NEI REPORT

Roadmap for Regulatory Acceptance of Advanced Manufacturing Methods in the Nuclear Energy Industry

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Executive Summary

Advanced manufacturing methods (AMM) have the potential to transform the nuclear industry by producing high quality components faster and cheaper, and enhancing the performance of current operating plants and advanced reactors. AMM could also be used to quickly supply replacement parts for obsolete components and to reduce warehouse inventories.

A number of companies are preparing to use AMM to fabricate components for current operating plants and future advanced reactors. However, a lack of clarity on the regulatory pathways, and on the ability to gain timely regulatory approval (if it is needed), for AMM fabricated nuclear components are potential barriers to their use. A manufacturing method is identified in this report as being "advanced" if it has not yet been utilized to fabricate components for the nuclear industry, even though some of these methods are currently being used in other industries.

"There is clear and growing interest in AMM in the U.S. nuclear industry as evidenced by DOE funded research, industry funded activities to demonstrate the viability of AMM, and efforts by the NRC to develop an action plan for AMM."

Of the 55 advanced manufacturing methods identified as having potential applicability, there are 16 AMM that are of the most interest to manufacture components for nuclear power plants. Additive manufacturing – or 3-D printing – is the most well-known AMM; however, there are many others – such as powder-metallurgy hot-isostatic pressing and electron beam welding – that have tremendous potential for the nuclear industry. Companies are interested in deploying AMM fabricated components as early as 2019/2020, with anticipated use of AMM beginning to increase dramatically around 2022.

Efforts by major commercial nuclear vendors and suppliers to develop and deploy AMM for nuclear components are being supported by intense R&D, testing and qualification by the U.S. Department of Energy, National Laboratories, Electric Power Research Institute, and others. However, nuclear industry efforts to incorporate AMM into the supply chain are not as far along as other industries. Aerospace, defense, automotive and other industries have already begun putting advanced manufactured components into use, which is enabled in part by the long-standing and resourced regulatory and standards development activities in these industries. In contrast, the American Society of Mechanical Engineers (ASME) has only one code case under way for AMM for the nuclear industry. Other standards organizations such as the International Organization for Standardization (ISO) and ASTM International have not even considered nuclear industry applications, despite their significant efforts in developing standards for AMM.

The U.S. Nuclear Regulatory Commission (NRC) has also recognized the need to clarify the qualification, standards and regulatory pathways for using AMM. To meet these challenges, the NRC has issued a draft action plan to prepare the agency for review of applications for AMM to manufactured nuclear components, and to provide clarity to the industry on expectations for their use. It is important to note that using a new or advanced process such as AMM does not necessarily require a licensing submittal in order to adhere to applicable regulatory requirements.

This report provides a perspective on the potential regulatory considerations for AMM manufactured nuclear components. It also includes approaches being considered to enable a more rapid adoption of AMM in the nuclear industry.

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1 INTRODUCTION

The purpose of this report is to describe nuclear industry activities and plans to employ advanced manufacturing methods in current operating plants as well as in future advanced nuclear reactor designs. This report addresses the range and level of current industry interest in applying these advanced methods, approaches for using advanced manufacturing methods for components used in nuclear power plants, and the issues the industry could be challenged with in gaining timely regulatory approval (when applicable) of these techniques, and the approaches being considered to address these potential challenges.

Advanced manufacturing methods are defined for the purposes of this report as methods that have not been utilized in the manufacture of components for the nuclear industry. These methods could be emerging technologies, or methods that have been successfully used by other industries. The term AMM is used in this report to refer to the use of advanced methods to manufacture components.

Advanced manufacturing methods have the potential to produce components faster and cheaper, and to produce components that cannot be produced with "current" manufacturing methods. AMM has the potential to be game changing in the nuclear industry. AMM can be used to quickly produce replacement parts for obsolete components and to produce components with complex geometries to enhance the performance of current operating plants and advanced reactors.

AMM span a wide range of methods and technologies which can be used to fabricate a complete component, at or near its final shape in some cases, join or weld components, modify the surface of components, produce components using advanced machining methods, allow for metallurgical modification to produce ultrafine grained materials, and advanced inspection methods. The use of advanced construction methods is beyond the scope of this report.

Use of components fabricated using AMM in the nuclear industry is expected to involve demonstrating that the advanced methods produce components that perform their design function over their full design life. Demonstrating the capabilities of AMM involves research, analysis, testing, and in-service inspection, coupled with efforts by a number of Standards Development Organizations (SDOs) to promulgate consensus standards that will support the production and use of components that consistently meet the quality standards of the nuclear industry. Demonstrating that the AMM fabricated component will serve its intended design function over its design life involves testing and evaluation of the fabricated materials and component, including consideration of potential operating environments. This testing will help assess performance including applicable age-related degradation mechanisms, such as creep, creep-fatigue, irradiation embrittlement, stress corrosion cracking, and other mechanisms pertinent to the specific reactor design and operating environment.

Testing to demonstrate performance in simulated operating environments is often time consuming and could result in significant delays for the industry to be able to make use of AMM. The nuclear industry is seeking to identify approaches that accelerate the time it takes to demonstrate the acceptable, safe use of AMM in nuclear power plants, including regulatory approval when necessary.

AMM have gained widespread acceptance in a number of industries, including aerospace, defense, medical, automotive, and machinery manufacturers. The types of components manufactured using AMM are extensive. Most, if not all, of these AMM components have been manufactured using what is termed as “additive manufacturing”, or “3D” printing. Operating experience for components manufactured using additive manufacturing methods continues to expand.

While additive manufacturing, and particularly additive manufacturing that employs the laser powder bed fusion method, has a number of potential uses in the nuclear industry, such as the manufacture of fuel assembly components, it is limited in the size of component that can be printed. Generally, components manufactured using the laser powder bed fusion method are currently limited to weights less than about 50 lbs. Another additive method, termed directed energy deposition, can currently produce components with weights up to about 500 lbs. (Ref. 1) There are nuclear components in these size ranges that could be manufactured using additive methods in less time, and arguably for less cost, than using conventional methods. However, there are many larger components that can benefit from other advanced manufacturing methods, such as Powder Metallurgy – Hot Isostatic Pressing. Advanced Manufacturing is a rapidly evolving technology, offering a wide array of methods that have potential application in the nuclear industry.

Other AMM related methods offer similar advantages in reducing fabrication time and improved quality of the component over conventional fabrication methods. For example, electron beam welding has been shown capable of making relatively thick section welds in a matter of hours rather than days using traditional arc welding processes. Electron beam welding using traditional post-weld heat treatment temperatures has been approved by the ASME. (Ref. 2) Ongoing research shows that using appreciably higher heat treat temperatures can provide further improvements in the quality of the electron beam welds.

2 ADVANCED MANUFACTURING METHODS

This section identifies the AMM which are currently of most interest to the nuclear industry, the nuclear industry's activities to develop and implement AMM, and activities by SDOs and other industries to use AMM.

AMM technologies have been successfully implemented in a number of different industries such as aerospace and in the medical field and have allowed advanced product designs to be developed and produced. These advanced product designs could not have been produced easily using existing manufacturing techniques. While implementation of AMM in the nuclear industry is at an early stage, there are a number of notable efforts that are nearing deployment that will change that scenario.

2.1 Advanced Manufacturing Methods Relevant to the Nuclear Industry

A review of pertinent meeting summaries and technical presentations identified at least 55 Advanced Manufacturing Methods with potential applicability to the nuclear industry. These are listed in Appendix A. When exploring the general technical literature, not surprisingly, most of the publications relate to additive manufacturing. However, the literature pertinent to the nuclear industry describes a broad range of AMM.

Table 1 lists methods that a survey of industry organizations identified as being of the most interest in the manufacture of components for nuclear power plants. This is a subset of the AMM identified in Appendix A.

Appendix B provides a brief description of the various methods based on open source descriptions. It is anticipated that the operating fleet of plants would find the AMM of most use in producing replacement components, or when component production or machining can be enhanced and more cost-effective. These methods can also be employed for manufacturing existing components as well as in other support areas, such as tooling. For advanced reactors, the opportunities to fabricate significant portions of components in these plants using AMM are significant.

While all of the methods shown in Appendix A could eventually be employed in fabricating components for the nuclear industry, Table 1 highlights the methods that are most likely to be deployed first and most abundantly for the nuclear industry. Industry stakeholders were surveyed to determine interests in pursuing specific methods, or groups of methods, for fabricating components for use in nuclear power plants. The survey respondents included reactor designers, component designers, fabricators/manufacturers, constructors, facility owners/operators, and potential owner/operators. Respondents included those primarily focused on existing light water reactors and those focused on advanced reactors. Interests in potential applications of AMM and uses of the AMM listed in Table 1 were included in the survey. The survey also explored potential timelines for deployment of AMM fabricated components.

The results of the survey indicated interests in using AMM for replacement of obsolete parts, to reduce manufacturing time and costs, to improve quality or performance of the parts, and to enable advanced reactor technologies. Potential applications for AMM included large vessels, vessel internals, fuel assembly components, and piping components of varying sizes. Respondents indicated interest in all of the AMM listed in Table 1, with no clear preference for an individual method or category of methods.

Timelines for deploying AMM fabricated components began as early as 2019/2020, with interests increasing in 2022/2024, and peaking beyond 2026, which was the last timeframe listed in the survey.

Table 1 List of AMM Pertinent to Nuclear Power Plants

ADDITIVE MANUFACTURING
Powder Bed
Directed Energy Deposition
Binder Jetting
NEAR NET SHAPE MANUFACTURING
Powder Metallurgy - Hot Isostatic Pressing
Investment Casting
JOINING/CLADDING
Adaptive Feedback Welding
Diode Laser Cladding
Electron Beam Welding with High PWHT
Friction Stir Welding (FSW)
Hybrid Laser Arc Welding
Hybrid Laser-GMAW
Laser Cladding Technology (LCT)
SURFACE MODIFICATION/COATING
Chemical Vapor Deposition (CVD)
Cold Spray Additive Manufacturing
Laser Peening
Physical Vapor Deposition (PVD)

2.2 Development of AMM for Use in the Nuclear Industry

There has been a significant effort to research and develop AMM for the nuclear industry in recent years. Research funded by DOE through the Advanced Methods for Manufacturing program is pursuing a number of AMM related methods that offer the fabrication of “near net shape” components in a variety of sizes and configurations. For example, one demonstration project is using AMM powder metallurgy and Hot Isostatic Pressing or HIP technology to produce a 2/3 scale model of a NuScale reactor pressure vessel upper head. (Ref. 3) This is a complicated geometry with a number of penetrations in the head. The powder metallurgy-HIP demonstration project is showing that the NuScale reactor pressure vessel upper head component could successfully be fabricated using the Powder Metallurgy-HIP technology. Currently, the size of the component is limited by the size of available HIP equipment. However, equipment suppliers have indicated that larger equipment is technically achievable, which would make this method available to the nuclear industry for relatively large, intricate components.

Efforts by major commercial nuclear vendors to develop and deploy nuclear related components, most notably for fuel assemblies, have been ongoing for the last few years.

Westinghouse has performed significant design, development and testing of AMM produced fuel components, including irradiation testing of AMM produced materials, with the goal of employing AMM produced components in the near future. As a demonstration of AMM capabilities, Westinghouse plans to deploy a thimble plugging device in a commercial reactor in the 2019/2020 time frame. This will allow more advanced fuel components such as nozzles and grids to be developed allowing for improved fuel performance and cost savings.

GE-Hitachi Nuclear Energy, LLC, is exploring AMM for applications in next generation fuel bundle assemblies, reactor internal repair hardware, and small modular reactor vessel components.

Framatome is actively applying AMM to nuclear fuel assembly, control and core internal components to expand product performance, optimize costs, increase design flexibility for customization as well as providing shorter time-to-market and production times, all while maintaining high product quality.

BWX Technologies, Inc., in collaboration with Oak Ridge National Laboratories (ORNL), is developing the ability to implement Additive Materials Manufacturing to the fabrication process for high temperature alloys for nuclear applications.

NuScale is exploring potential uses of AMM as part of their longer-term activities in coordination with the consensus standard community. NuScale's longer-term potential uses evaluated for future adoption include PM-HIP for complex geometry vessel components, high-deposition cladding technologies, and wire-based Direct Energy Deposition additive manufacturing for built-up features, as well as a host of other technologies adopted by lower-tier suppliers of primary and balance-of-plant equipment. Overall, there is appreciable design, development and testing that have been completed which has demonstrated the acceptability of employing AMM technologies for nuclear industry applications.

Efforts by the nuclear industry, DOE and others to develop and demonstrate a wide range of AMMs are also leading to standardization efforts. This combination of technical development and standards development will provide the sound basis needed for employing advanced manufacturing methods in the manufacture of many different components for nuclear power plants.

2.3 Standards Development Activities

Interest in additive manufacturing as well as other advanced manufacturing methods has been very active in a number of industries. That interest has led to efforts in the consensus standards community to develop appropriate standards for the use of AMM methods. Domestic and international standards organizations have been developing and publishing relevant standards. In particular, ASTM, ISO, and SAE International have published standards for AMM. Appendix C provides a listing of some of the relevant standards.

The international interest in these standards is reflected through the partnering of ASTM International and ISO to craft the "Additive Manufacturing Standards Development Structure," which is described as a framework which will help meet the needs for new technical standards in the fast-growing AMM field.

Similarly, SAE International formed the Aerospace Material Specification Committee on Additive Manufacturing (AMS-AM). The AMS-AM committee is made up of more than 350 participants from 15 countries, representing aircraft, spacecraft, and engine original equipment manufacturers, material suppliers, operators, equipment/system suppliers, service providers, regulatory authorities, and defense agencies.

The efforts of ASTM International, ISO, and SAE International reflect the broad-based interest in Additive Manufacturing in a number of industries.

ASTM International has a major initiative to develop additive manufacturing, providing education on the methods, and developing a broad range of standards. (Ref. 4) Similarly, America Makes and the American National Standards Institute (ANSI) Additive Manufacturing Standardization Collaborative (AMSC) have recently published Version 2.0 of their “Standardization Roadmap for Additive Manufacturing.” (Ref. 5) The National Institute of Standards and Technology (NIST) also has a major program addressing additive manufacturing. (Ref. 6) While none of these programs are specific to nuclear power plant applications, they all provide relevant information and standardization activities applicable to AMM methods/technologies.

Interest in additive manufacturing has been increasing in the commercial nuclear industry in large part due to the successful use of the technology in other industries. As a consequence, the standards development activities have not focused on nuclear-specific interests. However, over the last several years that interest has expanded and there are initiatives underway to develop and standardize AMM specific to the nuclear industry. This industry interest has led to significant investment in method development, both from the industry and from the Department of Energy (DOE) funding via the Advanced Methods for Manufacturing program. There also are efforts underway by the ASME through the BPTCS/BNCS Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment. The BPTCS/BNCS effort currently is assessing gaps between current Code provisions and those that are warranted to address AMM.

Beyond the ASME effort, EPRI and DOE are pursuing an effort to develop a Code Case addressing AMM using the laser powder bed fusion method and 316L material. This activity is well underway with demonstration components being manufactured for detailed evaluation and testing. The proposed Code Case is expected to be submitted to ASME Section III in late 2019 or early 2020. It will provide an approach to ensuring additively manufactured components would demonstrate consistently high quality commensurate with the expectations for nuclear grade components.

The variety of standardization activities coupled with the method development and demonstration activities being funded by industry and the DOE, are providing a sound technical and standardization base for the deployment of components manufactured using Advanced Manufacturing Methods in the nuclear industry.

2.4 Use of AMM in Other Industries

The broad interest in additive manufacturing methods is reflected in a number of industry and government programs.

There are extensive activities nationally and internationally to develop advanced manufacturing methods and to demonstrate the performance of the manufactured components. AMM and additive manufacturing in particular are being pursued by a number of industries, including aerospace, defense, medical, automotive, and machinery manufacturers. High integrity components for critical applications and challenging environments are particularly important in the aerospace and defense industries.

Recent announcements of approved applications include an enhanced thruster control system using additively manufactured components for NASA's Orion crew vehicle (Ref. 7), and a valve developed by Huntington Ingalls Industries Newport News Shipbuilding Division and approved by Naval Sea Systems Command (NAVSEA). The valve is to be installed on the USS Harry S. Truman (CVN 75) nuclear aircraft carrier where it will be subjected to 12 months of operational testing. (Ref. 8)

Underlying specific component approvals are extensive efforts to develop and standardize specific applications. For example, NASA's Marshall Space Flight Center has published a standard on the qualification of laser powder bed fusion metallurgical processes (Ref. 9) and a separate standard on hardware manufactured using laser powder bed fusion. (Ref. 10) These standards are specific to laser powder bed fusion and are supplemented by broader NASA standards on strength and life assessment (Ref. 11) and fracture assessment. (Ref. 12) The overall approach used by the Marshall Space Flight Center builds on all of the existing NASA structural requirements but includes specific requirements on laser powder bed fusion processes.

While these standards are specific to Marshall Space Flight Center and laser powder bed fusion, there is an effort underway to broaden the scope to include directed energy deposition with wire feed, and to elevate the approval of the standards to be NASA-wide.

The Federal Aviation Administration (FAA) has drafted a "roadmap" document that describes that agency's expectations for manufacturing and approving additively manufactured components for use in commercial aviation applications. Similarly, the Department of Defense has prepared a "roadmap" for additive manufacturing.

The DoD effort involved developing a roadmap for each major service (a total of four) and one integrated, joint roadmap representing the interests of all of the stakeholders. A series of nine workshops were conducted through a cooperative agreement with America Makes. There were two workshops for each Service/Agency and one joint workshop that brought together stakeholders from all four organizations. The workshops aligned to the technical focus areas from the America Makes Technology Roadmap: Design, Material, Process, and Value Chain. (Ref. 5) Additionally, while not specific to technology development, some of the stakeholders identified three key factors that will be crucial to the eventual success of additive manufacturing efforts: Cultural Change (increasing knowledge of and comfort with additive manufacturing, driving institutional acceptance); Workforce Development (readying the workforce with the skills to harness additive manufacturing); and Data Management (developing the policies, architectures, and procedures to properly manage massive, multimodal additive manufacturing data).

3 REGULATORY FRAMEWORK FOR AMM

It is fully expected that AMM has the potential for broad applicability in the nuclear industry. In some cases AMM can be used absent prior regulatory approval, while in other cases prior regulatory approval may be required. This section provides an overview of the regulatory framework for AMM. Section 3.3 addresses the situations where prior regulatory approval is not required to implement AMM components. Section 4 discusses regulatory pathways for use of AMM, when prior NRC approval is required. For instances that do require prior NRC approval, gaining regulatory approval of a method or process has the potential to be a multi-faceted effort.

3.1 Qualification

Developing and validating the specific method(s) to be used in fabricating components is an essential step in ensuring that the components meet the quality expectations for nuclear applications and that their long-term performance will meet their design function. The nuclear industry qualifies components, including the methods used to manufacture the components, whether or not they require prior NRC approval. The scope of qualification can take a graded approach and depend on the safety and risk significance of the component.

The extensive development and qualification efforts by many agencies and organizations for safety-related applications contribute to efforts by the DOE and domestic nuclear industry to provide a sound technical qualification basis. It is this overall body of information and experience that addresses the first step in demonstrating the suitability of advanced manufacturing for commercial nuclear applications, e.g., demonstrating that the advanced methods consistently produce high quality components.

Demonstrating the capabilities of AMM involves research and testing in developing the various methods, typically coupled with efforts by SDOs to promulgate consensus standards that will support the production of components that consistently meet quality standards. There are common interests and approaches across the various industries and government agencies to demonstrating the capability to consistently produce high quality components. These common interests and approaches are providing a robust basis for developing manufacturing standards and acceptance criteria that can be tailored and adopted by the nuclear industry without the need for extensive nuclear-specific development activities.

Demonstrating that the fabricated component will serve its intended function over its design life involves testing and evaluation of the fabricated materials and component in a simulated operating environment. This testing provides a basis to assess the component performance in the face of applicable age-related degradation mechanisms, such as creep, creep-fatigue, irradiation embrittlement, stress corrosion cracking, and other degradation mechanisms pertinent to the specific reactor design and operating environment(s).

Demonstrating that the component will perform its function over its design life is application-specific and will involve a combination of analysis and testing under credible loading and environmental conditions. This type of testing is well developed and routinely used by the nuclear industry and accepted by the NRC.

The combination of the extensive development and standardization efforts across numerous industries and agencies, and the well-established performance testing methods used in the nuclear industry, provides a sound technical basis for use of components manufactured using AMM in the nuclear industry. However, there are implementation strategies that need to be considered.

As with any new manufacturing technology, the implementation strategies involve a broad range of stakeholders. First, developing a thorough and common understanding of the various AMM processes and their implementation for both the industry and the regulator will be vital to successful implementation. Next, the technology developers, SDOs, and the regulator arrive at a common understanding of acceptable AMM processes, e.g., process control, material properties, and quality management. Finally, gaining agreement among the organizations that inspect and oversee quality in the construction of nuclear components and nuclear power plants will be vital to successful deployment. This will include activities such as the ASME processes (B&PV Code section development, NQA-1, and N-stamp processes), the NRC's vendor inspection program, the industry's Nuclear Procurement Issues Corporation (NUPIC) reviews, the NRC's construction inspection program, and the Authorized Nuclear Inspectors. There will be other organizations and activities that will have an interest in the deployment of AMM in the nuclear industry, but these would be addressed on a case-by-case basis as AMM is deployed.

There is clearly significant interest in AMM in the U.S. as evidenced by the broad ranging activities being conducted across the spectrum of fabrication industries and the extensive and growing interests of several U.S. government agencies. There also is significant activity in the international community. Efforts on the part of individual companies and on the part of governments in Europe and Asia clearly show that AMM is gaining acceptance in the international community. This international activity will also contribute to the technical basis underpinning AMM and to the basis for regulatory acceptance in the U.S.

While there is broad and growing acceptance of AMM in the national and international industrial communities, AMM has not been significantly employed in the nuclear community. There is clear and growing interest in AMM in the U.S. nuclear community as evidenced by DOE funded research, industry funded activities to demonstrate the viability of AMM, and efforts by the NRC to develop an action plan for advanced manufacturing technologies or AMM. (Ref. 13) Still, there is not widespread awareness or acceptance of AMM for nuclear applications. Outreach to staff at the International Atomic Energy Agency and the Nuclear Energy Agency revealed that neither organization has on-going activities exploring AMM, although the Generation IV International Forum (GIF) has initiated exploratory activities in this area. Similarly, outreach to representatives of the World Nuclear Association's Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group showed that they also are interested but have no current activities in this area.

Interests in AMM clearly are expanding in the nuclear community and the topic has been included in technical sessions in major conferences and technical meetings for the nuclear industry. There are conferences and industry-wide trade shows focused on AMM and these are beginning to include areas specific to the nuclear power industry. Developing broader awareness and acceptance of AMM in the nuclear power industry will benefit from expanding technical understanding of the various methods pertinent to the nuclear industry through widely attended meetings, workshops, and conferences. The NRC hosted a pivotal public meeting on this subject in November 2017, and the DOE, EPRI, and NEI have sponsored focused workshops over the last few years. These meetings and workshops provide an initial step toward broader activities to improve awareness and acceptance.

3.2 Regulatory Requirements

The design, fabrication, testing, and performance of systems, structures and components in a nuclear reactor is governed by a number of regulations specified in Title 10 of the Code of Federal Regulations, Part 50, “Domestic Licensing of Production and Utilization Facilities.” The technical requirements for reactors licensed under Title 10, Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants,” are contained in Part 50. Contents for Construction Permit and Operating License applications are detailed in 10 CFR 50.34, while contents for Design Certification Applications are detailed in 10 CFR 52.47 and contents for Combined License Applications are detailed in 10 CFR 52.79. Each of these regulations requires an applicant to provide information on the design of the facility, and specifically information relative to materials of construction. These regulations also require the description of the quality assurance program to be applied to the design, fabrication, construction, and testing of the structures, systems, and components of the facility. 10 CFR 50, Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants,” sets forth the requirements for these quality assurance programs.[1] Appendix B to Ref. 13 lists additional related regulations.

Under the requirements of 10 CFR 50.34, 10 CFR 52.47, and 10 CFR 52.79, the applications must include the principal design criteria for a proposed facility. The principal design criteria establish the necessary design, fabrication, construction, testing and performance requirements for structures, systems, and components important to safety.

Appendix A to 10 CFR 50, “General Design Criteria,” establishes the minimum requirements for the principal design criteria for water-cooled nuclear power plants similar in design and location to plants for which construction permits have previously been issued by the Commission and provides guidance to applicants. The NRC published Regulatory Guide 1.232, “Guidance for Developing Principal Design Criteria for Non-Light Water Reactors,” in April 2018, to provide guidance in developing principal design criteria for non-LWR designs.

General Design Criteria 1, 2, 3, and 4 provide overall requirements that are pertinent to the design, fabrication, and deployment of AMM components. Criterion 1 states that structures, systems, and components important to safety shall be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety functions to be performed. Criterion 2 states that structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena. Criterion 3 states that structures, systems, and components important to safety

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[1] 10 CFR 50.34(a)(3)(iii) addresses the requirement to address materials of construction in a Construction Permit application, while 10 CFR 50.34(a)(7) addresses the requirement to describe the quality assurance program.

10 CFR 52.47(a)(3)(iii) addresses the requirement to address materials of construction in a Design Certification application, while 10 CFR 52.47(a)(19) addresses the requirement to describe the quality assurance program.

10 CFR 52.79(a)(4)(iii) addresses the requirements to address materials of construction in a Combined License Application, while 10 CFR 52.79(a)(25) addresses the requirement to describe the quality assurance program.

shall be designed and located to minimize, consistent with other safety requirements, the probability and effect of fires and explosions. Criterion 4 states that structures, systems, and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. Additionally, Criterion 4 requires that these structures, systems, and components be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, and discharging fluids.

The specific design of structures, systems, and components is addressed in 10 CFR 50.55a, "Codes and Standards." Under 10 CFR 50.55a(b) systems and components of boiling and pressurized water-cooled nuclear power reactors must meet the requirements of the ASME Boiler and Pressure Vessel Code. It should be noted that 10 CFR 50.55a(z) allows alternatives to the requirements of 10 CFR 50.55a if the applicant demonstrates that (1) the proposed alternative would provide an acceptable level of quality and safety, or (2) compliance with the specific requirements of 10 CFR 50.55a would result in hardship or unusual difficulty without a compensating increase in the level of quality and safety.

The NRC staff's review of applications for a construction permit, operating license, design certification, or combined license is generally governed by the acceptance criteria and review procedures described in NUREG-0800, "Standard Review Plan" (SRP). There are sections of the SRP that address all of the structures, systems, and components where AMM components might be employed. The regulations governing applications for a Construction Permit, Operating License, a Design Certification, or a Combined License require an evaluation of the facility against the SRP revision that is in effect 6 months before the docket date of the application. The regulations note that the SRP is not a substitute for the regulations, and compliance with the SRP is not a requirement. However, where a difference between the design features of the facility and the SRP acceptance criteria is identified, the applicant is required to discuss how the proposed alternative provides an acceptable method of complying with the Commission regulations. Thus, the SRP provides a convenient and comprehensive reference for the applicable regulations, staff review procedures, and acceptance criteria. It should be noted that one task in the NRC's action plan (Ref. 13) is assessing whether any regulatory guidance (e.g. Regulatory Guides, SRP sections, etc.) need to be updated or created to clarify the process and procedures for reviewing submittals with AMM components.

3.3 Use of AMM without Prior NRC Approval

There are essentially two situations for which licensees can use AMM components without prior regulatory approval. The first is for components not addressed in the facility's Final Safety Analysis Report that have no nexus to a design function which is addressed in the FSAR. The second is for components where the provisions of 10 CFR 50.59 are satisfied.

For nuclear power plants licensed under 10 CFR Part 50, incorporating AMM components in situations where the provisions in 10 CFR 50.59 are satisfied would permit a licensee to incorporate the component without specific regulatory approval. Similar provisions are incorporated into 10 CFR Part 52 for plants licensed under that regulation and that reference a certified design (see 10 CFR 52.98(c) and Section VIII of the various Design Certification Appendices often noted as a "50.59-like" process). For those applications that are consistent with 10 CFR 50.59 and the "50.59-like" process in Part 52, this is a straightforward and efficient approach to deploying AMM components.

3.4 Contents of Regulatory Submittals

For those situations where prior NRC approval is required, more rigorous approval processes would be employed, such as the license amendment process in 10 CFR 50.90. The NRC staff has indicated they expect to approve components using a performance-based approach (Ref. 14) rather than approve specific advanced manufacturing methods.

The content of applications for construction permits, operating licenses, design certifications, and combined licenses include information relative to materials of construction, general arrangement, and approximate dimensions sufficient to provide reasonable assurance that the design will conform to the design bases with an adequate margin for safety. In the context of employing AMM components, demonstrating compliance with 10 CFR 50.55a, and compliance with the ASME Boiler and Pressure Vessel Code, provides sufficient information.

The NRC staff's review of applications is guided by the SRP. Specific review procedures in the pertinent SRP sections address materials of construction and compliance with ASME Code design criteria. The applications provide sufficient detail for the staff to conduct its review. This includes material specifications for individual components or sub-components, and sufficient information on dimensions, loadings, and configurations for the staff to assess compliance with the applicable ASME Code requirements.

For AMM components, providing this information becomes more challenging, particularly for those situations where the ASME Code has not endorsed the AMM method. As noted in Section 3.2, an applicant may propose alternatives to the provisions of the ASME Code under 10 CFR 50.55a(z). As specified in SRP Section 5.2.1.1, to exercise the alternatives provision, the technical submittal should identify differences between the specific portions of the code and code addenda to which each component has been constructed and that are required for compliance with 10 CFR 50.55a and provide justification for the proposed alternatives. For AMM components, that justification would be expected to include comparison of fabricated component material properties, such as strength, ductility, and fracture toughness, to the properties of materials and product forms approved in Section II of the ASME Code. It would also be expected to include discussion of any unique quality requirements imposed on the fabrication of the component, including results of any pre-service inspections that demonstrate that the integrity of the component would not be challenged by any remaining fabrication defects. Overall, the content of the application would be expected to provide sufficient information for the NRC staff to conduct the reviews specified in the pertinent SRP section(s).

4 REGULATORY PATHWAYS

The regulatory pathways in this section are only applicable if prior NRC approval is necessary, as discussed in Section 3.4. It is expected that NRC approval will involve demonstrating that the methods consistently produce high quality components which satisfy the quality standards for nuclear components, and that those components can fulfill their function over their full design life with acceptable margins against failure.

The typical and perhaps most direct pathway to gaining regulatory approval is to make use of the ASME B&PV Code language that has been endorsed by the NRC in 10 CFR 50.55a. The NRC can also issue relief requests for Code Cases which have been endorsed in the applicable Regulatory Guide. For situations where the ASME has not published Code language applicable to the AMM process or desired material, or where the Code approval and publication process is not consistent with industry deployment timelines, a different pathway is warranted. Two additional pathways for seeking regulatory approval are described below.

4.1 Use of Codes and Standards

The "Development and Qualification Using ASME Process," depicted in Figure 1 pathway (a), is a process for gaining regulatory approval of AMM components building on ASME Code language, and is consistent with historical NRC approval processes. For simplicity, the end product of this pathway is shown as a license amendment, although other approval processes (e.g., exemption, relief request) could be invoked for existing licensees and would be addressed through design certification and licensing for new applications. The pathway includes development of a topical report to support the end product, but this is an optional activity. Referencing approved ASME Code processes in the regulatory approval process provides an accepted method that will produce components of the expected quality. Companion testing to demonstrate that the component will fulfill its design function over its design life would provide the overall basis for approval of the component for use in either an operating plant or in a new design.

Often, as a precursor to incorporating language in a specific Code Section, a Code Case is published by ASME. These Code Cases are reviewed by the NRC staff and, if found acceptable, are incorporated in a Regulatory Guide. Regulatory Guide 1.84, "Design, Fabrication, and Materials Code Case Acceptability, ASME Section III" is pertinent to Code Cases for AMM. [2] The Code Case Regulatory Guides are incorporated by reference in updates to 10 CFR 50.55a. The approved Code Cases provide a voluntary alternative to the mandatory Code provisions. Often, the provisions of Code Cases are incorporated into specific provisions of the Code, which are then reviewed and, if acceptable, are endorsed in a periodic update to 10 CFR 50.55a.

These activities can be very time consuming, first in gaining Code approval and then in gaining endorsement in 10 CFR 50.55a. An alternative is for the NRC staff to review a Code Case and, if acceptable, to approve it using Interim Staff Guidance (ISG). This would provide more timely "approval for use" of the Code Case, allowing the industry to make use of the AMM process.

[2] Code Cases relevant to Section XI are endorsed in Regulatory Guide 1.147, "Inservice Inspection Code Case Acceptability, ASME Section XI, Division 1", while Code Cases relevant to the OM Code are endorsed in Regulatory Guide 1.192, "Operation and Maintenance Code Case Acceptability, ASME OM Code."

The pathway building on the ASME process has three major elements and begins by relying on ASME Code activities to evaluate specific AMM processes to demonstrate that the process consistently produces high quality components and to determine appropriate material properties for the fabricated component. In some cases these properties may be the same as those provided in the ASME Code, Section II. In other cases, properties may need to be developed for the deposited material. It is anticipated that the ASME codification process would also detail appropriate quality requirements for the AMM process and component. The ASME process is expected to first produce a Code Case detailing the process, material properties, and appropriate quality requirements. Code activities would continue, producing specific language to be incorporated into the Code.

The ASME process pathway anticipates the NRC staff would review the Code Case and, if found acceptable, would develop an Interim Staff Guidance endorsing the Code Case for use. The NRC can endorse the Code Case in an ISG faster than through the applicable Regulatory Guide, enabling earlier use of the AMM. Once a Code Case is endorsed by the NRC in 10 CFR 50.55a, a licensee or applicant would reference the Code Case rather than the ISG. This portion of the pathway addresses the need to demonstrate that the codified AMM process will consistently produce high quality components.

The second major element in the ASME process pathway is to demonstrate the component will satisfy its design function over its design lifetime. Historically, testing of the materials would be conducted under conditions to simulate the operating environment, e.g., creep/creep fatigue conditions, neutron irradiation, stress corrosion cracking, cyclic loading. The testing would reflect exposure to the simulated operating environment for the full design life. This is often time consuming and could result in a significant delay in deploying an AMM component.

This element of the pathway proposes to address developing the qualification data for the specific nuclear application by first identifying the specific testing and data needs to justify operation of the component for its full design life. An initial set of tests are conducted to justify operation of the component for an initial period, followed by tests and periodic inspections and tests to support full qualification of the component and its unrestricted operation.

The final element of the ASME pathway involves developing a License Amendment Request (LAR) or other approval processes (e.g. exemption, relief request), a request for an alternative under 10 CFR 50.55a(z), or input for a Design Certification or Combined License Application, referencing the ISG and including detail on the results of the initial testing, and the full testing and data needs to justify unrestricted operation over the design life of the component. The premise of the LAR, alternative, or license application is that approval would be granted for the initial operating period. Testing would continue during this initial period to provide the data to justify unrestricted operation. If the test results did not support unrestricted operation, the component would have to be replaced by the end of the initial operating period. It is anticipated that license conditions could be imposed to provide supplemental inspection or testing to ensure that the component was not exhibiting unanticipated aging during the initial period of operation. As the full set of testing is completed to justify unrestricted operation the license conditions would be removed. This process is analogous to prototype facility licensing addressed under 10 CFR 50.43(e)(2) and discussed in NRC's Regulatory Review Roadmap for Non-Light Water Reactors. (Ref. 15).

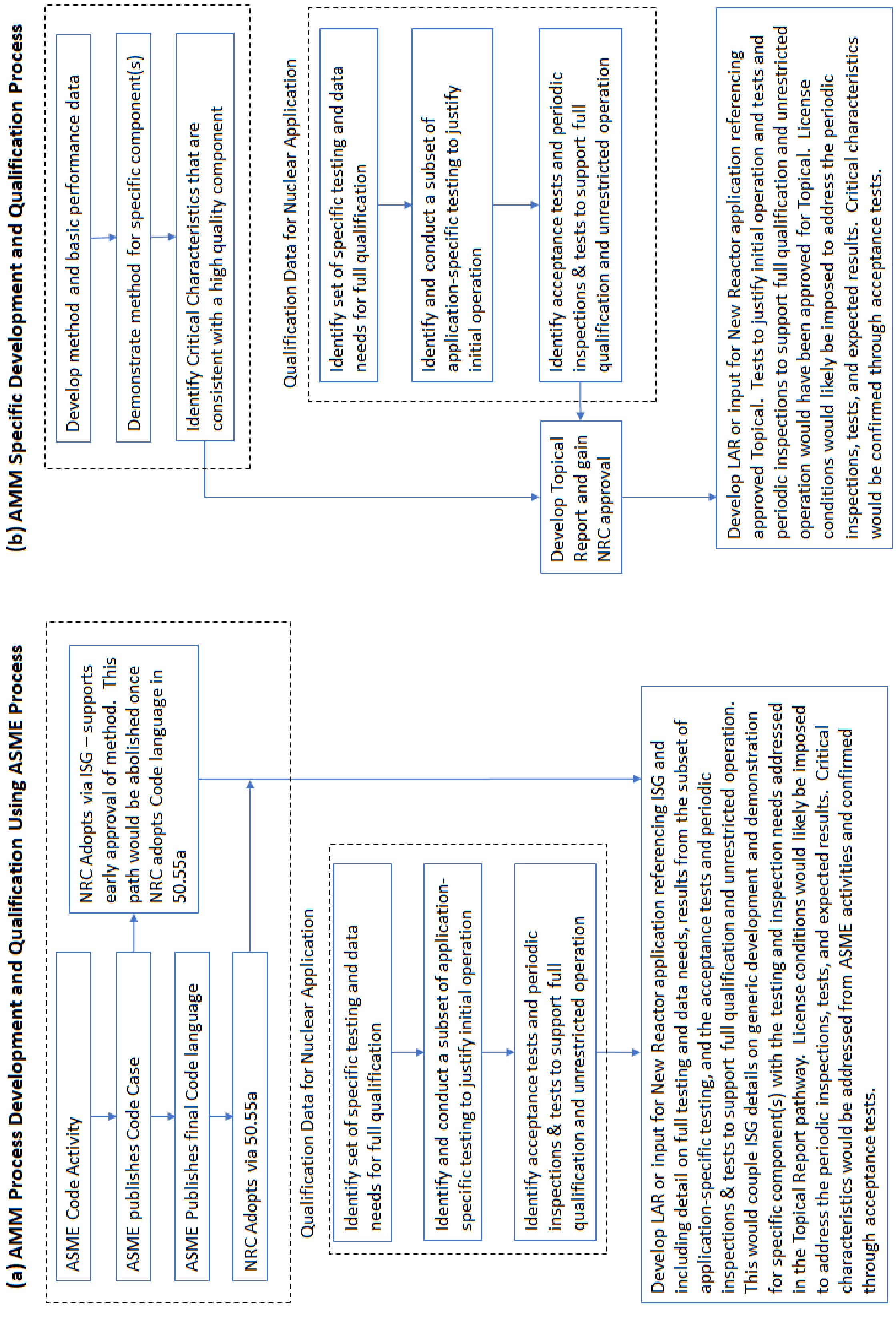

Figure 1. Pathways to Gaining Regulatory Approval for AMM Components

4.2 Specific AMM Approval Process

The “AMM Specific Development and Qualification Process,” depicted in Figure 1 pathway (b), is a demonstration pathway that is independent from ASME Code activities. The ASME Code process coupled with the NRC 10 CFR 50.55(a) endorsement process can take several years to complete. Current Code activities are only addressing one AMM process and one material. To expand the scope to address additional processes and materials would generally not be consistent with deployment timelines desired by the nuclear industry. The specific approval pathway can be applied to any of the AMM processes and to any material. The time to complete this pathway is expected to be appreciably shorter than the ASME Code based pathway. As with the ASME Code based pathway, for simplicity the end result of the specific AMM approval process is shown as a topical report and license amendment. It should be noted that developing the topical report is an optional activity. Other approval processes (e.g. exemption, relief request) could be invoked for existing licensees and would be addressed through design certification and licensing for new applications.

The specific AMM pathway has four major elements. The first is to develop and qualify an AMM and to demonstrate that components fabricated using that method consistently meets the quality expectations for nuclear components. This element would also identify critical characteristics that can be measured to ensure the high quality of the fabricated components. The extensive efforts by other industries to develop and qualify various AMM and AMM fabricated components for safety critical applications, are expected to provide vital information and data to support this pathway for nuclear applications. In fact, relying on efforts in other industries could be an important aspect of building a robust submittal seeking timely approval of AMM.

The second element in this pathway is the same as the second element in the ASME process pathway. Testing and data needs are identified that would demonstrate that the AMM fabricated component would satisfy its design function over its design lifetime. An initial set of tests are conducted in the simulated operating environment to support analysis that would justify an initial period of operation, including appropriate in-service inspection. Subsequently, the remaining testing and analysis needed to justify unrestricted operation is conducted. If that testing does not demonstrate acceptable performance over the design lifetime, then the component would need to be replaced prior to the end of the period for which it has been qualified. Appropriate in-service testing could be included as part of the overall justification.

The third element is to develop and submit a Topical Report for NRC staff review. As noted, development of a Topical Report is an optional activity, where the detailed information could be included in the application under the fourth element. The Topical Report would provide the process description, the testing conducted and results of that testing, and a description of the quality management activities implemented during the qualification effort and that would be implemented during component fabrication. This report would provide the comprehensive demonstration that the process, materials, and fabricated component(s) would be of high quality, consistent with the quality expectations for nuclear components, and that the fabricated components would fulfil their design function over the initial period of operation and that the subsequent testing would demonstrate successful performance over the full design life of the component.

The fourth element is to develop a LAR or input for a Design Certification or Combined License Application to gain approval for use of the AMM component during the initial period and, once justified, over the full design life of the component. This element is similar to the third element of the ASME process pathway. The major difference being AMM process development and qualification step would be the responsibility of the licensee or applicant rather than relying on the ASME process. The Topical Report review and approval element would include the types of development, review, and approval that would be implicit in the ASME Code process. As with the ASME process pathway, this specific process pathway builds on the concept of approving use of an AMM component for an initial period, imposing appropriate interim requirements for inspection and testing to ensure any unanticipated aging is identified and corrected or the component replaced. Once the full complement of testing is completed to justify unrestricted operation, the limitations on operation, i.e., license conditions, would be removed.

There are some advantages and disadvantages to either pathway. For example, the specific approval pathway places the burden for developing and qualifying the process and components on the licensee or applicant. While this development and qualification is expected to build on activities in other industries, the responsibility for presenting the complete case rests with the licensee or applicant. A significant benefit to the licensee or applicant is that they would have a much larger part in driving the process following this pathway. Conversely, the ASME process pathway builds on development and qualification activities conducted to support the ASME Code Case and eventual Code language and NRC endorsement in the regulations, all of which can be time consuming. Additionally, the Topical Report development and submittal would be the responsibility of the licensee or applicant, while the burden for activities to publish Interim Staff Guidance and promulgate rulemaking for 10 CFR 50.55a would be the responsibility of the NRC.

5 PATH FORWARD

Gaining broad industry and regulatory acceptance of AMM is a multifaceted task. The following actions have been identified as keys to facilitating the use of AMM for fabricating components for nuclear power plants.

5.1 Engagement with the NRC

There is significant industry interest in using AMM. A number of companies have near term plans to use AMM fabricated components in nuclear power plants. It is prudent for industry to systematically engage with the NRC at both the staff and management levels to help inform the NRC's plans, even in cases where prior NRC approval is not necessary.

The NRC staff has developed a draft action plan regarding advanced manufacturing methods. The stated purpose of that action plan is to develop a strategy that will enable the NRC staff to effectively, efficiently, and transparently regulate components manufactured using advanced manufacturing methods. Many of the considerations and activities described in the NRC's action plan parallel actions in this roadmap.

The following specific actions for NRC-industry engagement would help clarify the regulatory acceptance process and accelerate the use of AMM in the nuclear industry.

- Companies pursuing AMM can schedule drop-in meetings with the staff, and subsequently senior managers, potentially including individual Commissioners, to discuss the plan and schedule for engaging the staff.

- The NRC can hold public meetings to better understand industry and other stakeholder perspectives, including discussion of this report and the proposed approval pathways. This would include discussion and alignment on the degree to which experience with specific AMM processes from other industries can be credited in gaining NRC approval.

- The NRC and the DOE can co-host AMM technology workshops, similar to workshops held for advanced reactors, in order to gain a common and more thorough understanding of AMM technologies.

5.2 Development of AMM Codes and Standards

Developing a common understanding of the various Advanced Manufacturing Methods, how they can be applied, and their advantages and potential challenges is a key step in gaining acceptance. There have been technical meetings and workshops addressing AMM for the nuclear industry. While some AMM have received attention from the codes and standards committees, many methods lack sufficient attention to aid in their regulatory acceptance.

Specific actions can be undertaken by ASME and other standards organizations seeking to advance AMM in the nuclear power industry to accelerate the acceptance of AMM. For example:

- Work with the nuclear industry and other organizations to establish code cases for AMM for nuclear use, including establishing standard descriptions, and identify any R&D gaps for the methods and results of demonstrations and testing to illustrate how AMM can be applied for nuclear components.

- Work with ASTM International and Committee F42 on Additive Manufacturing Technologies and America Makes to have the nuclear industry included as one of their focus areas for standards development.

5.3 Research and Development of AMMs

Earlier sections of this report identified AMM processes that are pertinent to the nuclear industry, and the industry survey results identified those processes that are of the most interest for near term deployment. Providing adequate resources to pursue all of these processes and to continue research to develop additional innovative AMM processes does not seem practical in today's budget environment. The industry survey was specifically not intended to limit resource allocations for technology development or innovation. Rather, it was designed to identify those processes of most interest to the nuclear industry for initial deployment.

Those organizations providing resources for AMM development, both private and government, should work together to ensure adequate resources are available to pursue development and deployment of the AMM processes identified as most important in the industry survey. Clearly, such interactions would have to be conducted within the applicable legal boundaries, but providing adequate resources to support early deployment will be essential to furthering AMM use in the nuclear industry. DOE and the national laboratories in particular can be helpful in accelerating the use of AMM by focusing on R&D that addresses the data needed for regulatory and code and standard approval.

5.4 Workforce Development

Pursuit of AMM in the nuclear industry has largely been a technology development activity. Experts from industry, the National Laboratories, and academia have made significant progress in building on AMM from other industries as well as developing and adapting methods for application in the nuclear industry. However, if AMM use is to become common place in the nuclear industry, developing a skilled workforce to both design and produce AMM components will be a major consideration.

The ASTM International identified training and education as one of its pillar initiatives in additive manufacturing. Training and education is similarly identified as a "core activity" for the ASTM Center of Excellence for Additive Manufacturing.

Training, particularly for machine operators, figures prominently in the America Makes Roadmap.

Clearly, education and training are seen as important in the key industries identified by ASTM and America Makes. However, the nuclear industry is not yet one of the identified key industries.

Building on the education and training activities by ASTM and America Makes would be a logical starting point, expanding those activities as necessary to address nuclear-specific considerations. The goal is to educate and train a well-qualified workforce for designing and fabricating AMM components for the nuclear industry. Such training would be focused on industry and NRC inspectors that provide an oversight and inspection function for nuclear applications, such as NUPIC team members, American Nuclear Insurers' (ANI), and NRC's vendor inspectors and Regional Inspectors. A cost-effective approach to developing such training would be to work with ASTM and America Makes to have the nuclear industry included as one of their focus areas for standards development and incorporate nuclear-specific topics as part of their overall training and education activities. Such training could be focused on industry and NRC inspectors that provide an oversight and inspection function for nuclear applications, such as NUPIC team members, ANI's, and NRC's vendor inspectors and Regional Inspectors.

5.5 Quality management and oversight

As noted earlier, strategies for implementing AMM in the nuclear industry will involve a broad range of stakeholders. Developing quality assurance, or taken more broadly quality management, requirements for the various processes and the fabrication of components, consistent with the requirement for high quality components in the nuclear industry needs to be pursued. Quality in AMM processes has been stressed by virtually every implementing organization and by the SDOs that are involved. It is anticipated that the quality assurance requirements that exist today will generally be applicable to AMM fabrication. However, it also is anticipated that additional requirements will be needed to ensure the overall fabrication and construction activities meet expectations.

Additionally, there are a number of related quality activities, coupled with oversight and inspection responsibilities, which should be addressed as part of an overall AMM implementation strategy. Examples of specific actions that could be undertaken include:

- Collaboration among AMM developers, SDO's, other industry organizations such as America Makes, and nuclear industry quality assurance experts to develop appropriate quality assurance requirements for the AMM processes identified as of most interest to the nuclear industry.

- Collaboration among the cognizant SDO's (principally ASME), industry quality assurance experts, and the NRC to develop and codify specific quality assurance requirements. These requirements would be suitable for endorsement by NRC through Interim Staff Guidance or through endorsement in 10 CFR 50.55a or an appropriate Regulatory Guide.

- ASME to establish appropriate processes for approving AMM components for use as pressure boundary components, e.g., the N-stamp process.

- The various organizations that have oversight and inspection responsibilities for nuclear component fabrication and plant construction to adapt existing oversight and inspection guidelines to address any unique aspects of AMM fabricated components. These organizations would include ASME, The National Board of Boiler and Pressure Vessel Inspectors (the organization that commissions Authorized Nuclear Inspectors), NUPIC, and the NRC's Vendor Inspection organization and the NRC's Regional inspectors.

- NRC to host workshops or other appropriate meetings to bring together representatives from all implementation strategy stakeholders to review the overall strategy and each element of that strategy, thereby ensuring that AMM implementation and deployment of AMM fabricated components in the nuclear industry can proceed unimpeded.

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APPENDIX A: ADVANCED MANUFACTURING METHODS

	Reference
ADDITIVE MANUFACTURING – METALS	
Binder Jetting	22
Direct Energy Deposition (DED)	1
Direct Metal Deposition (DMD)	4
Direct Metal Laser Melting (DMLM)	5
Direct Metal Laser Sintering (DMLS)	1
Electron Beam Direct Energy Deposition Wire	2
Electron Beam Melting (EBM)	1
GTAW Direct Energy Deposition Wire	2
Investment Casting	4
Laser Direct Energy Deposition Wire	2
Laser Engineered Net Shaping (LENS)	1
Laser Powder Bed	9
Laser Powder Bed – Fusion (LPB-F)	10
Laser Wire Directed Deposition	11
Powder Metallurgy Hot Isostatic Pressing (PM-HIP)	12
Wire Plus Arc AM (WAAM)	1
ADDITIVE MANUFACTURING – NON-METALS	
Additive Layer Manufacturing	1
Blown Powder Laser	3
Electron Beam Freeform Fabrication	7
Electron Beam Powder Bed (EB-PB)	2
Electron beam-enabled Advanced Manufacturing (EBEAM)	8
Laser Deposition Technology (LDT)	1
Laser Direct Energy Deposition Powder	2
Laser Freeform Manufacturing Technology (LFMT)	1
Material Extrusion	22
Material Jetting	22
Plasm Arc Directed Deposition	11
Powder Bed Fusion	1
Rapid Plasma Deposition (RPD)	1
Robocasting or Direct Ink Writing	13
Selective Laser Melting (SLM)	1
Sheet Lamination	22
Ultrasonic Additive Manufacturing (UAM)	1
JOINING	
Adaptive Feedback Welding	14
Electron Beam Welding (EBW)	12
Friction Stir Welding (FSW)	20
Hybrid Laser Arc Welding	15
Hybrid Laser-GMAW	16
MACHINING	
Advanced Machining	12

Cryogenic Machining	25, 26
Ultrasonic Machining	24
METALLURGICAL MODIFICATION	
Equal channel angular pressing (ECAP)	18
High-pressure torsion (HPT)	18
SURFACE MODIFICATION/CLADDING	
Cold Spray Additive Manufacturing	19
Diode Laser Cladding	12
Friction Stir Additive Manufacturing (FSAM)	20
Hollow Cathode Plasma Nitriding	21
Laser Cladding Technology (LCT)	1
Laser Peening	23
Laser Surface Nitriding	16
Nanocoatings	27
SUPPORTING TECHNOLOGIES	
Advanced NDE Methods	
Improving weld quality through use of integrated optical sensors	17
Real-time Flaw Detection	
Metrology Methods	

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APPENDIX B: DESCRIPTION OF ADVANCED MANUFACTURING METHODS

Method	Description
Blown Powder Laser	Laser Powder Deposition is a type of Directed Energy Deposition that uses a laser beam to melt blown powdered material into fully dense 3D structures, as well as coat the surface or build features on pre-existing parts.
Direct Metal Laser Melting (DMLM)	DMLM is an Additive Manufacturing (AM) process that uses lasers to melt ultra-thin layers of metal powder to build a three-dimensional object. Process begins with a roller spreading a thin layer of metal powder on the print bed. Next, a computer directs a laser to create a cross-section of the object by completely melting metal particles. The print bed is then lowered so the process can be repeated.
Direct Metal Laser Sintering (DMLS)	DMLS uses lasers to partially melt particles so they adhere to one another. The DMLM process is very similar, except that the material is completely melted to create ultra-thin liquid pools which solidify as they cool. DMLS is often used to refer to both processes, although the term DMLM is gradually emerging as the preferred way to reference the process when complete melting occurs.
Laser Powder Bed	These are subsets of the direct energy deposition process. A thin layer of metallic powder is put down and then the laser selectively melts it based on the model. Another layer is put down and the laser melts that, and the process repeats. One distinction between Electron Beam (EB) and laser methods is that EB requires a vacuum chamber.
Laser Powder Bed – Fusion (LPB-F)	Same as Laser Powder Bed.
Direct Energy Deposition (DED)	DED is a complex printing process commonly used to repair or add additional material to existing components. A typical machine consists of a nozzle mounted on multi axis arm, which deposits melted material onto the specified surface, where it solidifies. The process is similar in principle to material extrusion but the nozzle can move in multiple directions and is not fixed to a specific axis. The material, which can be deposited from any angle due to 4 and 5 axis machines, is melted upon deposition by a laser or electron beam. Can be used with polymers or ceramics, but is typically used with metals in the form of either powder or wire.
Direct Metal Deposition (DMD)	DMD is an AM technology used to repair and rebuild worn or damaged components, to manufacture new components, and to apply wear and corrosion resistance coatings. DMD produces fully dense, functional metal parts directly from CAD data by depositing metal powders pixel-by-pixel using

	laser melting and a closed-loop control system to maintain dimensional accuracy and material integrity. With the feedback system six-axis deposition, and multiple material delivery, DMD can coat, build, and rebuild parts having very complex geometries. (WWW.asmeinternational.org)
Electron Beam Direct Energy Deposition Wire	This is a subset of the general direct energy deposition, where an Electron Beam is the energy source and wire is the feedstock.
Electron beam-enabled Advanced Manufacturing (EBEAM)	EBEAM is similar to laser melting but working with an electron beam instead of a laser. The machine distributes a layer of metal powder onto a build platform, which is melted by the electron beam. This is distinct from laser sintering as the raw material fuses having completely melted.
Electron Beam Freeform Fabrication	The operational concept of EBF3 is to build a near-net-shape metal part directly from a computer aided design file. Current computer-aided machining practices start with a CAD model and use a post-processor to write the machining instructions (G-code) defining the cutting tool paths needed to make the part. EBF3 uses a similar process starting with a CAD model, numerically slicing it into layers, then using a post-processor to write the G-code defining the deposition path and process parameters for the EBF3 equipment. It uses a focused electron beam in a vacuum environment to create a molten pool on a metallic substrate. The beam is translated with respect to the surface of the substrate while metal wire is fed into the molten pool. The deposit solidifies immediately after the electron beam has passed, having sufficient structural strength to support itself. The sequence is repeated in a layer-additive manner to produce a near-net-shape part needing only finish machining. EBF3 process is scalable for components from fractions of an inch to tens of feet in size, limited mainly by the size of the vacuum chamber and amount of wire feedstock available. (Wikipedia)
Friction Stir Additive Manufacturing (FSAM)	A solid-state thermo-mechanical process for deposition of metal or metal matrix composites used for a variety of manufacturing and repair applications. Due to its additive nature, the method can be used for coating, repair, or additive manufacturing of similar or dissimilar materials.
GTAW Direct Energy Deposition Wire	Another version of DED, using GTAW equipment for the plasma arc rather that EB or Laser.
Laser Direct Energy Deposition Powder	Laser version of Direct Energy Deposition for Powder.
Laser Direct Energy Deposition Wire	Laser version of Direct Energy Deposition of Wire.
Laser Deposition Technology (LDT)	LDT is a blanket name that encompasses many “like” processes – direct metal deposition (DMD), laser additive manufacturing (LAM), laser metal deposition, and others –

	that use a focused laser beam as the heat source for depositing powdered metals. LDT is a process in which metal powder is injected into the focused beam of a high-power laser under tightly controlled atmospheric conditions. The focused laser beam melts the surface of the target material and generates a small molten pool of base material. Powder delivered into this same spot is absorbed into the melt pool, thus generating a deposit that may range from 0.005 to 0.040 in. thick and 0.040 to 0.160 in wide. The resulting deposits may then be used to build or repair metal parts for a variety of different applications. Three main areas where LDT can be used: Laser Repair Technology – the repair of worn components Laser Cladding Technology – the application of cladding materials as a way to restore a worn surface Laser Freeform Manufacturing technology – performing near-net-shape freeform builds directly from CAD files. (Rpm-innovations.com)
Laser Engineered Net Shaping (LENS)	The process (copyrighted by Sandia National Laboratories) fabricates metal parts directly from the CAD solid models using metal powder injected into a molten pool created by a focused, high-powered laser beam. Simultaneously, the substrate on which the deposition is occurring is scanned under the beam/powder interaction zone to fabricate the desired cross-sectional geometry. Consecutive layers are sequentially deposited, thereby producing a three-dimensional metal component.
Laser Freeform Manufacturing Technology (LFMT)	Laser Freeform Manufacturing technology – producing near-net-shape freeform builds directly from CAD files.
Laser Wire Directed Deposition	One version of direct energy deposition but same as Laser Direct Energy Deposition Wire. (above)
Plasma Arc Directed Deposition	One version of direct energy deposition where a plasm arc is the energy source.
Rapid Plasma Deposition (RPD)	Patented process by Norsk Titanium. Uses dual plasma torches in a super-clear argon environment to deposit Ti wire. FAA certified. Fact sheet says it is 100 times faster than powder-based additive manufacturing. This appears to be another version of directed energy deposition.
Selective Laser Melting (SLM)	This is another name for Direct Metal Laser Melting described above.

Wire Plus Arc AM (WAAM)	This is another version of direct energy deposition, and similar to GTAW-direct energy deposition wire. WAAM hardware. Currently uses standard, off the shelf welding equipment; welding power source, torches and wire feeding systems. Motion can be provided either by robotic systems or computer numerical controlled gantries. Whenever possible, MIG is the process of choice: the wire is the consumable electrode, and its coaxiality with the welding torch results in easier tool path. MIG is perfect for materials such as aluminum and steel, but with titanium this process is affected by arc wandering. Consequently, tungsten inert gas or plasm arc welding is currently used for titanium deposition.
Powder Metallurgy Hot Isostatic Pressing (PM-HIP)	A process where metal powder is encapsulated in a form mirroring the desired part. The encapsulated power is exposed to high temperature and pressure, densifying the powder and producing a uniform microstructure. After densification, the capsule is removed, yielding a near-net shape component where final machining and inspection can be performed.
Ultrasonic Additive Manufacturing (UAM)	UAM process creates objects directly from a CAD model of the required object. The file is then sliced into layers which results in the production of a file that can be used by the UAM machine to build the required object, layer by layer. The general process is: A base plate is placed onto the machine anvil and fixed into place. Metal foil is then drawn under the sonotrode, which applies pressure through a nominal force and the ultrasonic oscillations, and bonded to the plate. This process is then repeated until the required area has been covered in ultrasonically consolidated material. A CNC mill is then used to trim the excess foil from the component and achieve the required geometry. The deposit and tri-cycle is repeated until a specified height is reached, typically 3-6 mm. At this height a smaller finishing mill is used to create the required tolerance and surface finish of the part. The deposit, trim and finish cycle continues until the finished object has been manufactured, at which point it is taken off the anvil and the finished part is removed from the base plate. (Wikipedia)
Binder Jetting	Binder Jetting is an additive manufacturing process in which a liquid binding agent is selectively deposited to join powder particles.
Investment Casting	Refers to the process for making a ceramic mold (termed the investment). Not cost-effective for short-run productions. (Wikipedia) Investment casting is a manufacturing process in which a wax

	pattern is coated with a refractory ceramic material. Once the ceramic material is hardened its internal geometry takes the shape of the casting. The wax is melted out and molten metal is poured into the cavity where the wax pattern was. The metal solidifies within the ceramic mold and then the metal casting is broken out….Parts manufactured in industry by this process include dental fixtures, gears, cams, ratchets, jewelry, turbine blades, machinery components and other parts of complex geometry.
Material Extrusion	ISO/ASTM definition: “material extrusion – an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.” Material Extrusion can also be known as: direct ink writing, extrusion freeform fabrication, fused deposition modeling, fused filament fabrication, glass 3D printing, liquid deposition modeling, micropen writing, plastic jet printing, robocasting or robotic deposition.
Material Jetting	A process that operates in a similar fashion to 2D printers. In material jetting, a printhead (similar to the printheads used for standard inkjet printing) dispenses droplets of a photosensitive material that solidifies under ultraviolet light building a part layer-by-layer. (www.3dhubs.com/.../introduction -material-jetting-3d-printing)
Robocasting or Direct Ink Writing	Same as Material Extrusion.
Selective Laser Sintering (SLS)	Uses a laser as the power source to sinter powdered material (typically nylon/polyamide), aiming the laser automatically at points in space defined by a 3D model, binding the material together to create a solid structure. It is similar to direct metal laser sintering; the two are implementations of the same concept but differ in technical details.
Sheet Lamination	ISO/ASTM definition: “an additive manufacturing process in which sheets of material are bonded to form a part.” Sheet lamination is also known as: computer-aided manufacturing of laminated engineering materials, laminated object manufacturing, plastic sheet lamination, selective deposition lamination, ultrasonic additive manufacturing, and ultrasonic consolidation. Original implementation was for rolls of paper and a CO2 laser, then a new company developed a similar system using sheets of PVC plastic rather than paper. The version using ultrasonics to bond the sheets was described for metals. Paper and plastic versions are still in use.

Adaptive Feedback Welding	Use of unique hardware and software to precisely adjust welding parameters in real time to improve weld quality.
Diode Laser Cladding	Laser cladding is similar to arc welding cladding methods but the laser is used to melt the surface of the substrate and the clad material which can be in wire, strip, or powder form. Laser cladding produces a high quality clad having extremely low dilution, low porosity, and good surface uniformity. High-powered diode lasers have been introduced, providing systems that offer advantages in terms of reliability and ease of integration over most other laser types. (www.photonics.com)
Friction Stir Welding (FSW)	FSW is a solid-state joining process that uses a non-consumable tool to join two facing workpieces without melting the workpiece material. Heat is generated by friction between the rotating tool and the workpiece material, which leads to a softened region near the FSW tool. While the tool is traversed along the joint line, it mechanically intermixes the two pieces of metal, and forges the hot and softened metal by the mechanical pressure, which is applied by the tool, much like joining clay or dough. It is primarily used on wrought or extruded aluminum and particularly for structures which need very high weld strength. FSW is found in modern shipbuilding, trains, and aerospace applications. (Wikipedia)
Hybrid Laser Arc Welding	Laser hybrid welding is a type of welding process that combines the principles of laser beam welding and arc welding. The combination of laser light and an electrical arc into an amalgamated welding process has existed since the 1970’s, but has only recently been used in industrial applications. There are three main types of hybrid welding process, depending on the arc used: TIG, plasma arc, or MIG augmented laser welding. While TIG-augmented laser welding was the first to be researched, MIG was the first to go into industry and is commonly known as hybrid laser welding. (Wikipedia)
Hybrid Laser-GMAW	Hybrid laser GMAW welding is an automated, high performance welding process which results in a very narrow heat-affected zone (HAZ) with deep penetration and high travel speeds relative to traditional processes. (Wikipedia)
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. In LCT, additional material can be placed precisely where desired; a very wide choice of different materials can be deposited and deposited onto; deposits are fully fused to the substrate with little or no porosity; minimal heat input results in a narrow HAZ and also limits distortion of the substrate and reduces the need

	for additional corrective machining; and it is easy to automate and integrate into CAD/CAM and CNC production environments.
Advanced Surface Plasma Nitriding	DOE funded development of a new plasma nitriding technique which is able to uniformly nitride fuel cladding tube surfaces, including both the outer and inner tube surfaces. The key is to use a cathodic cage to stabilize plasma distribution, providing a uniform layer, minimizing edge effects, increasing temperature uniformity, and reducing arcing.
Chemical Vapor Deposition (CVD)	Chemical vapor deposition (CVD) is a deposition method used produce high quality, high-performance, solid materials typically under vacuum. In CVD, a substrate is exposed to one or more volatile precursors, which react and/or decompose on the substrate surface to produce the desired deposit.
Cold Spray Additive Manufacturing	Powder is sprayed at supersonic velocities onto a metal surface and forms a diffusion bond with the part. This can be used to repair existing parts or to create complete parts. (additivemanufacturing.com, GE article)
Hollow Cathode Plasma Nitriding	A plasma nitriding system with an auxiliary cathode the surface of which is furnished with holes. The auxiliary cathode fulfills two functions: (i) it intensifies the nitriding discharge by hollow cathode discharges generated in the holes and (ii) it strongly sputters its material. As the material of the auxiliary cathode can be different from that of the parts to be nitrided, the surfaces of nitride substrates can be improved by the addition of selected materials such as Mo, Cr, Ti, V, etc. Very hard surfaces of the nitrided part can be created.
Laser Peening	A mechanical surface enhancement process that uses a high-energy pulsed laser beam to generate shock waves that propagate through the target material and produce compressive residual stresses. (www.lsptechnologies.com)
Nanocoatings	Ultra-thin layers or chemical structures that are built upon surfaces by a variety of methods. One industry definition is a coating that is no more than 1-100 nanometers thick. Nanocoatings are used to impart a particular chemical or physical function to a surface. (www.nanoslic.com)
Physical Vapor Deposition (PVD)	A technique to coat substrates with thin films. The substrate and the coating material are in a vacuum chamber. The coating material is evaporated. This can be achieved by different methods like electron beam, laser beam, arc discharge or sputtering. PVD can only be performed in a high vacuum. It is the preferred method to deposit metals and alloys because no chemical reaction takes place. (www.plasma-electronics.com)

APPENDIX C: CONSENSUS STANDARDS FOR ADVANCED MANUFACTURING

The following list of consensus standards related to additive manufacturing was developed through broad-based web searches and searches for specific Standards Development Organizations (SDOs). The searches identified relevant standards published by ASTM International, ISO, cooperatively by ASTM International and ISO, and by SAE International. Note that there are several more ISO standards than listed here, but they are for more detailed subjects.

These standards have not been reviewed for applicability to nuclear applications, but they have been developed and published for use in other safety critical applications.

Organization	Designation	Title
ASTM/ISO	ISO/ASTM 52915-16	Standard Specification of Additive Manufacturing File Format (AMF) Version 1.2
ISO/ASTM	ISO/ASTM 52910-18	Additive Manufacturing – Design – Requirements, guidelines and recommendations
ASTM	F2924-14	Standard Specification for Additive Manufacturing Titanium-6, Aluminum-4, Vanadium with Powder Bed Fusion
ASTM	F3001-14	Standard Specification for Additive Manufacturing Titanium-6, Aluminum-4, Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
ASTM	F3049-14	Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
ASTM	F3055-14a	Standard Specification of Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
ASTM	F3056-14e1	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion
ASTM	F3091/F3091M-14	Standard Specification for Powder Bed Fusion of Plastic Materials
ASTM	F3184-16	Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion
ASTM	F3187-16	Standard Guide for Directed Energy Deposition for Metals
ASTM	F3213-17	Standard for Additive Manufacturing – Finished Part Properties – Standard Specification for Cobalt-28, Chromium-6, Molybdenum via Powder Bed Fusion
ASTM	F3301-18a	Standard for Additive Manufacturing – Post Processing Methods – Standard Specification for Thermal Post-Processing Metal

		Parts Made via Powder Bed Fusion
ASTM	F3302-18	Standard for Additive Manufacturing – Finished Part Properties – Standard Specification for Titanium Alloys via Powder Bed Fusion
ASTM	F3303-18	Standard for Additive Manufacturing – Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications
ASTM	F3318-18	Standard for Additive Manufacturing – Finished Part Properties – Specification for AISI10Mg with Powder Bed Fusion – Laser Beam
ISO/ASTM	ASTM 52901-17	Standard Guide for Additive Manufacturing – General Principles – Requirements for Purchased AM Parts
ISO/ASTM	ASTM 52900-15	Standard Terminology for Additive Manufacturing – General Principles – Terminology
ASTM	F2971-13	Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
ASTM	F3122-14	Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes
ISO/ASTM	ASTM 52921-13	Standard Terminology for Additive Manufacturing – Coordinate Systems and Test Methodologies
ASTM	A1080-15	Standard Practice for Hot Isostatic Pressing of Steel, Stainless Steel, and Related Alloy Castings
ISO/TC 261	ISO 17296-2:2015	Additive Manufacturing – General Principles – Part 2: Overview of process categories and feedstock
ISO/TC 261	ISO 17296 -3:2014	Additive Manufacturing – General Principles – Part 3: Main characteristics and corresponding test methods
ISO/TC 261	ISO 17296 -4:2014	Additive Manufacturing – General Principles – Part 4: Overview of data processing
ISO/TC 261	ISO/ASTM DIS 52907 (under development)	Additive Manufacturing – Technical specifications on metal powders
ISO/TC 261	ISO/ASTM AWI 52908 (under development)	Additive Manufacturing – Post-processing methods – Standard specification for quality assurance and post processing of powder bed fusion metallic parts
ISO/TC 261	ISO/ASTM AWI 52909 (under development)	Additive Manufacturing – Finished part properties – Orientation and location dependence of mechanical properties for metal powder bed fusion
ISO/TC 261	ISO/ASTM DIS 52911-1 (under development)	Additive Manufacturing – Technical design guideline for powder bed fusion – Part 1: Laser-based powder bed fusion of metals
ISO/TC 261	ISO/ASTM WD 52941 (under development)	Additive Manufacturing – System performance and reliability - Standard test method for

		acceptance of powder-bed fusion machines for metallic materials for aerospace application
ISO/TC 261	ISO/ASTM WD 52942 (under development)	Additive Manufacturing – Qualification principles – Qualifying machine operators of metal powder bed fusion machines and equipment used in aerospace applications
ISO/TC 261	ISO/ASTM CD 52950 (under development)	Additive Manufacturing – General principles – Overview of data processing
SAE Int'l	AMS 7000	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Nickel Alloy, Corrosion and Heat-Resistant, 62 Ni – 21.5 Cr – 9.0 Mo – 3.65 Nb Stress Relieved, Hot Isostatic Pressed and Solution Annealed
SAE Int'l	AMS 7001	Nickel Alloy, Corrosion and Heat-Resistant Powder for Additive Manufacturing, 62 Ni - 2.5 Cr – 9.0 Mo – 3.65 Nb (pre-alloyed powder)
SAE Int'l	AMS 7002	Process Requirements for Production of Metal Powder Feedstock for Use in Additive Manufacturing of Aerospace Parts
SAE Int'l	AMS 7003	Laser Powder Bed Fusion Process