear Industries in January 2022. CAMiNA also collaborates with international groups, including the GIF AMME Task Force, and has hosted events like the Advanced Manufacturing Workshop at the G4SR-4 conference in 2022 to promote AMT adoption in the advanced reactor supply chain [232].

Canadian Nuclear Society (CNS)

The annual CNS international conference on Disruptive, Innovative, and Emerging Technologies in the Nuclear Industry is a valuable Canadian initiative that facilitates AMT adoption by providing a forum for nuclear industry professionals, academics, and regulators to exchange views, ideas, and information on innovative technologies that are available or currently impacting the nuclear industry [233].

Next Generation Manufacturing Canada (NGen)

NGen funded a project titled Advanced Manufacturing for Small Modular Reactors: Implications for the Saskatchewan Supply Chain led by the Saskatchewan Industrial & Mining Suppliers Association Inc. [7]. The project assessed how AMTs could support SMR manufacturing in Saskatchewan, highlighting existing pain points in nuclear manufacturing. It included a review of AMTs, analysis of Saskatchewan's manufacturing capabilities, and surveys of active SMR vendors in Canada to understand their interests in AMTs and potential applications and adoption timelines. The study identified key opportunities for local industry participation, shortlisted high-impact AMT applications, and outlined skills and training needs to support a future SMR manufacturing ecosystem, pending proposed SMR deployments in the province.

Appendix C – Summary Tables of CSA Nuclear Standards Review

This appendix presents tables providing an overview of specific CSA nuclear standards that may be relevant to advanced manufacturing techniques (AMTs).

Table C1: Overview of standards that may be relevant to AMTs: CSA N285 series

CSA N285 Series: CANDU nuclear power plant pressure-retaining systems and components	
Relevant standards in the series	▪ CSA N285.0:23/N285.6, *General requirements for pressure retaining systems and components / Material standards for reactor components* [124] ▪ CSA N285.4, *Periodic inspection of CANDU nuclear power plant components* [127] ▪ CSA N285.5, *Periodic Inspection of CANDU nuclear power plant containment components* [128] ▪ CSA N285.7, *Periodic inspection of CANDU nuclear power plant balance of plant systems and components* [129]
Scope and relevance to AMTs	▪ Design, manufacturing, inspection, and testing of nuclear pressure boundary systems, components, and supports. ▪ Pressure boundary components that could be produced using AMT processes. ▪ Plant inspection and examination of what could be AMT-produced component.
Relevant topics	▪ Fatigue, creep, degradation mechanisms, periodic inspections, and examinations (including access), etc.

Key observations	▪ Design, manufacturing, inspection, and testing of nuclear pressure boundary systems, which could be AMT produced, are not addressed by CSA N285.0; however, the standard [124] refers to ASME BPVC, which can provide additional requirements specific to AMTs.
	▪ Additional requirements may need to be added for:
	  ▪ lack of inspectability of portions of some AMT-produced parts
	  ▪ degradation mechanisms potentially unique to AMTs for plant inspections
	  ▪ inspection or examination processes or degradation mechanisms that might be unique to AMTs or plant inspections

Table C2: Overview of standards that may be relevant to AMTs: CSA N286 and CSA N299 series

CSA N286 – Management systems [130]	
Scope and relevance to AMTs	▪ Management system requirements; components that might be supplied to a nuclear facility produced using AMTs. ▪ Requirements for producing quality products, which could include AMT-produced components.
Relevant topics	▪ Design, supply chain, purchasing requirements, supplier acceptability, etc.
Key observations	▪ Does not contain the level of detail that distinguishes specific requirements, such as those for the design, supplier acceptability, or procurement of specific processes like AMTs. ▪ It might be desirable to refer to another standard with details pertaining to AMT quality requirements.

CSA N299 – Quality assurance program requirements for the supply of items and services for nuclear power plants	
Relevant standards in the series	▪ CSA N299.1 through CSA N299.4 cover four progressive categories of quality assurance (QA) requirements, with CSA N299.1 having the most comprehensive applicable elements.
Scope and relevance to AMTs	▪ Detailed QA requirements for the procurement of items for nuclear power plants. ▪ Requirements for producing quality products which could include AMT-produced components. ▪ Includes requirements for special processes, which could include AMTs.
Relevant topics	▪ Design, supply chain, purchasing requirements, supplier acceptability, special processes
Key observations	▪ Provide details for QA pertaining to design, supplier acceptability, and procurement of items for NPPs; do not refer to method of fabrication. ▪ Contain requirements for specific processes, which could be used to guide the adoption of AMTs. ▪ Reference(s) to standard(s) that define AMT-specific QA processes may need to be added.

Table C3: Overview of standards that may be relevant to AMTs: CSA N287

CSA N287 – Concrete containment structures	
Relevant standards in the series	▪ CSA N287.1, *General requirements for concrete containment structures for nuclear power plants* [132] ▪ CSA N287.2, *Material requirements for concrete containment structures for nuclear power plants* [133] ▪ CSA N287.3, *Design requirements for concrete containment structures for nuclear power plants* [134] ▪ CSA N287.4, *Construction, fabrication, and installation requirements for concrete containment structures for nuclear power plants* [135] ▪ CSA N287.5, *Examination and testing requirements for concrete containment structures for nuclear power plants* [136] ▪ CSA N287.7, *In-service examination and testing requirements for concrete containment structures for CANDU nuclear power plants* [234] ▪ CSA N287.8, *Aging management for concrete containment structures for nuclear power plants* [137]
Scope and relevance to AMTs	▪ Concrete containment structures, including anchors and studs, metal liners, embedded parts and attachments, which could be produced using an AMT process.
Relevant topics	▪ Design, fabrication, inspection, examination and testing (including in-service), and aging management
Key observations	▪ No specific design considerations for AMT processes ▪ Allowable material specifications are listed, which may not address AMT material products. ▪ No specific inspection requirements for AMT products are addressed. ▪ Possible unique aging mechanisms for AMT products are not addressed. ▪ No specific criteria for potential AMT-related aging examination.

Table C4: Overview of CSA nuclear standards that may warrant AMT content: CSA N289

CSA N289 – Seismic design	
Relevant standards in the series	▪ CSA N289.1, *General requirements for seismic design and qualification of nuclear power plants* [138] ▪ CSA N289.3, *Design procedures for seismic qualification of nuclear power plants* [139]
Scope and relevance to AMTs	▪ Seismic design of nuclear power plants. Includes requirements for parts, components, structural members, or brackets, which could be produced using an AMT process.
Relevant topics	▪ Seismic failure modes and aging mechanisms
Key observations	▪ No specific restrictions on seismic design by analysis for new AMT product forms. ▪ No consideration of possibly unique AMT aging mechanisms that could affect a seismic analysis.

Table C5: Overview of CSA nuclear standards that may warrant AMT content: CSA N290

CSA N290 – Reactor control systems, safety systems, and instrumentation	
Relevant standards in the series	▪ CSA N290.0, *General requirements for safety systems of nuclear power plants* [140] ▪ CSA N290.1, *Requirements for the shutdown systems of nuclear power plants* [141] ▪ CSA N290.3, *Requirements for the containment system of nuclear power plants* [142] ▪ CSA N290.8, *Technical specification requirements for nuclear power plant components* [143] ▪ N290.13, *Environmental qualification of equipment for nuclear power plants* [144] ▪ N290.20, *Aging management requirements for nuclear power plants* [145]
Scope and relevance to AMTs	▪ CSA N290.0, CSA N290.1, and CSA N290.3 address aspects such as design, qualification, and inspection of safety systems of some components, which could be produced using AMT processes. ▪ CSA N290.8 addresses technical specification requirements for mechanical components, which could be produced from an AMT process. ▪ CSA N290.8 addresses electrical and instrumentation and control components, which could have metal housings or bracketry, which could be produced from an AMT process. ▪ CSA N290.13 addresses environmental qualification of components, which could be produced from an AMT process. ▪ CSA N290.20 addresses aging management of components, which could be produced from an AMT process.
Relevant topics	▪ Materials, design, environmental qualification, failure modes, aging, inspection, non-destructive examination, special process considerations
Key observations	▪ No specific requirements for AMT-produced items in any of the standards in this series. ▪ CSA N290.8 contains requirements for the submission of special process procedures but does not specifically indicate if this requirement should extend to AMT processes. ▪ CSA N290.0 and CSA N290.1 discuss failure modes but there is no specific reference to new failure modes that could be unique to AMTs. ▪ CSA N290.0 addresses operating experience for reliability analysis but there is no specific mention of AMTs, which might be lacking operating experience. ▪ CSA N290.3 discusses qualification of materials selected for equipment but does not address AMT materials. ▪ CSA N290.20 discusses aging but there is no mention of potential new aging mechanisms from AMT-produced parts. ▪ CSA N290.13 discusses environmental qualification but no mention of potential new mechanisms from AMT-produced parts.

Table C6: Overview of CSA nuclear standards that may warrant AMT content: CSA N291

CSA N291 – Requirements for safety-related structures for nuclear power plants [146]	
Scope and relevance to AMTs	▪ Non-pressure boundary safety-related structures and their components, including brackets and their attachments, which could be produced from an AMT process.
Relevant topics	▪ Materials, special processes, in-service inspection, aging management (degradation and inspection).
Key observations	▪ Allows the specification of other materials with satisfactory material tests conducted, which could be an entry point for AMT products. ▪ Refers to need for welding procedure qualification requirements for welds but does not address other potential special processes such as AMTs. ▪ Considers degradation mechanisms and inspection of embedded parts but there is no discussion about degradation mechanisms or inspection methods unique to AMTs.

Appendix D – Cold Spray (CS)

This appendix provides a detailed review table of the relevant CS standards reviewed in this study.

Table D1: Detailed review of relevant CS standards

#	Criteria	MIL-STD-3021 [148]	MIL-DTL-32495A [147]
1	**Scope**	High pressure/ low pressure/manual or automatic CS deposition for a range of materials (metals, ceramics, polymers, etc.).	Covers the production/procurement of a wide range of powder materials (steel, nickel, aluminum, etc.) for cold spray processes.
2	**Design considerations/ requirements**	Not applicable	Not applicable
3	**Personnel qualification**	Addressed; specifies detailed personnel qualification and certification requirements.	Not applicable; this standard is not for operation of equipment.
4	**Feedstock material control/ characterization**	Partially addressed; specifies particle size ranges, storage conditions and recommends manufacturer's instructions.	Addressed; detailed specifications for feedstock characterization and control for different alloy systems.
4.1	Powder contamination control	Addressed; specifies blast contamination control for powders.	Not applicable
4.2	Substrate material prep	Addressed; specifies cleaning, handling, and storage requirements for substrates; requires records of thickness, heat treatment condition, surface conditions and roughness.	Not applicable
5	**Process qualification**	Addressed; specifies requirements for process control, process qualification testing and certification.	Addressed; specifies requirements for qualification and approval by cognizant engineering authorities and entry into qualified products database.
5.1	Parts classification	Not applicable	Not applicable
5.2	Process parameter control	Addressed; specifies the range of operating parameters for high pressure cold spray and low pressure cold spray, including working gas, gas pressure, gas preheat, gas flow rate, maximum gas Mach, powder flow rate, and particle size.	Not applicable
6	**Equipment qualification**	Partially addressed; specifies calibration requirements for gauges, metres, and sensors used must be specified in the contract.	Not applicable
6.1	Environmental conditions/ build atmosphere	Not addressed; no requirements outside of the setup of the equipment itself.	Not applicable
6.2	Process monitoring systems requirements	Partially addressed; requires control procedures for maintaining specified operating parameters during the cold spraying operation.	Not applicable

#	Criteria	MIL-STD-3021 [148]	MIL-DTL-32495A [147]
7	**Qualification testing**	Addressed; detailed requirements, including the test specimen specifications for metallographic and bond strength testing; specifies requirements for first article testing.	Addressed; for chemical composition by a certified testing agency, plus control of non-metallic impurities, particle size distribution, and additives.
7.1	Witness Testing	Partially addressed; implied but not specifically mentioned.	Partially addressed; implied but not specifically mentioned.
8	**Production execution—Requirements for planned and unplanned interruptions**	Not applicable	Not applicable
9	**Post-processing specifications**	Not addressed	Not applicable
10	**Part inspection and testing**	Addressed; detailed requirements for part testing—visual, microscopic, oxides and porosity, bond strength, non-destructive examination (NDE) as contract-specified.	Addressed; detailed requirements for powder testing—visual, microscopic, tensile, hardness, NDE as contract-specified.
10.1	Acceptance criteria	Partially addressed; acceptance criteria available for porosity and oxide content in coatings; other criteria to be specified in the contract or purchase order.	Partially addressed; criteria for particle size variations.
10.2	AM welding requirements	Not applicable	Not applicable
11	**Documentation, data management, and traceability**	Partially addressed; part identification and data sheet for record of all process parameters.	Partially addressed; traceability implied, but no specific requirements imposed.
12	**Nuclear-specific considerations**	Not addressed	Not addressed

Appendix E – Powder Metallurgy – Hot Isostatic Pressing (PM-HIP)

This appendix provides information on the adoption PM-HIP specifications into ASME BPVC, and detailed review table of the relevant PM-HIP standards reviewed in this study.

Table E1: Adoption of PM-HIP specifications into ASME BPVC [61]

Applicable materials	ASTM specification	ASME code case number	ASME section	Nuclear use
316L SS	ASTM A988	N-834 [77]	Section III	Approved for use by the NRC in Reg. Guide 1.84 for Class 1 components
Duplex SS	ASTM A988	N-2840-1 [166]	Section VIII	No nuclear approval
Cr-Mo steels (Gr. 91 and Gr. 22)	ASTM A989	N-2770-1 [235]	Section I	No nuclear approval
Nonferrous alloys (Inconel 600, 690, 625, 718, and AL-6XN)	ASTM B834	N-2916 [236]	Section I	No nuclear approval
SS (304, 304L, 316, 316L, 317LM, 254 SMO), and AL-6XN	ASTM A989	N-2930 [237]	Section I	No nuclear approval
Grade 9 (9Cr-1Mo)	ASTM A989	N-2931 [238]	Section I	No nuclear approval
Low alloy steel (A508)	None	None	None	None

Table E2: Review of relevant PM-HIP standards

#	Criteria	ASTM A988/A988M [153]	ASTM A989/A989M [154]	ASTM B834-22 [155]	ASME Code Case N-834 [77]	ASME Mandatory Appendix XXVII [161]
1	**Scope**	Cover PM-HIP for production of stainless steel piping components for use in pressure systems.	Similar scope to ASTM A988-23 except for it covers alloy steels (K90941, K90901, K31545, K21590, K21590).	Consolidated PM for production of nickel alloy pipe flanges, fittings, valves, and parts (Ni Alloys N06625 (Gr.1 and2), N08367, N06600, N06690, and N07718).	PM-HIP per ASTM A988/ A988M-11 for UNS S31603.	Covers PM-HIP for nuclear pressure boundary components.
2	**Design considerations / requirements**	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed
3	**Personnel qualification**	Not addressed, except for weld repairs where operators must be qualified in accordance with ASME Section IX.	Not addressed, except for weld repairs where operators must be qualified in accordance with ASME Section IX.	Not addressed	Partially addressed; refers to applicable ASME Code / Section.	Partially addressed; refers to applicable ASME Code / Section.
4	**Feedstock material control / characterization**	Partially addressed; specifications for powder chemical composition, particle size and density; nothing on storage, handling or transportation.	Partially addressed; specifications for powder chemical composition, particle size and density; nothing on storage, handling or transportation.	Partially addressed; specifications for powder chemical composition, particle size and density; nothing on storage, handling or transportation.	Partially addressed; similar to A988/A988M; additional requirements for powder storage, and maximum feedstock particle size and oxygen content.	Partially addressed; similar to ASME Code Case N84.
4.1	Feedstock storage / contamination control	Not addressed	Not addressed	Partially addressed; protection requirements for powder in storage.	Not addressed	Not addressed
5	**Process qualification**	Not addressed; only explains process procedures.	Not addressed; only explains process procedures	Not addressed; only explains process procedures.	Not addressed	Not addressed
5.1	Parts classification	Partially addressed; distinctions made in hydro test requirements for flanges.	Partially addressed; distinctions made in hydro test requirements for flanges.	Partially addressed; distinctions made in hydro test requirements for flanges and for items intended for service under ASME code rules.	No distinctions (beyond what ASME Sec III covers).	No distinctions (beyond what ASME Sec III covers).
5.2	Process parameter control	Partially addressed; only generic mention of requirements to heat and pressurize.	Partially addressed; only generic mention of requirements to heat and pressurize.	Partially addressed; only generic mention of requirements to heat and pressurize.	Similar to ASTM A988/A988M	Partially addressed; specifies the duration and temperatures for HIP and solution annealing.
6	**Equipment qualification**	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed
6.1	Environmental conditions / build atmosphere	Partially addressed; inert gas coverage of powder required immediately after atomization to prevent oxidation.	Not addressed	Not addressed	Partially addressed; nitrogen or inert gas coverage of powder required immediately after atomization to prevent oxidation.	Not addressed
6.2	Process monitoring systems requirements	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed

#	Criteria	ASTM A988/A988M [153]	ASTM A989/A989M [154]	ASTM B834-22 [155]	ASME Code Case N-834 [77]	ASME Mandatory Appendix XXVII [161]
7	**Qualification testing**	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed
7.1	Witness testing	Not specifically addressed in this document but may be covered at least for specimens in referenced procedures.	Not specifically addressed in this document but may be covered at least for specimens in referenced procedures.	Not specifically addressed in this document but may be covered at least for specimens in referenced procedures.	Not addressed	Not addressed
8	**Production execution—requirements for planned and unplanned interruptions**	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
9	**Post-processing specifications**	Addressed; detailed requirements for heat treatments depending on alloy and contract requirements; specifies machining or pickling for can removal from final component as required by contract.	Addressed; detailed requirements for heat treatments depending on alloy and contract requirements; specifies machining or pickling for can removal from final component as required by contract.	Addressed; detailed requirements for heat treatments depending on alloy and contract requirements; specifies mentions can removal but doesn't mention how.	Addressed; can removal by machining or pickling; additional requirements for grinding of surfaces exposed to process fluids to a specified if pickling is used.	Addressed; similar to ASME Code Case N84; specifications for times and temperatures for solution annealing.
10	**Part inspection and testing**	Addressed; detailed requirements for material property testing; multiple non-destruction examination (NDE) and destructive examination (DE) processes required or as dictated by contract.	Addressed; detailed requirements for material property testing; multiple NDE and DE processes required or as dictated by contract.	Addressed; detailed requirements for material property testing.	Addressed; similar to A988/A988M, additional requirements for test specimens' protrusion length, intergranular corrosion and ultraviolent testing.	Addressed; similar to ASME Code Case N84.
10.1	Acceptance criteria	Addressed; for porosity, density, surface roughness; the final part should be free of machining burrs.	Addressed; for porosity, density, and surface roughness; the final part should be free of machining burrs.	Partially addressed; general requirements for dimensional variations, workmanship, finish and appearance only.	Not addressed	Not addressed
10.2	AM welding requirements	Partially addressed; specifies requirements for repair welding in accordance with ASME Section IX and additional specifications for welding area and thickness limits, and marking parts repaired by welding; no repair welding permitted without prior approval of the purchaser.	Partially addressed; similar to ASTM A989/A989M but doesn't allow repair welding for S41000 Classes 3 and 4.	Not addressed	Not specifically mentioned, but it is covered in ASTM A988/A988M.	Similar to ASME Code Case N84.
11	**Documentation, data management, and traceability**	Partially addressed; refers to a separate standard for product marking requirements.	Partially addressed; refers to a separate standard for product marking requirements.	Partially addressed; refers to a separate standard for product marking requirements.	Partially addressed; requires case number to be marked on material and Certified Material Test Report.	Not addressed in this article.
12	**Nuclear-specific considerations**	Not addressed	Not addressed	Not addressed	Addressed; gives maximum in service neutron dose limits.	Addressed; gives maximum in service neutron dose limits.

Appendix F – Additive Manufacturing (AM)

This appendix provides information on relevant AM standards and documents, and a detailed review table of relevant AM standards reviewed in this study.

Table F1: Some relevant AM standards and documents

Category	Standard reference	Title / description
Terminology	ISO/ASTM 52900:2021 [239]	Additive manufacturing — General principles — Fundamentals and vocabulary
	ISO 17295:2023 [240]	Additive manufacturing — General principles — Part positioning, coordinates, and orientation
Design	ISO/ASTM 52910:2018 [207]	Additive manufacturing — Design — Requirements, guidelines, and recommendations
	ASTM F3530-22 [206]	Standard guide for additive manufacturing — Design — Post-processing for metal PBF-LB
Software	ISO/ASTM 52915:2020 [241]	Specification for additive manufacturing file format (AMF) version 1.2
Feedstock	SAE AMS7031 [242]	Batch processing requirements for the reuse of used powder in additive manufacturing of aerospace parts
	ASTM F3049-14(2021) [243]	Standard guide for characterizing properties of metal powders used for additive manufacturing processes
	ISO/ASTM 52907:2019 [244]	Additive manufacturing — Feedstock materials — Methods to characterize metal powders
Process control	MSFC-SPEC-3717 [189]	Specification for control and qualification of laser powder-bed fusion metallurgical processes
	NASA-STD-6033 [190]	Additive manufacturing requirements for equipment and facility control
	AWS D20.1/D20.1M [191]	Specification for metal component fabrication using additive manufacturing
	ASME PTB-13 [103]	Criteria for pressure-retaining metallic components using Additive Manufacturing
Machine calibration	SAE AMS7032 [245]	Machine qualification for fusion-based metal additive manufacturing
	ISO/ASTM TS 52930:2021 [246]	Additive manufacturing — Qualification principles — Installation, operation, and performance (IQ/OQ/PQ) of PBF-LB equipment
	SAE ARP7064 [247]	Machine requalification considerations for fusion-based metal additive manufacturing

Category	Standard reference	Title / description
Material processing	ASTM F3184-16 [187]	Standard specification for additive manufacturing stainless steel alloy (UNS S31603) with powder bed fusion
	ISO/ASTM 52904 [186]	Additive manufacturing — Process characteristics and performance: practice for metal powder bed fusion process to meet critical applications
Process monitoring	SAE WIP ARP7068 (in progress) [194]	In-situ process monitoring considerations for metal fusion additive manufacturing
Qualification and certification	ISO/ASTM 52926, Parts 1–5 [248], [249], [250], [251]	Additive manufacturing of metals — Qualification principles for operators of additive manufacturing equipment
Post-processing	ASTM F3301-18a [252]	Standard for additive manufacturing — Post processing methods — Standard specification for thermal post processing metal parts made via powder bed fusion
Testing and evaluation	ISO/ASTM TR 52905:2023 [253]	Additive manufacturing of metals — Non-destructive testing and evaluation — Defect detection in parts
	ISO/ASTM 52908:2023 [254]	Additive manufacturing of metals — Finished part properties — Post-processing, inspection and testing of parts produced by powder bed fusion
	MSFC-STD-3716 [188]	Standard for additively manufactured spaceflight hardware by laser powder bed fusion in metals
	ASTM F3122-14(2022) [255]	Standard guide for evaluating mechanical properties of metal materials made via additive manufacturing processes
	ASTM F2971-13(2021) [256]	Standard practice for reporting data for test specimens prepared by additive manufacturing
	ISO/ASTM 52901-16 [257]	Standard guide for additive manufacturing — General principles — Requirements for purchased am parts

Table F2: Review of selected relevant AM standards

#	Criteria	**ISO/ASTM 52904** [186]	**ASTM F3184-16** [187]	**AWS D20.1/D20.1M** [191]	**MSFC-STD-3716 / MSFC-SPEC - 3717** [188], [189]	**NASA-STD-6030 / NASA-STD-6033** [120], [190]	**ASME PTB-13-2021** [103]
1	**Scope**	Metallic PBF components for critical conditions.	Powder bed fusion (PBF) of UNS S31603 components.	PBF and direct energy deposition (DED) metal additive manufacturing (AM) (covers multiple variants).	NASA-specific process and equipment control for laser-powder bed fusion (L-PBF) (metals).	NASA-specific process and equipment control for laser-powder bed fusion (L-PBF) (metals).	Pressure-retaining components using L-PBF or electron beam (EB)-PBF.
2	**Design considerations/ requirements**	Not addressed	Not addressed	Partially addressed; design requirements for witness specimens for different classes of L-PBF and DED components.	Partially addressed; only mentions requirements AM designers should consider.	Partially addressed; only mentions requirements AM designers should consider.	Partially addressed; some considerations for testing; design requirements should follow requirements in the applicable ASME code or standard.
3	**Personnel qualification**	Partially addressed; refers to another standard – ISO/ASTM 52926.	Partially addressed; mentions it should be present in the manufacturing Plan.	Addressed; Detailed AM operator training and qualification requirements.	Addressed in MSFC-SPEC-3717.	Addressed in NASA-STD-6033.	Not addressed
4	**Feedstock material control / characterization**	Partially addressed; to be included in Manufacturing Plan; also refers to applicable ISO standards.	Partially addressed; Refers to other applicable standards; specifies elemental composition for UNS S31603.	Addressed; specifies feedstock characterization requirements, storage conditions, and refers to applicable standards.	Addressed; MSFC-SPEC-3717 provides info on feedstock specification and associated controls.	Addressed; specifies requirements for powder, wire, thermoplastic filament, and photopolymeric thermoset resin.	Partially addressed; powder specifications and controls to be included in Powder Specification document; refers to applicable ISO/ASTM standards.
4.1	Feedstock storage/ contamination control	Addressed; allowed, provided every constituent of blended powders conforms to the use specification requirements prior to blending.	Partially addressed; allowed, based on supplier/ purchaser agreement, with limits based on part class.	Addressed; allowed, must meet pre-build conformance tests.	Addressed; allowed, requires quantitative tracking of feedstock reuse limits.	Addressed; allowed, requires quantitative tracking of feedstock reuse limits.	Addressed; allowed but prohibits elemental powder blending.
5	**Process qualification**	Partially addressed; yes, requires a manufacturing plan which is used to produce sufficient test specimens in statistically significant quantity for the purpose of qualification.	Partially addressed; processing shall be conducted in accordance with applicable standards or as agreed upon by the component supplier and purchaser to a manufacturing plan (8.1).	Addressed; detailed graded approach based on component criticality.	Addressed; detailed statistical-based qualification with process variability considerations.	Addressed; detailed statistical-based qualification with process variability considerations.	Addressed; detailed performance-based statistical qualification; it provides a graded approach to procedure qualification based on the maturity level of the procedure.
5.1	Parts classification	Not addressed; no mention	Addressed; based on thermal post-processing— Conditions A–F.	Addressed; based on failure consequences (Class A, B, and C).	Addressed; based on failure consequence – structural demand, and AM risk – Parts A, B.	Addressed; based on failure consequence – structural demand, and AM risk – Parts A, B,C.	Addressed; pressure-retaining components only.
5.2	Process parameter control	Partially addressed; references ISO 52930.	Partially addressed; listed as content of manufacturing plan.	Partially addressed; required to be part of AM Procedure Specification.	Partially addressed; mentions process governing parameters be specified.	Partially addressed; mentions process governing parameters be specified.	Partially addressed, listed as requirements for process qualification in Table 7.1.
6	**Equipment qualification**	Partially addressed; refers to ISO/ ASTM 52930. Requirements for AM equipment maintenance and frequency.	Partially addressed; listed as part of the Manufacturing Plan, as agreed upon by the component supplier and purchaser.	Addressed; detailed requirements for AM machine qualification.	Addressed; yes; specifies equipment calibration, maintenance, and qualification requirements.	Addressed in NASA-STD-6033.	Partially addressed; to be covered in AM qualification procedure as per requirements of Table 7.1 (Sec 7.0).
6.1	Environmental conditions/ build atmosphere	Partially addressed; mentions temperature and humidity controls must be in accordance with the machine and feedstock manufacturer's specifications.	Not addressed	Partially addressed; mentions general cleanliness and gas specification, nothing specific about temperature and humidity.	Partially addressed; MSFC-SPEC-3717 requires they be defined as part of process control variables.	Partially addressed; mentions they be defined as part of process control variables.	Partially addressed; only mentions as part of requirements for process variables requirements for qualification (Table 7.1).
6.2	Process monitoring systems requirements	Partially addressed; not specific; mentions in-process monitoring equipment shall be set up according to the manufacturer's instructions.	Not addressed	Addressed; in-process monitoring methods that do not alter or control any qualified variable are allowed.	Addressed; active in-situ process monitoring is not allowed.	Addressed; active in-situ process monitoring is not allowed.	Addressed; in-process monitoring methods that control machine operation are not permitted by these criteria; only those for data acquisition are allowed.

#	Criteria	**ISO/ASTM 52904** [186]	**ASTM F3184-16** [187]	**AWS D20.1/D20.1M** [191]	**MSFC-STD-3716 / MSFC-SPEC - 3717** [188], [189]	**NASA-STD-6030 / NASA-STD-6033** [120], [190]	**ASME PTB-13-2021** [103]
7	**Qualification testing**	Partially addressed; refers to ISO/ASTM 52930.	Partially addressed; references applicable standards; when agreed upon by the component supplier and purchaser, a first-article inspection shall be performed.	Addressed; extensive guidelines for pre-production test specimens, quantity, size, and orientation within build.	Addressed; specifies testing requirements for qualifying AM process, including pre-article testing.	Addressed; specifies testing requirements for qualifying AM process, including pre-article testing.	Addressed; detailed qualification testing with detailed requirements for fabricated prototypes, including test specimen quantity, size, location, etc.
7.1	Witness testing	Not addressed; not mentioned	Partially addressed; implied but not specifically mentioned.	Addressed; required for AM qualification.	Addressed; required, includes specifications for test specimen orientation, location and geometry variability.	Addressed; required, includes specifications for test specimen orientation, location and geometry variability.	Addressed; required, includes detailed acceptance criteria.
8	**Production execution – requirements for planned and unplanned interruptions**	Partially addressed; mentions unplanned interruptions and failures during build cycle shall be considered a failed process, rejected, and recorded.	Not addressed; not mentioned	Addressed; yes, specifies requirements for build interruptions.	Addressed; yes, specifies requirements for build interruptions.	Addressed; yes, specifies requirements for build interruptions.	Not addressed
9	**Post-processing specifications**	Not addressed	Partially addressed; specifies thermal processing requirements, which varies by condition type of the components.	Partially addressed; not detailed but required to be specified in additive manufacturing procedure specification.	Partially addressed; references applicable standards for post-processing operations; MSFC-SPEC-3717 covers thermal post-processing (heat treatment, HIP, stress-relief) operations.	Partially addressed; references applicable standards for a broad range of post-production processes, including due to extended scope of processes.	Partially addressed; references applicable standards for post-processing. Specifies some heat treatment requirements.
10	**Part inspection and testing**	Partially addressed; refers to applicable standards. Part inspection criteria left to supplier/purchaser agreement.	Partially addressed; Provides specifications for tensile testing and HIP. Refers to applicable standards and rely on contract agreements for another requirement.	Addressed; Detailed requirements for part property testing.	Addressed; MSFC-SPEC-3717 specifies testing requirements for part property testing; references applicable standards; specifies methods for establishing material property design values.	Addressed; Specifies testing requirements for a range of metal and polymer classes; references applicable standards; specifies methods for establishing material property design values.	Addressed; Detailed requirements for part property testing.
10.1	Acceptance criteria	Not addressed; not provided	Partially addressed; criteria provided for tensile tests.	Addressed; detailed acceptance criteria provided.	Partially addressed, acceptance criteria to be developed as part of PCRD (Process Control Reference Distribution); the PCRD is a simple statistical model used to create acceptance criteria for evaluation of witness specimens to monitor the AM process.	Partially addressed, acceptance criteria to be developed as part of PCRD.	Addressed; detailed acceptance criteria provided.
10.2	AM welding requirements	Not addressed; no specifications for welding AM components provided.	Not addressed; no specifications for welding AM components provided.	Not addressed; no specifications for welding AM components provided.	Partially addressed; references appropriate standards; no specific guides on welding L-PBF parts.	Partially addressed; references other applicable standards; no specifications for welding AM parts.	Partially addressed; hybrid construction incorporating AM components joined (welded or brazed) to non-AM components is acceptable – joining procedure to follow the requirements of applicable ASME code or standard.
11	**Documentation, data management, and traceability**	Partially addressed; specifies requirements for documentation, sample manufacturing plan provided; references ISO/ASTM 52930 for software and data control requirements; nothing on data security / cybersecurity.	Partially addressed; mentioned but not detailed.	Addressed; specifies requirements for documentation; Informative Annex A – provides several qualification records samples.	Partially addressed; documentation requirements mentioned across every stage; provides guidelines for data traceability; mentions requirements for data/cyber security.	Partially addressed; documentation requirements mentioned across every stage; provides guidelines for data traceability, but nothing on data security/cybersecurity.	Partially addressed; specifies requirements for documentation records, but nothing on data/cyber security.
12	**Nuclear-specific considerations**	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed

Note. ISO = International Organization for Standardization; **ASTM** = American Society for Testing and Materials; **AWS** = American Welding Society; **MSFC** = NASA Mashall Flight Center; **STD** = Standard; **SPEC** = Specification; **NASA** = National Aeronautics and Space Administration; **ASME** = American Society of Mechanical Engineers; **PTB** = Pressure Technology Bulletin.

Appendix G – Interconnections Between Physical Advanced Manufacturing and Digital Solutions

A key advantage of advanced manufacturing techniques (AMTs) is their ability to integrate seamlessly with advanced digital solutions to enhance manufacturing efficiency, precision, and scalability through enhanced connectivity, data analytics, artificial intelligence (AI), and human-machine interaction. While physical AMTs provide benefits over traditional processes, their performance, reliability, and cost efficiency are often optimized through complementary digital solutions. Relevant digital advanced manufacturing tools complementing AMTs include:

- AI and Machine Learning (ML): Predictive analytics, defect detection, and process optimization.
- Industrial Internet of Things (IIoT): Facilitates connectivity, real-time monitoring, predictive maintenance and process automation.
- Automation and Simulation: Supports process validation, virtual prototyping, and digital twins.
- Advanced Data Analytics and Cloud Computing: Enables large-scale data analysis, storage, and collaboration.

While some of these digital solutions are fundamental to the operation of specific advanced manufacturing processes, others act as enhancements, optimizing performance, but are not essential for execution. These digital solutions can be categorized into two streams:

- Integrated Digital Solutions: Essential for AMT operation, ensuring process consistency, real-time monitoring, and qualification. This includes process modelling, in-situ monitoring, and control algorithms that allow AMTs to function reliably.
- Independent Digital Solutions: Enhance AMT performance but are not strictly necessary performance. These include AI-driven defect prediction and data analytics, cloud-based data management, augmented and virtual reality (AR/VR), and digital twin technology.

Recent CSA studies [258], [259] offer a more detailed analysis, highlighting key digital technologies and their anticipated applications within Canada's nuclear sector and providing valuable insights into the broader context of smart manufacturing.

Integrated Digital Solutions

Some digital tools are directly embedded directly into AMTs to enhance precision, repeatability, and consistent part quality across the manufacturing lifecycle. Digital tools for process modelling, simulation, and visualization are essential for optimizing AMT workflows by predicting distortions, residual stress accumulation, and thermal gradients before fabrication begins. Simulation techniques such as finite element analysis optimize design and processing parameters, improving material behaviour predictions and reducing costly trial-and-error runs [260].

For example, cold spray relies on computational modelling of powder flow dynamics to optimize important process control parameters, ensuring high deposition efficiencies and bonding strengths [39], while powder metallurgy – hot isostatic pressing (PM-HIP) uses simulation software to predict can geometry and shrinkage during HIP cycles [61].

During production, process monitoring systems capture real-time data related to process quality and machine discontinuities using advanced sensing tools (visual, acoustic, thermal, and so forth). These systems function in either an open-loop (data collection for post-fabrication analysis only) or closed-loop (data collection for real-time process adjustments) frameworks [97].

AMT equipment with integrated monitoring systems has become a standard industry practice; however, the extent of these integrations varies across AMTs and original equipment manufacturers. For example, laser power bed fusion (L-PBF) machines typically include integrated sensors for powder bed imaging to detect recoater issues or powder inconsistencies, enabling early fault detection [97], [261], when direct energy disposition systems require real-time track height monitoring to maintain optimal nozzle distance for precise material deposition [261]. These features are generally seen as critical for process stability, but their qualification remains a challenge [261]. Existing qualification frameworks primarily focus on qualifying only the physical AM processes, while digital tools such as in-situ monitoring, closed-loop control, and AI-driven defect detection, are either loosely addressed or entirely absent. Existing standards like the AWS D20.1M [191] and the ASME-PTB-13 [103] typically allow open-loop monitoring, as it does not affect locked process parameters for the qualified process. These standards, however, restrict closed-loop feedback systems that actively modify process parameters in real time [261]. Some initiatives are ongoing to address this, but underlying challenges, such as the industry's lack of a consensus framework for validating sensors and analysis techniques, make it difficult [261], [262].

In addition, advanced sensors and IIoT systems provide critical insights into machine condition tracking and monitor variables (such as feedstock levels), build atmosphere, and laser focus, to help ensure repeatability and stability across multiple production cycles [97], [261]. In many cases, this form of in-situ monitoring is necessary for the normal operation of AMT systems and is generally mature for flagging out-of-normal conditions against reference values [261].

Independent Digital Solutions

Beyond essential process controls, various digital tools optimize advanced manufacturing by improving efficiency, reducing waste and enhancing predictive capabilities.

AI/ML driven analytics are increasingly used in qualification processes, analyzing large datasets to detect defects and optimize build parameters [261], [263], [264]. AI-driven defect detection also allows real-time identification of flaws, reducing rework, and improving component consistency [97]. And AI-driven analytics support ex-situ inspection, validation, and process refinement by identifying production patterns and recommending optimizations for future manufacturing cycles [261].

Digital twin technology is another transformative tool in advanced manufacturing. It creates virtual representations of components, machinery, and process parameters, enabling real-time projection, adaptive control, and optimization. By integrating physics-based simulations with ML algorithms, digital twins allow manufacturers to simulate and mirror the behaviour of an advanced manufacturing process before committing to physical production [265].

IIoT-enabled sensors provide enhanced traceability, enabling real-time monitoring of machine health, environmental conditions, and material properties. Predictive maintenance tools analyze sensor data to anticipate

equipment failures, reducing downtime and improving reliability. Additionally, cloud-based data management platforms streamline AM documentation, facilitating compliance with nuclear regulatory requirements and standardizing qualification methodologies.

Advancements in non-destructive testing methods also hold promise for part validation. Non-destructive testing methods are evolving, with advanced sensing, networking and computing, and more recently, AI/ML technologies [263]. Automated defect recognition ML algorithms improve accuracy in X-ray Computed Tomography, ultrasonic scans, and eddy current testing, reducing manual analysis time and enhancing defect detection accuracy [266].

AR/VR applications are emerging as valuable tools for training, process visualization, and assembly guidance. In advanced manufacturing, augmented reality overlays can help operators interact with machines more intuitively, improving accuracy during post-processing and quality assurance. Virtual reality environments also allow simulated training for AMT operators, reducing the learning curve for complex AMT operations and maintenance [267].

Many of these digital solutions represent revolutionary advancements but still require more research and development and regulatory validation before they can be fully integrated into advanced manufacturing systems. However, they offer potential to further optimize advanced manufacturing systems.

Important Considerations for Physical AM-Digital Solutions Interconnections

While the integration of digital tools with AMTs enables transformative capabilities such as those described above, challenges and areas of risk associated with these integrations must be considered. For a more in-depth analysis of emerging digital technologies in the Canadian nuclear space, refer to CSA's research report on this topic [259].

- **Qualification and Standardization Barriers:** Current frameworks (e.g., ASME-PTB-13, AWS D20.1M) restrict advanced integrations such as closed-loop control and automated process adjustments, limiting the possibilities of real-time monitoring [103], [191]. Consensus is lacking on validating in-situ monitoring systems, AI, and advanced non-destructive examination (NDE) tools against traditional qualification methods [261].
- **Process Adaptability vs. Stability:** Closed-loop control and AI-driven adjustments must balance process adaptability with consistency. Qualification standards typically mandate locked process parameters, making integrating dynamic digital adjustments without regulatory changes difficult [262].
- **High Data Requirements and Costs:** AI, in-situ monitoring systems, and advanced NDE systems require massive, high-quality datasets that capture process variability. Collecting and labelling these datasets is expensive and time-intensive [261], [263].
- **AI/ML Adoption Challenges:** AI's "black box" nature raises concerns about transparency and explainability, particularly in safety-critical applications like nuclear [268]; bias in training datasets can also affect reliability, necessitating robust validation frameworks [261]; and ensuring the traceability and reliability of AI-based defect assessments [263].
- **Cybersecurity Risks:** Increased connectivity in advanced manufacturing systems exposes vulnerabilities, including data breaches and system manipulation, requiring stringent cybersecurity measures. Cybersecurity is a well-recognized risk within the industry, and several initiatives are underway to address it [269], [270]. Various mitigation strategies have been implemented, but ongoing vigilance and frequent updates of cybersecurity measures remain essential.

- **Workforce Adaptation Skills and Training:** Emerging digital AMTs is expected to create a skills gap, requiring expertise in both traditional manufacturing and emerging digital technologies. As automation, AI, and advanced process monitoring reduce manual interventions, reskilling or restaffing from conventional manufacturing roles to address training for digital and AM-based processes might be needed. To enable effective integration, upskilling programs will be essential to bridge the potential skill gap and help workers gain the knowledge and skills required to adopt and utilize AM techniques. This might be especially relevant in the nuclear sector, where quality frameworks, and improving dataset availability are essential unlocking the full potential of these technologies.

Despite these challenges, ongoing research and cross-industry collaboration drive advancements in digital-physical AM integration [261], [263], [271]. Addressing standardization gaps, refining AI and NDE validation frameworks, and improving dataset availability is believed to be key to unlocking the full potential of these technologies.

Reference documents for further reading:

- CSA's research report "Unlocking the potential of smart manufacturing in Canada" [258].
- CSA's research report "Emerging digital technologies within the Canadian nuclear industry" [259].
- NASA and ASTM AM COE's "Strategic guide: In-situ technology readiness" [261].
- EU SNETP's Nuclear Generation II and III Alliance (NUGENIA) "Qualification of non-destructive testing systems that make use of machine learning" [264].

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

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