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Advanced Materials and Manufacturing Technologies

ADVANCEMENT OF CERTIFICATION METHODS AND APPLICATIONS FOR INDUSTRIAL DEPLOYMENTS OF COMPONENTS DERIVED FROM ADVANCED MANUFACTURING TECHNOLOGIES

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ABSTRACT

One goal of the Advanced Materials and Manufacturing Technologies subprogram, within the Department of Energy's (DOE) crosscutting technology development program, is to advance the qualification and certification of parts and components created via additive manufacturing (AM). AM offers a new paradigm for the design and optimization of new nuclear components, and for observing and tracking manufacturing performance and potential defects in a way that is not possible with traditional approaches. Tracking and evaluating these in situ data can lead to the estimation of local material properties and, with the use of engineering analysis tools, the estimation of component performance during operation. To achieve these objectives, a digital platform certification approach was developed and is summarized in this report.

The central hypothesis of this effort is that the total cost to manufacture and certify components produced through this approach will be less than traditional manufacturing and certification costs. Proving this hypothesis is then critical to broad industry adoption. Testing of this hypothesis requires setting experimental (i.e., manufacturing) limits and bounds to focus the effort and avoid cost and schedule inflation. Recommended bounds on this testing effort are proposed which take advantage of the significant investment that DOE has made through this program and the Transformational Challenge Reactor program. The recommended bounds include

- using the laser powder bed fusion AM technology
- using AM stainless steel 316
- using ultimate tensile strength as the critical material property of interest to achieve the possible functions where AM components could be employed in a nuclear application

A roadmap is presented with tasks and a representative schedule that could lead to broad industry adoption. A condensed roadmap is also proposed wherein the recommended bounds are employed, leading to a 2–3× reduction in schedule. If testing of this hypothesis with different bounds is desired (i.e., different materials, critical AM parameters, or different material properties of interest), then significant challenges are foreseen.

1. INTRODUCTION

Since its inception, the Transformational Challenge Reactor (TCR) program, led by research staff at Oak Ridge National Laboratory (ORNL) and at the Manufacturing Demonstration Facility (MDF), has been investigating the use of digital data to support the certification of additively manufactured components to reduce the reliance on supplemental testing data beyond a final component build. In the fall of 2020, the focus of the program has shifted away from demonstrating a reactor, and instead toward delivering on four key thrust areas: (1) artificial intelligence (AI) –informed design, (2) advanced materials, (3) integrated sensing and control, and (4) the digital platform (DP). A larger emphasis has now been placed on exploring the certification of additively manufactured components. The thrust area most pertinent to this effort is the DP [1]. At the start of FY 2022, the TCR program was merged into the Department of Energy's (DOE) crosscutting technology development subprogram, Advanced Materials and Manufacturing Technologies (AMMT). This work and emphasis have continued under AMMT, as there is significant potential to change the paradigm of nuclear component certification through a strong reliance on the DP.

Additive manufacturing (AM) and advanced manufacturing technologies (AMTs) are used as umbrella terms to cover a broad range of novel and nontraditional manufacturing methods that are just now being introduced to the US nuclear industry and have yet to be formally standardized (e.g., through nuclear codes and standards, through a submittal, or other processes resulting in US Nuclear Regulatory Commission [NRC] approval/endorsement). The NRC is investing several different AMTs, including

- laser powder bed fusion (LPBF)
- directed energy deposition (DED)
- powder metallurgy—hot isostatic pressing (PM-HIP)
- electron beam (EB) welding
- cold spray

Of these, LPBF is of significant interest to the nuclear industry and is the focus of using the DP to inform certification of nuclear components. For the current operating fleet, traditionally manufactured parts are being identified for potential replacement with those derived from AM. Currently, two AM parts, both produced by LPBF, have been inserted into reactor operation [2][3]. This approach is being established for commercial reactors with new published guidance that outlines the different processes depending on the application of AMT-derived parts and components [4]. For new proposed reactor designs, a broad spectrum of potential applications is being investigated [5].

Certification and qualification of processes and/or parts produced through advanced manufacturing presents a significant challenge for the nuclear power industry. Current approaches rely on extensive post-build evaluations and often require several build iterations to demonstrate convergence of part build quality and variability. In situ data (e.g., data about the component or part collected during the AM process) is used to confirm or highlight potential issues, but it has not yet been used as a surrogate or to supplant traditional quality evaluations.

This report builds on the work established last year to support the certification of AMT-derived components for nuclear application [6]. There are several key differences and similarities between these two reports. This report focuses on a proposed roadmap for industry adoption and on articulating the challenges and pathways for successful implementation of a DP-informed certification approach. It is recommended that the FY 2021 report, ORNL/TM-2021/2210 [6], be reviewed for additional background on the following:

- AMT vs. traditional materials
- NRC AMT regulatory framework development progress
- AMT technology overviews
- non-nuclear AMT applications and qualification aspects
- nuclear codes and standards such as ASME NQA-1-2008

To provide motivation and context for the DP-informed certification approach and the proposed roadmap for industry adoption, the DP, the certification process, and some review of NRC processes are discussed herein.

Through this effort, a principal goal is established:

> *To inform the certification of AMT-derived components for nuclear application using the digital platform to reduce and/or eliminate supplemental testing requirements so that the total replacement or new construction cost of a part or component is reduced as compared to traditional manufacturing approaches.*

This goal is occasionally misunderstood to refer to AM components as being "born qualified." This expression is a misrepresentation because under no circumstance do parts or components rely solely on in situ data. Principally, a comprehensive material data collection program is necessary to establish the material property correlations to the final part. Additionally, some nondestructive evaluations (NDEs) may be necessary to further characterize the final part or component to support quality evaluations. Additionally, other elements such as staff and operator training, environmental controls, procurement requirements, and records management are expected; and no AM process could be considered "qualified" without such elements.

Owing to practical limitations, which are discussed in more detail later, the goal of this effort is proposed for a specific application domain:

- components produced by **LPBF** using **AM stainless steel grade 316** and
- applications in which **ultimate tensile strength** is the dominant material property of interest or associated with the most limiting failure mode likely to occur during operation

Certification of components for nuclear application under this application domain using the DP would represent a significant milestone that would allow additional materials, material properties of interest, and other AMTs to be expanded. Certification, in these senses, implies that many different components with either similar or different functions within the nuclear power plant, which fall within the specified application domain, could be certified for use using the DP and correlated performance estimations from the in situ data and reasonable post-build verification and examination steps. This certification could be accomplished without the need for costly destructive evaluations, duplicate builds, and other supplemental testing processes. This approach would result in several transformative changes in the way new AM parts and components are certified for applications, assuming that the final component is within the certified domain and all standard quality assurance processes are followed:

- allowances for design changes or modifications to AM components, safety-significant or not

- allowances for new AM components that are replacing existing traditionally manufactured components

- allowances for new AM components that are part of a new reactor design or advanced reactor concept

These allowances would likely be in the form of reducing the need for testing and verification by relying on in situ data and correlated performance values.

To achieve this goal, critical challenges and questions remain. The following are a few of the critical questions:

- How will certainty of regulatory approval be measured?
- How does changing machines/printers affect the components produced in the application domain, or what parameters need to be reverified?
- How much data is needed to demonstrate component performance correlation?
- How does part criticality or safety significance affect the certification, and do limits on the parts produced in the application domain need to be modified?
- What is the role of modeling and simulation and do these analyses need to be nuclear qualified?
- And ultimately, **is this process worth the added expenses such as collecting physical data for correlating component performance?**

Therefore, it is not guaranteed that the principal goal can be achieved. Planning and commitment from DOE, as well as collaboration among ORNL and other national labs, universities, and other industry stakeholders, must continue to definitively answer the questions regarding cost and benefit.

Background on current certification processes, joint industry and NRC efforts, and the DP is presented in Section 2. The proposed DP-informed certification process is described in Section 3. Finally, these critical questions will be explored using a proposed roadmap that could result in industry adoption, assuming that cost reductions can be achieved.

2. BACKGROUND

Many companies and industries are using in situ data to inform the quality of their AM parts and components. Because of their safety significance or criticality to the mission, AM components produced for the nuclear and aerospace industries are particularly ripe for enhanced quality evaluations and the use of in situ data. However, those industries are also the most hesitant to directly employ certification approaches that rely heavily on in situ data because such approaches are not well established and could lead to unsuitable components compared with processes that rely on traditional quality evaluations and supplemental testing.

To better understand the DP-informed certification approach and what may need to occur to assist in its adoption by the nuclear industry, a summary of (1) the DP, (2) joint industry and NRC AMT initiatives, and (3) future NRC advanced reactor regulatory development is provided herein. More detailed information on some of these aspects can be found in the FY 2021 report [6].

2.1 DIGITAL PLATFORM AND ARTIFICIAL INTELLIGENCE

A key thrust under the AMMT program is the development and demonstration of a new advanced manufacturing paradigm that will produce parts qualified for service in nuclear systems in part by leveraging analytics driven by augmented intelligence relay and the concept of a *digital twin*. The cyber-physical infrastructure that supports this approach at the MDF is referred to as the DP. The DP provides design input to the 3D printers in the form of CAD, a robust computing, data storage, and networking capability; instrumentation for recording in situ processing information; details of post-fabrication treatment (e.g., annealing, wire electrical discharge machining, chemical vapor infiltration, scanning electron microscopy, and/or tensile testing) and equipment for measuring and characterizing the end product. To paint a full picture of the success (or failure) of a given 3D printed build, additional information such as feedstock utilization, printer calibration timelines, and printer maintenance timelines must also be captured by the DP. One aspect of the DP is a searchable database storing machine-readable metadata and linking to all the collected in situ and post-build characterization data. This information is accessible via a web interface, referred to as the Digital Tool (DT), which allows observation of each component's data throughout the entirety of its manufacturing and characterization process.

The totality of the data collected during manufacturing makes up the *digital thread*—the basis for constructing a *digital twin* computer model of a reactor component. A digital twin is a virtual representation of a physical object or system (its *physical twin*) across its lifecycle, using real-time data to enable understanding and to model how physical assets will perform under certain conditions, assist in monitoring the fabricated part's performance, and enable qualification in real time. Figure 1 is a partial graphical depiction of the digital thread under development at the MDF.

To maintain scalability, every manufacturing process is broken down into a sequence of *operations*. The digital thread of a manufactured part is then a collection of all the operations that went into the fabrication of the part. The operations associated with fabrication of parts vary greatly. Typical operations include AM (e.g., LPBF), subtractive manufacturing (e.g., wire electric discharge machining), post-printing treatments (e.g., curing and depowdering), metrology, and characterization. In addition to the operations that act directly on a part, operations associated with part fabrication may include maintenance and calibration records, powder particle size measurements, changes to the printer configuration, and so on.

Prediction of reactor-relevant part properties based on in situ data collected during the AM process is accomplished in part by the utilization of AI algorithms which ingest collections of digital threads to identify correlations between in situ data and part properties. Importantly, the prediction of part properties is accomplished through a relay of AI algorithms, with each interface between the algorithms being a checkpoint for human inspection to ensure that the subsequent AI is pointed in the correct direction. This approach is essential to consume the highly unstructured, multi-faceted, and high-dimensional in situ sensing data and to successfully link it to part property measurements without requiring a prohibitively large number of ex situ characterization experiments.

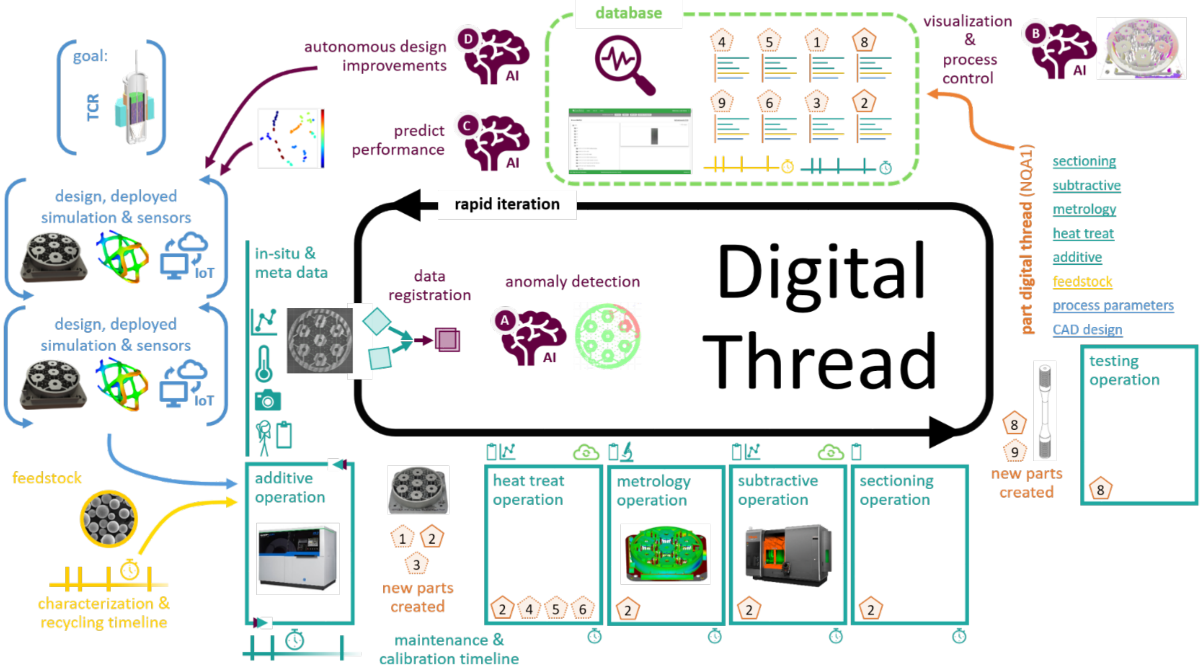

Figure 1. A graphical representation of the information contained within a digital thread of an additively manufactured component.

In general, AI algorithms can be loosely separated into four overlapping categories referred to as descriptive, diagnostic, predictive, and prescriptive (Figure 2). Descriptive AI is used to analyze raw data, for example, segmenting powder bed images and identifying process anomalies. Diagnostic AI summarizes large data sets and presents them to a human user or another algorithm. A diagnostic AI might flag certain layers of an AM operation for closer inspection by a human, or it might decide on an autonomous process intervention to attempt to correct a detected defect. A predictive AI seeks to predict part properties (e.g., fracture toughness) based in situ data, process parameter information, and part geometry. The demonstration of a predictive AI is an end goal of the program. Finally, a prescriptive AI would autonomously modify a part design to improve the predicted performance; this class of AI is beyond the scope of the TCR program but is the ultimate goal for the DP.

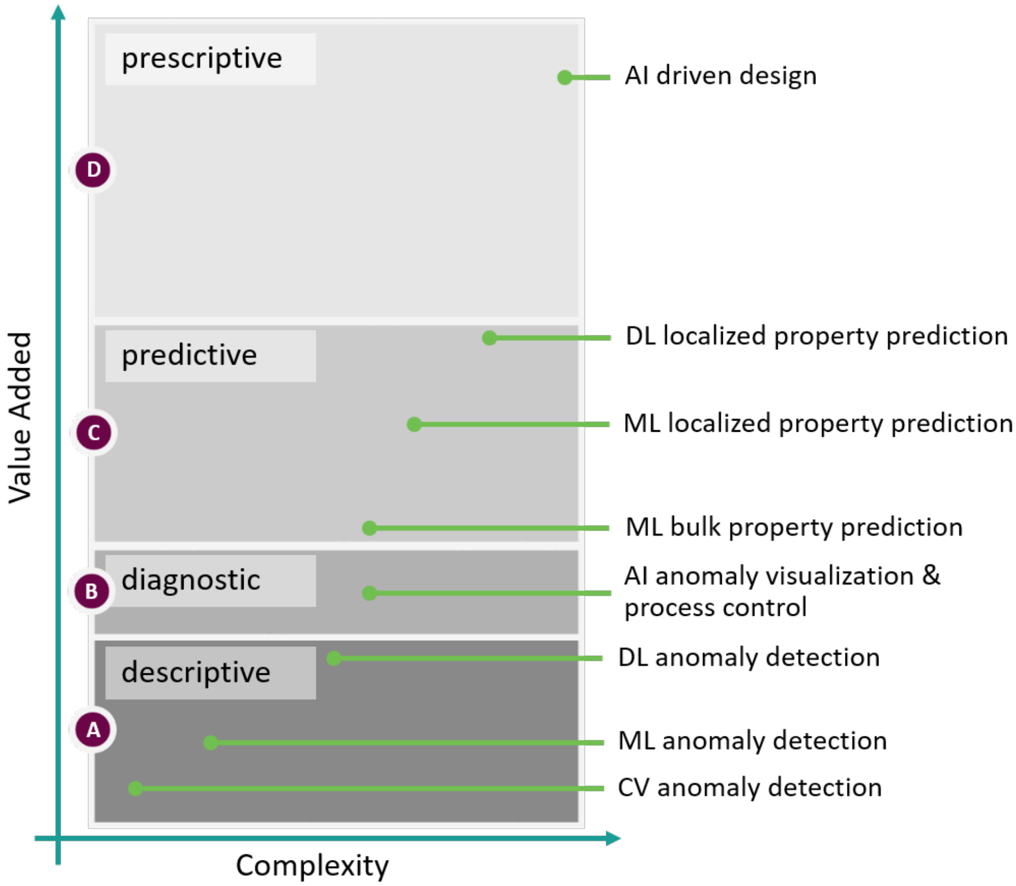

Figure 2. The approximate relative value and complexity of the different types of AI algorithms.

2.2 JOINT INDUSTRY AND NRC INITIATIVES

Owing to the growing interest in AM for nuclear applications, the NRC issued *United States Nuclear Regulatory Commission Action Plan for AMTs, Revision 0* on January 25, 2019. It was subsequently revised and published on June 22, 2020 [7]. This action plan is illustrated in Figure 3.

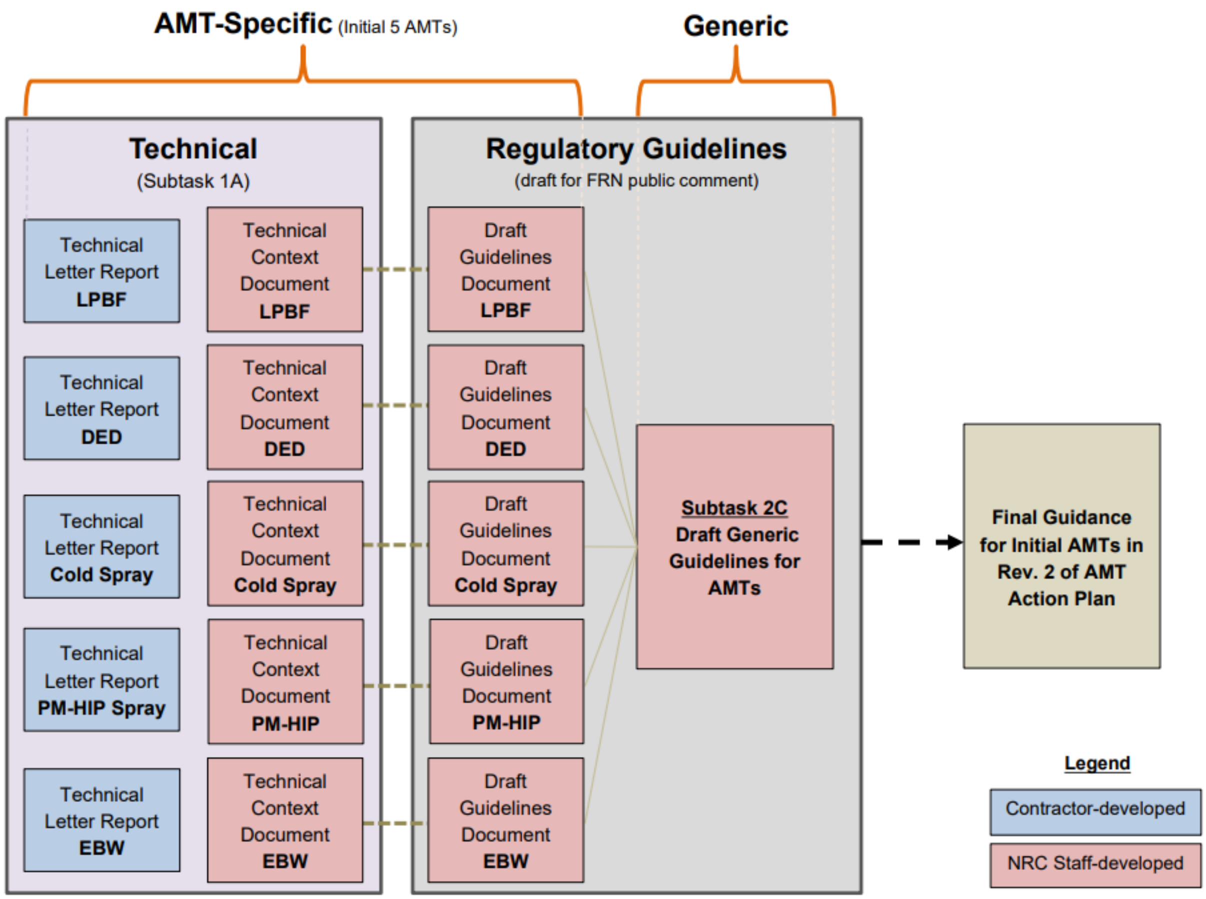

Figure 3. NRC AMT action plan flow chart [8].

Many of the AMT-specific reports and draft guidelines have been developed with industry input and presented at public stakeholder engagement meetings. Final guidance is expected in FY 2023.

Following on the initial publication of the AMT action plan, the Nuclear Energy Institute (NEI) published a roadmap for regulatory acceptance of advanced manufacturing methods in the nuclear energy industry [9]. In the NEI roadmap, two processes are outlined. The first is the traditional approach whereby ASME develops and publishes a code case, then the NRC adopts the code language while new applications reference the guidance and specify licensing conditions. The second, alternative, process would be specific to an AMT, and a topical report would be developed that includes both the qualification method and data for nuclear applications. The applicant would then incorporate the approved topical report for their application, along with licensing conditions and acceptance tests.

These processes are critical, as any new approach, such as the DP for AM certification, would likely follow one of the two processes. For the first process, however, it is unclear which standards development organization (SDO) would take on this effort. The second process appears more amenable to quicker deployment. However, the speed may come at a higher cost, as SDO efforts have a volunteer or in-kind component from the industry and the cost associated with NRC review time and the preparation of topical reports is not insignificant.

2.3 STANDARDS AND NON-NUCLEAR QUALIFICATION EFFORTS

Standards development continues to be a key focus area for support of the implementation of AMTs across all industries. The nuclear industry, in particular, has traditionally adopted mature technologies and standards based on demonstrated performance and case histories. Use of AMTs in the development of advanced reactor designs is more likely to be enabled by consistent industry standards that can be endorsed by the NRC and referenced in regulatory guidelines and methodology documents. Several standards development initiatives are ongoing for the industrial AM market and are discussed in the following subsections.

2.3.1 America Makes and American National Standards Institute Update

SDOs have been working together to identify gaps and develop new AMT standards to support industry adoption. One such collaboration, the America Makes and American National Standards Institute (ANSI) Additive Manufacturing Standardization Collaborative (AMSC) was established in March 2016 to help coordinate standards development across SDOs to ensure consistency and alignment [10].

In February 2017, the AMSC created a standardization roadmap for AM to identify existing standards and standards in development, assess gaps, and recommend priority areas for research and development [11]. The roadmap was created to help coordinate and accelerate the development of industry-wide AM standards and specifications. Revised in 2018, version 2.0 of the roadmap was updated and identified 93 open gaps where no published standard or specification exists. Ranked according to priority, gaps were found in five topical areas: design, process and materials, qualification and certification, nondestructive evaluation, and maintenance. Of that total, 18 gaps/recommendations have been identified as high priority, 51 as medium priority, and 24 as low priority.

The AMSC recently provided a progress report for the SDOs and others working to address the gaps identified in the roadmap [12]. Newly published standards and new standards projects were identified in addition to proposed future roadmap modifications. Several organizations continue to make progress in the development of standards in various gap focus areas. Based on the latest progress report, a number of standards are in development and are expected to be forthcoming in future updates. Table 1 includes a high-level breakdown of the gap focus areas and standards progress reported. An additional list of available AM-specific standards and the gap focus area they support is included in Appendix A. (Note that some of the identified standards may support multiple focus areas and therefore may be counted more than once, e.g., 2 of the Qualification and Certification standards also support Design and are included in the 30 Design standards).

Table 1. America Makes and ANSI Additive Manufacturing Standardization Collaborative gap summary.

AM focus area	Total (open)	High	Medium	Low	Closed	Published standards	In-development standards
Design	25	4	15	6	2	30	24
Process	23	4	12	7		37	51
Materials	14	4	5	5		34	48
Qualification and certification	15	4	8	3		6	25
NDE	8	2	4	2		4	8
Maintenance and repair	8		7	1		10	5
Total	93	18	51	24			

Source: Compiled from the ANSI Gaps Progress Report [12]

To date, only two identified gaps have been completely closed. Although a number of standards have been published or are in the final stages of approval, development of a complete suite of consistent, technology-inclusive standards is a large effort that will continue to take time—especially as the AM technology continues evolve. Continued periodic progress updates are expected as standards development work continues. Additional updates to the AMSC standardization roadmap are also anticipated to address new research findings, recommendations, and advances in AM technologies.

2.3.2 NASA Update

The National Aeronautics and Space Administration (NASA) is working to simplify rocket designs and reduce component costs using AMTs. To enable AM for advanced aeronautic applications, NASA has developed two standards to govern the production of AM parts for space flight and facility control systems. The first standard, NASA-STD-6030, *Additive Manufacturing Requirements for Spaceflight Systems*, [13] was created to address process control and part production. The second, NASA-STD-6033, *Additive Manufacturing Requirements for Equipment and Facility Control*, [14] is focused on equipment control and personnel training. By building on the existing quality management system and other agency standards, these two AM-specific standards have enabled the integration of AM into spaceflight hardware. As NASA is one of the first highly regulated agencies to successfully integrate AMTs into its program, NASA's AM deployment strategy is likely to be a viable reference for nuclear and other regulated industries.

2.4 NRC ADVANCED REACTOR REGULATORY DEVELOPMENT

One potential shift in the certification paradigm for nuclear components could result from the new advanced reactor regulatory development or 10 CFR Part 53 effort. Although nuclear quality assurance (NQA) requirements are not expected to be different for advanced reactors, the parts or components that fall under the NQA program may be significantly different than those for large light water reactors. The result may be a substantial number of components that are at not safety-related or safety-significant and thus are not part of the safety basis of the plant. Therefore, the vendor and utility could approve of a DP-informed certification approach without full NRC acceptance. Technical adequacy and robust component performance correlations would still be necessary to meet design, operation, and other systems engineering requirements. To make clear the difference in which components would fall under the safety basis following a 10 CFR 50/52 vs. a Part 53 approach, a brief review and status of the Part 53 development is presented in the following paragraphs.

Under the Nuclear Energy Innovation and Modernization Act (Public Law 115-439, dated January 2019), the NRC is required to complete a rulemaking to establish a technology-inclusive, regulatory framework for optional use for commercial advanced nuclear reactors no later than December 2027. A consolidated draft of Part 53 was published in February 2022 [15] with the draft Framework B published in June 2022 [16]. Framework A requires an expanded use of probabilistic risk assessment (PRA) to determine component safety requirements and safety classifications. The approach in Framework A has a long history of development and has been endorsed by the NRC [17]. It is this approach that could allow for PRA to demonstrate the non-risk and non-safety significance of AM parts or components. Although Framework B is newer and is still actively being discussed, it may be able to offer a similar level of component safety classification reduction.

In terms of reception, several industry organizations have expressed concern with multiple areas of the consolidated draft Part 53 publication [18]. Because of these public stakeholder engagement meetings and letter feedback, draft subparts are likely to change between now and final publication. However, considering the development history and the emphasis the commission has placed on the importance of PRA, it is unlikely that PRA-informed affordances for safety classification will be removed from Part 53. Therefore, any advanced nuclear vendor or component manufacturer considering AM components may realize more benefit from following an expanded use of a PRA, Part 53 application in conjunction with the DP-informed certification approach. Ultimately, the vendor will need to consider all aspects of the licensing process before making such a decision, and safety classification is only one of many critical areas.

3. DIGITAL PLATFORM–INFORMED CERTIFICATION PROCESS

In FY 2021, the TCR program developed an approach to use the DP to inform the certification of nuclear components. The goal of this approach is to replace supplemental verification testing of AM components using in situ data and AI-based correlations with relevant AM material properties under all anticipated machining conditions. The proposed approach relies on seven key elements, outlined in Figure 4.

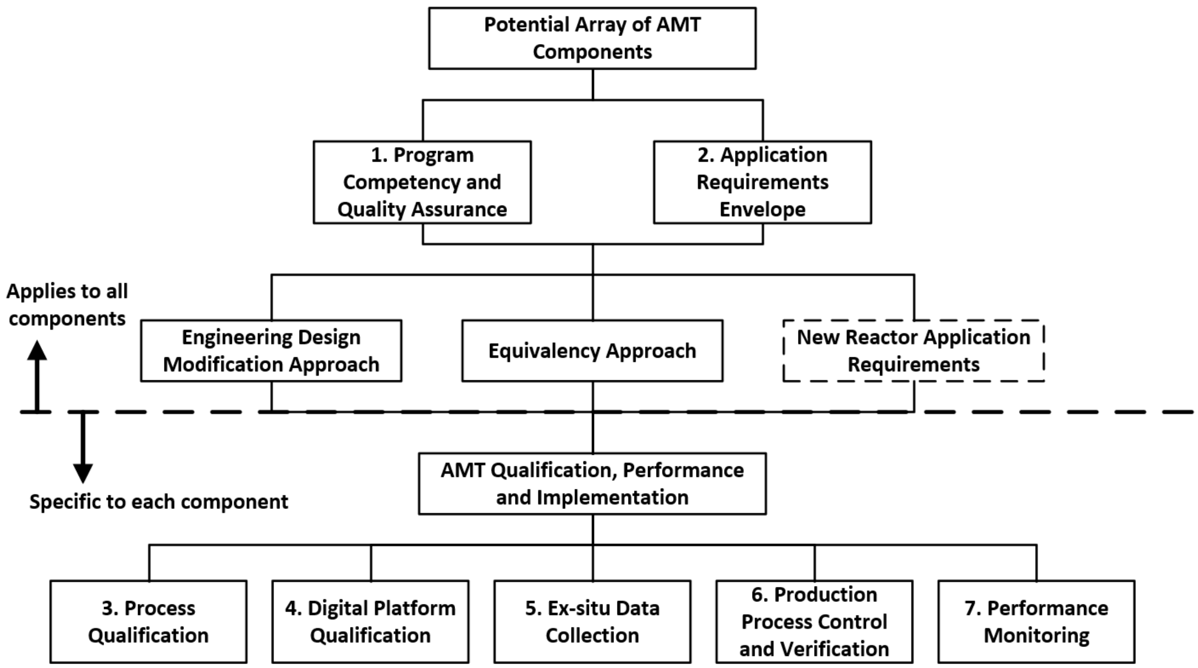

Figure 4. Proposed approach toward digital platform–informed certification.

In Figure 4, there are key components that must apply to any AM nuclear part. These include component 1, program competency and quality assurance, and component 2, the application requirements or requirements envelope. An *application requirements envelope* is defined as the span of critical AMT parameters and physical properties and parameters required to achieve the functions desired of the part or components. The critical AMT parameters are defined through the selection of printer, material powder, environment, and operational and use characteristics. These parameters include, for example, build chamber air temperature and humidity, build interruptions, laser characteristics, build scheme, and other characteristics. Physical properties and parameters are those material properties directly required for the part or component to achieve its function. These could include tensile strengths, thermal conductivity, density, and corrosion, among others. The application requirements envelope is illustrated in Figure 5.

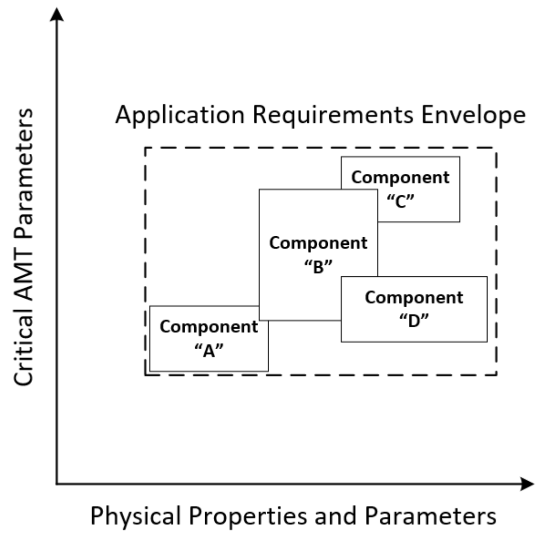

Figure 5. Application requirements envelope.

With Figure 5 in mind, the goal of the proposed approach is to thoroughly test and validate some number of components (e.g., Components A, B, C, and D) so that ranges are established to outline an envelope that would allow a new component (not shown), to be certified with less supplemental testing. This approach assumes that the new component's critical AMT parameters and desired physical properties and parameters are within the established ranges.

This approach is very similar to the draft AMT guidelines that NRC has published. The key difference is that elements 4 and 5 are replaced with supplemental testing in the NRC approach. Additionally, application requirements are for specific parts/components rather than for an envelope. New reactor application requirements are only partially listed on the proposed approach, as the licensing path will strongly influence the certification of specific components. However, there are no fundamental or inherent features of the proposed approach that would prohibit advanced reactor AM parts or components from having their certifications informed from a DP and in situ data.

For each of the seven elements of the proposed approach (Figure 4), sub-elements or steps are defined which contain specific goals and action items. These descriptions and action items for each element can be found in the FY 2021 report [6]. Part of these action items include assigning a *human grade* and a *computer grade* to the part after it is manufactured. The human grade includes the typical certification activities such as post-manufacturing inspections and other non-destructive evaluations and characterizations. The computer grade is the expected in-service performance as assessed through the DP and AI-based correlations, along with any engineering numerical assessments (e.g., finite-element analysis). Both grades result in a pass-fail test for certifying the part or component for use in the nuclear application. This process is illustrated in Figure 6.

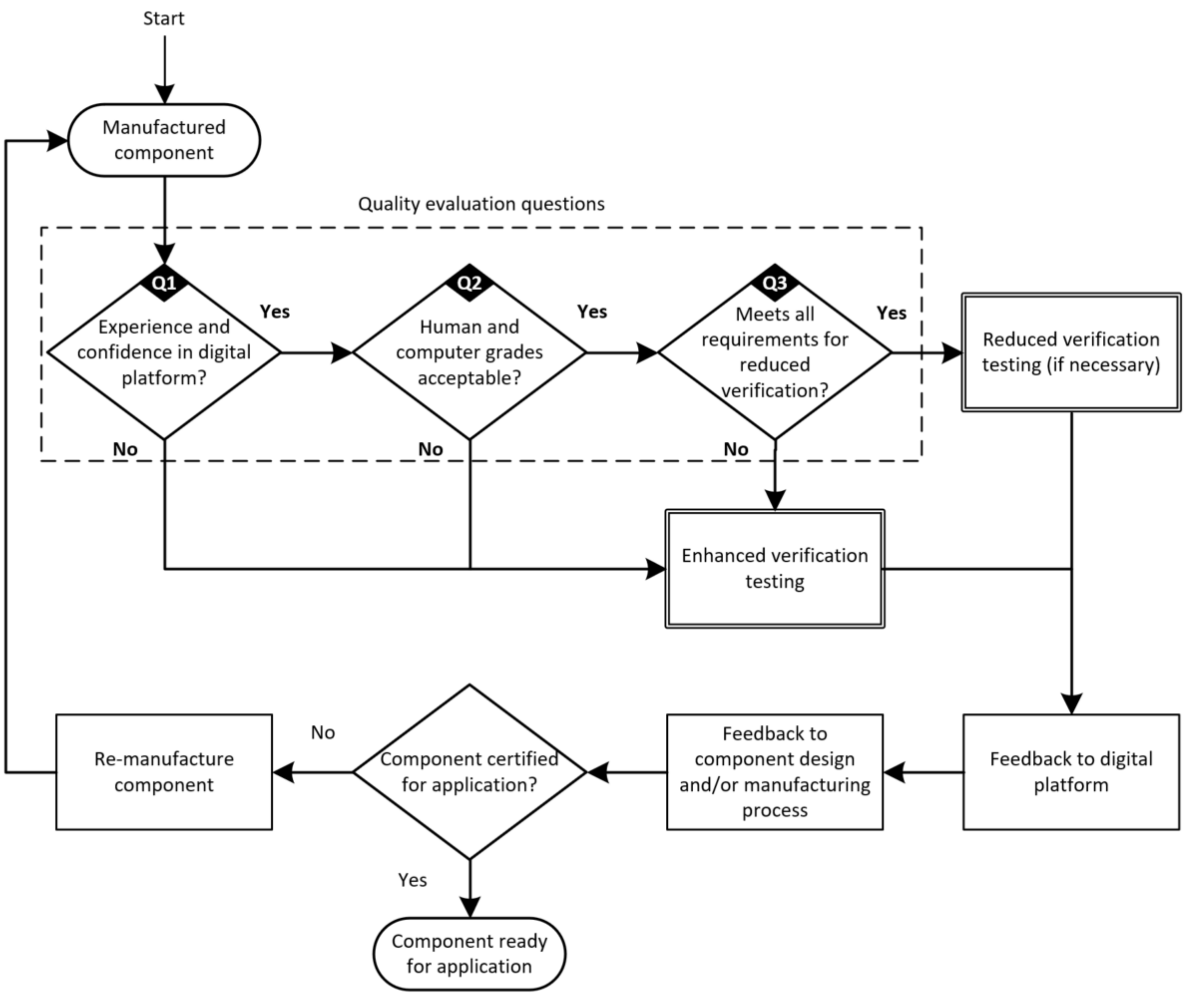

Figure 6. Proposed verification testing and quality evaluation process steps.

Implementing the process in Figure 6 is not without challenges. The quality evaluation questions begin with asking if there is both experience and confidence in the DP to inform the certification. The answer leads into questions regarding how much experience is required and what defines confidence in the DP. Although human and computer grades are conceptually understood, what requirement needs to be imposed so that the AM part or component achieves certification?

Answers to these questions begin with fundamentally understanding the AM process, what defects are, how they occur, where are they likely to occur, and whether the instrumentation and infrastructure are in place to identify and assess potential defects. Then, with an understanding of the application requirements (e.g., what the ultimate tensile strength needs to be across the part/component), values can be placed on the application requirements envelope. For some number of initial components, enhanced verification testing should be performed to confirm that the correct critical AMT parameters are identified and are correctly correlated with the physical properties and parameters of interest. “Enhanced,” in this sense, does not imply that any different or novel testing method is needed. Rather, the quantity of tests performed and the scale—either the whole part/component, or just a coupon or sample—is prescribed. Ideally, the quantity and scale would be much less for the “n-th of a kind” part than for the first.

Experience and confidence in the DP and the ability to correlate in situ data with expected component or part performance is gained through exercising the process for these initial components (i.e., Components A, B, C, and D in Figure 5). Theoretically, the minimum number of components would be three, to define an area (triangle) for the envelope of desired parts or components. In practice, this number will likely be larger, as different components may be more/less sensitive to different critical AMT parameters (e.g., part orientation). The exact number of components that can be produced before verification testing can be reduced (quantity, scale, or both) is unlikely to be set or known a priori. Therefore, answers to these challenging questions may be determined only through demonstration.

4. ROADMAP FOR INDUSTRY ADOPTION

The hypothesis of the proposed approach is that

> *using the digital platform, in-situ data correlated with part/component performance can replace destructive evaluations, excessive duplication, and supplemental testing which would lead to a lower net cost to manufacture and certify the host of desired AM parts/components.*

Only through demonstration can this hypothesis be tested. If it is proven correct, widespread industry adoption is then possible. Therefore, demonstration is critical for potential industry adoption and will require planning and commitment from many stakeholders.

This section provides one possible roadmap for industry adoption. The goal of the presented effort is to inform ORNL, DOE, and the larger AM research community that industry adoption of digitally informed certification of AM parts for nuclear applications is possible through collaboration and strong leadership. Of course, for different materials, for different desired applications with different critical material properties of interest, or even for different AMTs, the demonstration and testing of this hypothesis becomes more challenging. However, having one example that fully exercises the proposed approach would establish a framework for future applications with different materials or critical material properties, and could expedite the testing of the hypothesis under those conditions.

Generally, a roadmap consists of a planning schedule that outlines tasks that need to be completed over time to achieve a desired result. In this case, the desired result is that the hypothesis either is proved correct, or can be adequately proved to be incorrect, for the term while advanced nuclear energy systems are being investigated by both domestic and international agencies. To prove a hypothesis, an experiment needs to be performed. The bounds of the experiment should be chosen so that outside and environmental disruptions are minimized as much as possible. Assumptions and sources of uncertainty should be identified and tracked through the experiment.

The proposed experiment central to this roadmap is that

1. AM parts and components will be selected based on their relevance for potential nuclear applications and/or desire by the industry and sponsors.

2. AM parts and component selected for manufacturing and will have their critical material properties and critical AMT manufacturing parameters identified so that an application envelope is constructed.

3. Following the proposed DP-informed certification approach, AM parts and components will be gradually produced, characterized (both technically and economically), and put into service (either operating nuclear plant, research or test reactor, or surrogate operation) with the intention of reducing supplemental testing and enhanced verification.

4. When sufficient confidence in the DP is established, a new AM part, or series of parts, will be designed, manufactured, and put into service with the *desired minimum* post-build testing and characterization.

5. All technical, economic, schedule, safety, and quality information from this process will be evaluated to determine the net cost to manufacture and certify the host of desired AM parts/components.

For experiment step 5, this economic and schedule data can be divided among three phases. The first phase is related to steps 1 through 3, which is consistent with a program startup or initiation phase. The second phase is related only to step 3, in which the first new part is produced and put into service with the desired minimum post-build testing and characterization. Each individual part produced with the desired minimum post-build testing and characterization could be evaluated independently. Finally, phase 3 is related to the cumulative experiment over all phases, and cumulative over just the parts associated with the desired minimum post-build testing and characterization. Splitting the evaluation of economic and schedule data across these three phases will lead to better understanding of where the hypothesis breaks down or where areas of improvement could be found to potentially improve and validate the hypothesis.

Desired minimum post-build testing and characterization refers to the acknowledgement that destructive quality evaluations, excess witness specimen collections, excess redundant part/component builds, wasted powder and materials, and other time-consuming tests and characterizations detract from the commercial viability and potential for industry adoption. Ideally, for areas where in situ data and the DP can adequately predict quality, then that approach should be used. If there are tests that cannot be avoided, then these tests represent the *desired minimum*. Additionally, if there are tests that have a de minimis economic or schedule cost, such as visual checking, then those could also be included in the *desired minimum*.

In this section, a roadmap is proposed that describes tasks and subtasks related to the proposed experiment. It uses the proposed DP certification approach, which will lead to the adequate confirmation or denial of the hypothesis that a DP-informed certification is not only possible but also economical for a host of desired nuclear AM applications.

4.1 ESTABLISHING THE EXPERIMENTAL BOUNDS

The experimental bounds principally consist of the desired nuclear AM applications to test the hypothesis and to test what the critical functions are, which will drive the identification of critical material properties and what AMT (e.g., LPBF) and material are selected. Strong motivation exists for selecting potential nuclear parts and components consisting of AM SS316 made by LPBF, with only tensile strength as the critical material property related to its functions within the nuclear plant. This will be explained by describing the high-level tasks using the proposed DP certification approach.

Following the proposed approach (i.e., the steps shown in Figure 4), the following high-level tasks have been identified for the experiment.

1. Describe the quantity assurance, the program organization, and how the hypothesis is to be tested.

2. Select the AM applications and describe the application envelope.

3. Perform all necessary process qualification steps (codes and standards, knowledge of all critical defects, heat treatment and other post-operations).

4. Develop the DP and/or ensure the DP enables secure, accessible, and understandable access to in situ data and has the AI capabilities for material property correlations.

5. Develop a plan and collect the necessary ex situ data for material property correlations.

6. Perform all necessary production process control and verification steps for all manufacturing phases.

7. Measure the performance of the manufactured parts during operation and determine how this information will feed back into the DP.

For task 1, TCR successfully maintained an AM NQA program and served as an example for this step. [19][20] For industry adoption, DOE and the specific program supporting the effort (e.g., AMMT or another program) will need to define which organizations will be involved (e.g., national labs, universities), how quality assurance programs between organizations will be performed, and the scope that each organization will undertake to fully test this hypothesis.

For task 2, testing of the hypothesis may be achieved for a limited number of applications with a defined application envelope. One example application envelope is parts and components manufactured using LPBF of AM SS316, which has only mechanical performance requirements (i.e., tensile strength requirements). Under these conditions, there are many unique pressure-retaining and mechanical support components composed of AM316 that could be proposed for construction and use in a nuclear application to justify this certification approach using the DP. This application envelope is recommended because of the extensive experience base that TCR has generated [21]; its use would significantly lower the starting requirements for the execution of this roadmap.

For task 3, using the proposed application envelope, much of the knowledge base on formation of defects and the impact of defects on component quality would also transfer to the overall experiment. If a new material, a different AMT, or a different critical material property is selected, additional research and testing may need to be performed to obtain sufficient information on the range of possible defects, how they occur, and their impact on quality, which will drive the selection of necessary in situ measurement capabilities.

For task 4, the proposed application envelope would also reduce these requirements, as the DP, particularly the Peregrine software, has been used extensively by TCR and by several different companies through external license agreements. This is an area of ongoing area of research and development that it would be inefficient to repeat.

Task 5 could be a significant effort, depending on the material properties of interest and the tests needed to obtain such properties. Considering the multitude of different critical AMT parameters, and their impacts on the local material properties, to train and test the machine learning algorithm (generalized neural network) will likely require thousands, possibly tens of thousands, of specimens in the geometry relevant to the physical material property collection test [21]. TCR is continuing to contribute to the wealth of tensile data for AM SS316, which provides additional motivation for selecting it as the experimental bounds.

Tasks 6 and 7 are not expected to significantly impact the setting of the experimental bounds (i.e., the choice of material, AMT, or critical material properties). Measuring the performance during operation could be a challenge for some parts or components, based on their function. For many cases, post-operation inspection will be the primary means of evaluating performance during operation.

In considering other applications or materials, the availability of existing AM data and their applicability for machine learning applications should be one of the highest considerations from an efficiency and program initialization perspective.

4.2 TASKS AND SCHEDULE

Figure 7 provides an overview of the tasks and schedule for testing the hypothesis, leading to industry adoption of the DP-informed certification process.

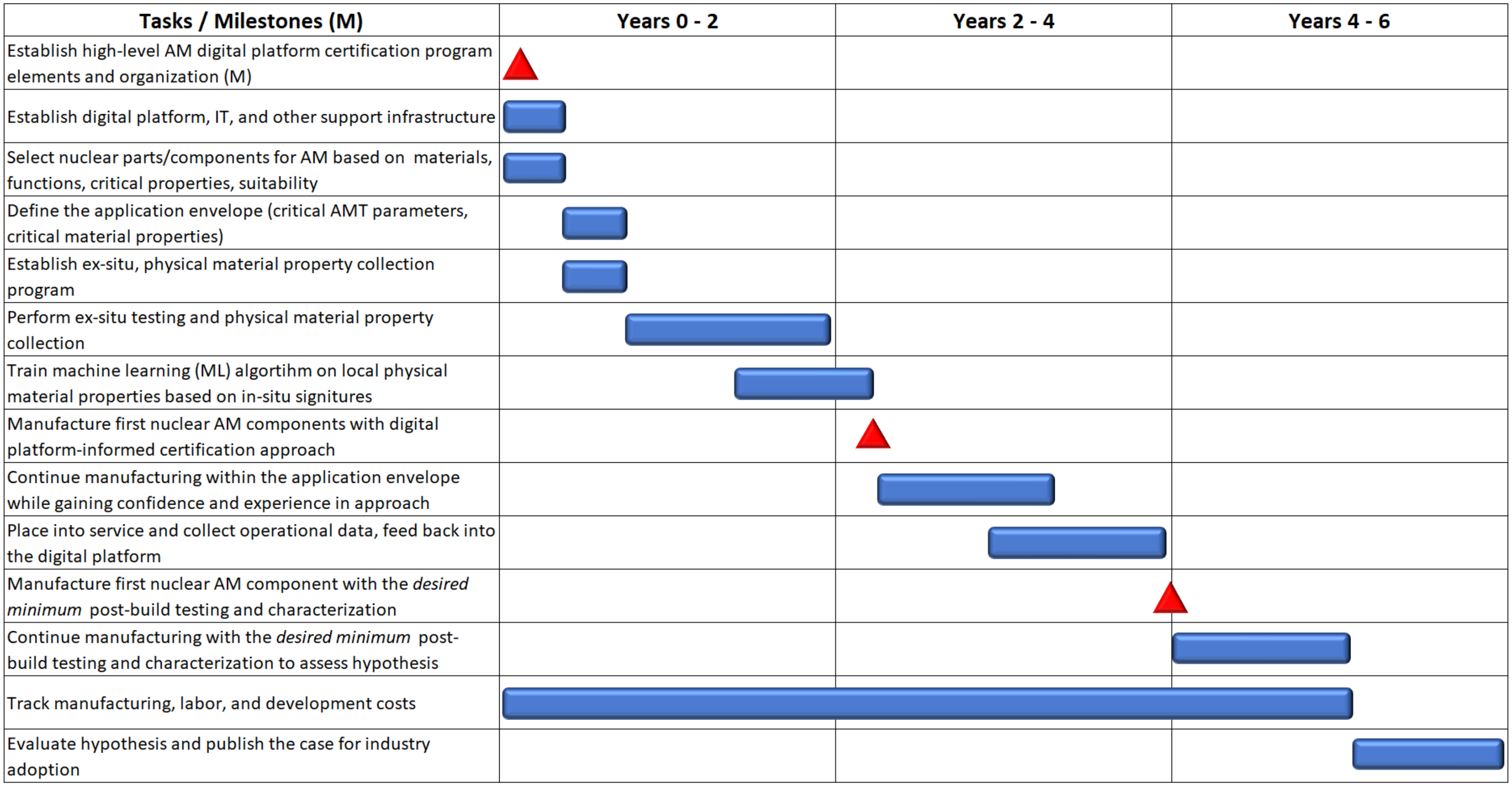

Figure 7. Roadmap for industry adoption of the digital platform–informed certification approach.

The schedule presented in the roadmap (Figure 7) is flexible, and the exact timeline will depend on several factors, many of which also depend heavily on the source and magnitude of the investment (e.g., DOE AMMT program). Those factors include

- availability and capability of obtaining ex situ data
- availability of infrastructure, printers/machines, sensors, and so on
- what operational service period is defined for the parts/components
- performance of the machine learning algorithm(s) and capability for in situ and ex situ correlations.

For example, using AM SS316 as the material, using LPBF, and using tensile strength as the critical material property, the timeline could be reduced by the first 2 year increment because those tasks and milestones have largely been completed by the TCR program. Additionally, based on AM part experience in reactor operation, like that by Framatome/TVA [2] and Westinghouse [3]a determination that reactor operation is unnecessary to adequately test the hypothesis could eliminate several years from the roadmap schedule (or even decades, depending on the quantity of AM parts to be tested in a reactor environment and the availability of utility reactor operation). Conceivably, this condensed roadmap could be accomplished within only a 2 year timeframe. In that case, the condensed roadmap might consist of only the following:

- establish the application envelope

- manufacture part/components following the DP–informed certification approach

- continue manufacturing while demonstrating that only the *desired minimum* post-build testing and characterization is needed

- evaluate economic and schedule information to adequately confirm or challenge the hypothesis

However, if an alternate material or critical material property is selected, then the roadmap schedule would likely range from 3 to 6 years, depending on several factors like those described earlier.

4.3 MOTIVATION FOR GOVERNMENT LEADERSHIP IN AM MATERIAL SCIENCE AND CERTIFICATION OF PARTS AND COMPONENTS FOR NUCLEAR AND OTHER CRITICAL INDUSTRIES

One of the fundamental truths of AM materials is that for any given material, there exists a range of physical properties, such as density and tensile strength, that a part may take on, depending on many different manufacturing and environmental factors. Assessing these material properties no longer involves just a handful of carefully controlled experiments that can be benchmarked and compared against each other. The conditions of the manufacturing process must be nearly exact to be able to ensure a proper comparison. Therefore, the construction of material property databases for AM will be much more complex and costly than for traditional materials. For example, private companies might withhold such information from the public because it is dependent on their propriety manufacturing process parameters. The result could be redundant work between organizations, which would create a high barrier to entry and high startup costs for any company considering AM for nuclear and other critical industries. The barrier for entry becomes even higher if the additional costs of sensors, information technology infrastructure, the DP, and correlation of situ manufacturing data with ex situ physical property measurements also must be recreated by each company looking to certify components through this approach.

Ideally, if a company produces an AM part/component and has all the necessary in situ data and measurement capabilities, the knowledge of whether that part/component can be certified for nuclear application should be accessible to any interested potential vendor. It is then the regulator's responsibility to check and ensure that safety requirements have been satisfied with respect to both the design and construction of that part/component.

However, to maintain regulatory independence, another central or public body should be responsible for AM physical material and in situ property correlations. If a commercial or nonprofit entity retains this information, then the cost or sale of this certification knowledge will depend on the cost of performing the data gathering and correlation steps. This information should arise out of the final phase, phase 3, of the proposed experimental bounds, in which economic and schedule data is compiled and assessed. If it is determined that this data gathering and correlation process is too costly, then no commercial entity may wish to undertake such a program. However, this ignores the possibility that if data gathering and correlation tasks can be performed, regardless of the cost, then the total cost of manufacturing and of putting those DP-informed certification components into operation may be substantially less than the cost of traditional techniques. In that case, only public funding and support by the government can reduce the high barrier for entry sufficiently to provide for the usage of a DP-informed certification approach. This government support would ultimately provide a net benefit to society by reducing energy costs through the expanded use and deployment of AM parts/components.

5. CONCLUSIONS

The DP-informed certification process aims to reduce the total cost of manufacturing and certifying new nuclear parts and components for operation by using in situ data correlated to material properties and then expected part performance. Industry adoption of a DP-informed certification process will require a clear evaluation of the costs and benefits following a demonstration. The bounds of the proposed experimental demonstration reflect the significant investment that DOE and ORNL have made and the knowledge acquired in the areas of AM material properties and correlations to in situ data and other critical AM parameters. Progress is being made in the areas of standards development and regulatory guidance; but a continued, coordinated effort among DOE, the national labs, universities, and other industry stakeholders is required to achieve a DP-informed certification approach for AM.

With a focused effort, using the proposed bounds of the experiment, a case for industry adoption could be made in as little as 2 years. For alternate materials, critical AMT parameters, or material properties of interest, significant challenges remain. In case an alternative bound for the experiment is needed, a roadmap is presented. However, the high-level tasks and total schedule will depend heavily on the availability of funding, on what material property is of interest for potential nuclear applications, and on the availability of experimental testing and information technology resources. A government organization, such as DOE, is best suited to perform this effort, as these factors can be more efficiently managed with the guarantee that any data collected can be used by all interested vendors and manufacturers.

AM offers a new paradigm not just for design and optimization of new nuclear components, but also for observing and tracking manufacturing performance and potential defects in a way that is not possible with traditional approaches. Ideally, anyone who has the ability to manufacture and to collect sufficient data should be able to determine, without supplemental testing or significant verification activities, that their component could be certified for nuclear application. If this process can be proved to be viable, a revolution in new components and optimizations, leading to reduced nuclear plant cost and maintenance requirements, is possible.

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APPENDIX A. AMT STANDARDS UPDATE

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Primary Focus Area	Standard	Title	Status	Link
Design	ISO/ASTM 52900:2021	Additive manufacturing — General principles — Fundamentals and vocabulary	Issued 11/2021	https://www.iso.org/standard/74514.html
Design	ISO/ASTM 52910-18	Additive manufacturing — Design — Requirements, guidelines and recommendations	Issued 7/2018	https://www.astm.org/f3154-18.html
Design	ISO/ASTM 52911-1:2019	Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals	Issued 7/2019	https://www.iso.org/standard/72951.html
Design	ISO/ASTM 52911-2:2019	Additive manufacturing — Design — Part 2: Laser-based powder bed fusion of polymers	Issued 9/2019	https://www.iso.org/standard/72952.html
Design	ISO/ASTM TR 52912:2020	Additive manufacturing — Design — Functionally graded additive manufacturing	Issued 9/2020	https://www.iso.org/standard/71905.html
Design	ISO/ASTM 52915:2020	Specification for additive manufacturing file format (AMF) Version 1.2	Issued 3/2020	https://www.iso.org/standard/74640.html
Design	ISO/ASTM TR 52916:2022	Additive manufacturing for medical — Data — Optimized medical image data	Issued 1/2022	https://www.iso.org/standard/75143.html
Design	ISO/ASTM 52921-13(2019)	Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies	Issued 10/2019	https://www.astm.org/f2921-13r19.html
Design	ISO/ASTM 52922-19e1	Guide for Additive Manufacturing — Design — Directed Energy Deposition	Issued 1/2022	https://www.astm.org/f3413-19e01.html
Design	ISO/ASTM 52950-21	Additive manufacturing — General principles — Overview of data processing	Issued 2/2021	https://www.astm.org/f3436-21.html
Design	ISO 14649-17:2020	Industrial automation systems and integration — Physical device control — Data model for computerized numerical controllers — Part 17: Process data for additive manufacturing	Issued 3/2020	https://www.iso.org/standard/72194.html
Design	ASTM F3055-14a(2021)	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion	Issued 10/2021	https://www.astm.org/f3055-14ar21.html
Design	ASTM F3056-14(2021)	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion	Issued 10/2021	https://www.astm.org/f3056-14r21.html
Design	ASTM F3335-20(2020)	Standard Guide for Assessing the Removal of Additive Manufacturing Residues in Medical Devices Fabricated by Powder Bed Fusion	Issued 3/2020	https://www.astm.org/f3335-20.html
Design	ASTM F3490-21	Standard Practice for Additive Manufacturing — General Principles — Overview of Data Pedigree	Issued 3/2022	https://www.astm.org/f3490-21.html
Design	ASTM F3529-21	Guide For Additive Manufacturing - Design - Material Extrusion Of Polymers	Issued 3/2022	https://webstore.ansi.org/Standards/ASTM/astmf352921
Design	ASME Y14.47-2019	Model Organization Practices	Issued 2/2019	https://webstore.ansi.org/Standards/ASME/ASMEY14472019

Primary Focus Area	Standard	Title	Status	Link
Design	SAE AMS7004	Titanium Alloy Preforms from Plasma Arc Directed Energy Deposition Additive Manufacturing on Substrate Ti-6Al-4V Stress Relieved	Issued 1/2019	https://www.sae.org/standards/content/ams7004/
Design	SAE AMS7008	Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 47.5Ni - 22Cr - 1.5Co - 9.0Mo - 0.60W - 18.5Fe	Issued 3/2019	https://www.sae.org/standards/content/ams7008/
Design	SAE AMS7012	Precipitation Hardenable Steel Alloy, Corrosion and Heat-Resistant Powder for Additive Manufacturing 16.0Cr - 4.0Ni - 4.0Cu - 0.30Nb	Issued 11/2019	https://www.sae.org/standards/content/ams7012/
Design	SAE AMS7013	Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 60Ni - 22Cr - 2.0Mo - 14W - 0.35Al - 0.03La	Issued 1/2019	https://www.sae.org/standards/content/ams7013/
Design	SAE AMS7014	Titanium Alloy, High Temperature Applications, Powder for Additive Manufacturing, Ti - 6.0Al - 2.0Sn - 4.0Zr - 2.0Mo	Issued 3/2019	https://www.sae.org/standards/content/ams7014/
Design	SAE AMS7018	Aluminum Alloy Powder 10.0Si - 0.35Mg	Issued 5/2020	https://www.sae.org/standards/content/ams7018/
Design	SAE AMS7021	Precipitation Hardenable Steel Alloy, Corrosion and Heat Resistant, Powder for Additive Manufacturing, 15.0Cr - 4.5Ni - 3.5Cu - 0.30Nb	Issued 11/2020	https://www.sae.org/standards/content/ams7021/
Design	SAE AMS7101	Fused Filament Fabrication, Material for	Issued 10/2019	https://www.sae.org/standards/content/ams7101/
Design	SAE ARP7042	Recommended Practice: Development Planning for Design of Additive Manufactured Components in an Aircraft System	Issued 3/2022	https://www.sae.org/standards/content/arp7042/
Design	SAE EIA649C	Configuration Management Standard	Issued 2/2019	https://www.sae.org/standards/content/eia649c/
Design	IEEE-ISTO: PWG 5100.21-2019	Internet Printing Protocol 3D Printing Extensions v1.1 (3D)	Issued 3/2019	https://ftp.pwg.org/pub/pwg/candidates/cs-ipp3d11-20190329-5100.21.pdf
Design	MIL-STD-31000B	Technical Data Packages	Issued 10/2018	https://webstore.ansi.org/Standards/DOD/MILSTD31000B
Design	AWS D20.1/D20.1M:2019	Specification for Fabrication of Metal Components Using Additive Manufacturing	Issued 12/2018	https://pubs.aws.org/p/1915/d201d201m2019-specification-for-fabrication-of-metal-components-using-additive-manufacturing
Design	ISO/ASTM DIS 52909	Additive manufacturing — Finished part properties — Orientation and location dependence of mechanical properties for metal powder bed fusion	Draft	https://www.iso.org/standard/74639.html
Design	ISO/ASTM CD TR 52910	Additive manufacturing — Design — Requirements, guidelines and recommendations	Draft	https://www.iso.org/standard/81934.html
Design	ISO/ASTM CD TR 52918	Additive manufacturing — Data formats — File format support, ecosystem and evolutions	Draft	https://www.iso.org/standard/76415.html?browse=tc

Primary Focus Area	Standard	Title	Status	Link
Design	ISO/ASTM DIS 52937	Additive Manufacturing of metals — Qualification principles — Qualification of designers	Draft	https://www.iso.org/standard/79530.html
Design	ASTM WK48549	New Specification for AMF Support for Solid Modeling: Voxel Information, Constructive Solid Geometry Representations and Solid Texturing	Draft	https://www.astm.org/workitem-wk48549
Design	ASTM WK62867	New Guide for Additive Manufacturing - General Principles - Guide for Design for Material Extrusion Processes	Draft	https://www.astm.org/workitem-wk62867
Design	ASTM WK64190	New Guide for Additive Manufacturing Design - Decision Guide	Draft	https://www.astm.org/workitem-wk64190
Design	ASTM WK65929	New Specification for Additive Manufacturing-Finished Part Properties and Post Processing - Additively Manufactured Spaceflight Hardware by Laser Beam Powder Bed Fusion In Metals	Draft	https://www.astm.org/workitem-wk65929
Design	ASTM WK65937	New Specification for Additive Manufacturing -- Space Application -- Flight Hardware made by Laser Beam Powder Bed Fusion Process	Draft	https://www.astm.org/workitem-wk65937
Design	ASTM WK66682	New Guide for Evaluating Post-processing and Characterization Techniques for AM Part Surfaces	Draft	https://www.astm.org/workitem-wk66682
Design	ASTM WK69732	New Guide for Additive Manufacturing -- Wire Arc Additive Manufacturing	Draft	https://www.astm.org/workitem-wk69732
Design	ASTM WK71395	New Practice for Additive manufacturing -- accelerated quality inspection of build health for laser beam powder bed fusion process	Draft	https://www.astm.org/workitem-wk71395
Design	ASTM WK72172	New Practice for Additive manufacturing -- General principles -- Overview of data pedigree	Draft	https://www.astm.org/workitem-wk72172
Design	ASTM WK72938	New Guide for Additive manufacturing -- Design -- Part 3: Electron-based powder bed fusion of metals	Draft	https://www.astm.org/workitem-wk72938
Design	ASTM WK73978	New Specification for Additive Manufacturing-General Principles-Registration of Process-Monitoring and Quality-Control Data	Draft	https://www.astm.org/workitem-wk73978
Design	ASTM WK74390	New Practice for Additive Manufacturing of Metals -- Data -- File structure for in-process monitoring of powder bed fusion	Draft	https://www.astm.org/workitem-wk74390
Design	ASTM WK76163	New Test Method for Additive Manufacturing -- Test Artifacts -- Compression Validation Coupons for Lattice Designs	Draft	https://www.astm.org/workitem-wk76163
Design	ASTM WK76970	New Practice for Additive Manufacturing -- General Principles -- Guidelines for Technical and Intellectual Property Authentication and Protection	Draft	https://www.astm.org/workitem-wk76970

Primary Focus Area	Standard	Title	Status	Link
Design	ASTM WK76983	New Practice for Additive Manufacturing -- Powder Bed Fusion -- Best Practice for In-situ Defect Detection and Analysis	Draft	https://www.astm.org/workitem-wk76983
Design	ASTM WK78115	New Guide for Additive Manufacturing -- Design -- Post-Processing for Metal PBF-LB1	Draft	https://www.astm.org/workitem-wk78115
Design	ASTM WK78322	New Guide for Additive Manufacturing -- General Principles -- Guidelines for AM Security	Draft	https://www.astm.org/workitem-wk78322
Design	ASME Y14.46-2017	Product Definition for Additive Manufacturing	Draft	https://www.asme.org/codes-standards/find-codes-standards/y14-46-product-definition-additive-manufacturing/2017/drm-enabled-pdf
Design	SAE ARP7043	AM component checklist	Draft	https://www.sae.org/standards/content/arp7043/
Design	SAE AS7041	Distributor for AM build distributors Requirements	Draft	https://www.sae.org/standards/content/as7041
Process	ISO/ASTM 52903-2:2020	Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 2: Process equipment	Issued 10/2020	https://www.iso.org/standard/69968.html
Process	ISO/ASTM 52904:2019	Additive manufacturing – Process characteristics and performance – Practice for metal powder bed fusion process to meet critical applications	Issued 8/2019	https://www.iso.org/standard/74637.html
Process	ISO/ASTM52930:2021 (ASTM F3434-21)	Additive manufacturing — Qualification principles — Installation, operation and performance (IQ/OQ/PQ) of PBF-LB equipment	Issued 11/2021	https://www.astm.org/f3434-21.html
Process	ISO/ASTM 52941:2020	Additive manufacturing — System performance and reliability — Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace applications	Issued 11/2020	https://www.astm.org/f3472-20.html
Process	ASTM F2924-14(2021)	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion	Issued 10/2021	https://www.astm.org/f2924-14r21.html
Process	ASTM F3001-14(2021)	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion	Issued 10/2021	https://www.astm.org/f3001-14r21.html
Process	ASTM F3055-14a(2021)	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion	Issued 10/2021	https://www.astm.org/f3055-14ar21.html
Process	ASTM F3056-14(2021)	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion	Issued 10/2021	https://www.astm.org/f3056-14r21.html
Process	ASTM F3091/F3091M-14(2021)	Standard Specification for Powder Bed Fusion of Plastic Materials	Issued 10/2021	https://www.astm.org/f3091_f3091m-14r21.html
Process	SAE AMS7000A	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Nickel Alloy, Corrosion- and Heat-Resistant, 62Ni - 21.5Cr -	Issued 05/2022	https://www.sae.org/standards/content/ams7000a

Primary Focus Area	Standard	Title	Status	Link
		9.0Mo - 3.65Nb Stress Relieved, Hot Isostatic Pressed and Solution Annealed		
Process	SAE AMS7002A	Process Requirements for Production of Metal Powder Feedstock for Use in Additive Manufacturing of Aerospace Parts	Issued 05/2022	https://www.sae.org/standards/content/ams7002a/
Process	SAE AMS7003A	Laser Powder Bed Fusion Process	Issued 08/2022	https://www.sae.org/standards/content/ams7003/
Process	SAE AMS7004	Titanium Alloy Preforms from Plasma Arc Directed Energy Deposition Additive Manufacturing on Substrate Ti-6Al-4V Stress Relieved	Issued 1/2019	https://www.sae.org/standards/content/ams7004/
Process	SAE AMS7005	Wire Fed Plasma Arc Directed Energy Deposition Additive Manufacturing Process	Issued 01/2019	https://www.sae.org/standards/content/ams7005
Process	SAE AMS7007	Electron Beam Powder Bed Fusion Process	Issued 07/2020	https://www.sae.org/standards/content/ams7007
Process	SAE AMS7008	Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 47.5Ni - 22Cr - 1.5Co - 9.0Mo - 0.60W - 18.5Fe	Issued 3/2019	https://www.sae.org/standards/content/ams7008/
Process	SAE AMS7010A	Laser Directed Energy Deposition Additive Manufacturing Process (L-DED)	Issued 10/2021	https://www.sae.org/standards/content/ams7010a/
Process	SAE AMS7012	Precipitation Hardenable Steel Alloy, Corrosion and Heat-Resistant Powder for Additive Manufacturing 16.0Cr - 4.0Ni - 4.0Cu - 0.30Nb	Issued 11/2019	https://www.sae.org/standards/content/ams7012/
Process	SAE AMS7013	Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 60Ni - 22Cr - 2.0Mo - 14W - 0.35Al - 0.03La	Issued 1/2019	https://www.sae.org/standards/content/ams7013/
Process	SAE AMS7014	Titanium Alloy, High Temperature Applications, Powder for Additive Manufacturing, Ti - 6.0Al - 2.0Sn - 4.0Zr - 2.0Mo	Issued 3/2019	https://www.sae.org/standards/content/ams7014/
Process	SAE AMS7015	Titanium 6-Aluminum 4-Vanadium Powder for Additive Manufacturing AMS7015	Issued 04/2022	https://www.sae.org/standards/content/ams7015
Process	SAE AMS7017	Titanium 6 - Aluminum 4 - Vanadium Powder for Additive Manufacturing, Extra Low Interstitial (ELI)	Issued 04/2022	https://www.sae.org/standards/content/ams7017/
Process	SAE AMS7018	Aluminum Alloy Powder 10.0Si - 0.35Mg	Issued 5/2020	https://www.sae.org/standards/content/ams7018/
Process	SAE AMS7020	Aluminum Alloy Powder 7.0Si - 0.55Mg - 0.12Ti	Issued 11/2021	https://www.sae.org/standards/content/ams7020/
Process	SAE AMS7021	Precipitation Hardenable Steel Alloy, Corrosion and Heat Resistant, Powder for Additive Manufacturing, 15.0Cr - 4.5Ni - 3.5Cu - 0.30Nb	Issued 11/2020	https://www.sae.org/standards/content/ams7021/

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Process	SAE AMS7022	Binder Jet Additive Manufacturing (BJAM) Process	Issued 11/2020	https://www.sae.org/standards/content/ams7022/
Process	SAE AMS7023	Gamma Titanium-Aluminide Powder for Additive Manufacturing Ti - 48Al - 2Nb - 2Cr	Issued 06/2021	https://www.sae.org/standards/content/ams7023/
Process	SAE AMS7025	Metal Powder Feedstock Size Classifications	Issued 04/2021	https://www.sae.org/standards/content/ams7025/
Process	SAE AMS7026	Titanium Ti-5553 (Ti - 5Al - 5Mo - 5V - 3Cr) Powder for Additive Manufacturing	Issued 07/2021	https://www.sae.org/standards/content/ams7026/
Process	SAE AMS7027	Electron Beam Directed Energy Deposition-Wire Additive Manufacturing Process (EB-DED-Wire)	Issued 11/2020	https://www.sae.org/standards/content/ams7027/
Process	SAE AMS7031	Batch Processing Requirements for the Reuse of Used Powder in Additive Manufacturing of Aerospace Parts	Issued 03/2022	https://www.sae.org/standards/content/ams7031/
Process	SAE AMS7033	Aluminum Alloy Powder 4.6Cu - 3.4Ti - 1.4B - 0.75Ag - 0.27Mg	Issued 06/2021	https://www.sae.org/standards/content/ams7033/
Process	SAE AMS7035	Precipitation Hardenable Steel Alloy, Corrosion and Heat-Resistant, Powder for Binder Jet Additive Manufacturing, 16.0Cr - 4.0Ni - 4.0Cu - 0.30Nb	Issued 06/2021	https://www.sae.org/standards/content/ams7035/
Process	SAE AMS7100	Fused Filament Fabrication, Process Specification for	Issued 10/2019	https://www.sae.org/standards/content/ams7100/
Process	AWS D20.1/D20.1M:2019	SPECIFICATION FOR FABRICATION OF METAL COMPONENTS USING ADDITIVE MANUFACTURING	Issued 12/2018	https://pubs.aws.org/p/1915/d201d201m2019-specification-for-fabrication-of-metal-components-using-additive-manufacturing
Process	PWG 5199.10-2019 (Printer Working Group)	IPP Authentication Methods v1.0	Issued 08/2019	https://ftp.pwg.org/pub/pwg/informational/bp-ippauth10-20190816-5199.10.pdf
Process	IETF RFC 7472 (Internet Engineering Task Force)	Internet Printing Protocol (IPP) over HTTPS Transport Binding and the 'ipps' URI Scheme	Issued 12/2018	https://datatracker.ietf.org/doc/rfc7472/
Process	ISO/ASTM CD 52904	Additive manufacturing of metals — Process characteristics and performance — Practice for Metal powder bed fusion process to meet critical applications (Revision of 2019 Version)	Draft	https://www.iso.org/standard/82919.html
Process	ISO/ASTM DIS 52908	Additive manufacturing of metals — Finished Part properties — Post-processing, inspection and testing of parts produced by powder bed fusion	Draft	https://www.iso.org/standard/81779.html
Process	ISO/ASTM PRF TR 52917	Additive manufacturing — Round robin testing — General guidelines	Draft	https://www.iso.org/standard/75757.html
Process	ISO/ASTM DIS 52924	Additive manufacturing of polymers — Qualification principles — Classification of part properties	Draft	https://www.iso.org/standard/76909.html

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Process	ISO/ASTM DIS 52927	Additive manufacturing — General principles — Main characteristics and corresponding test methods	Draft	https://www.iso.org/standard/81802.html
Process	ISO/ASTM CD 52928	Additive manufacturing — Feedstock materials — Powder life cycle management	Draft	https://www.iso.org/standard/78527.html
Process	ISO/ASTM DTR 52931	Additive manufacturing of metals — Environment, health and safety — General principles for use of metallic materials	Draft	https://www.iso.org/standard/74641.html
Process	ISO/ASTM AWI 52933	Additive manufacturing — Environment, health and safety — Consideration for the reduction of hazardous substances emitted during the operation of the non-industrial ME type 3D printer in workplaces, and corresponding test method	Draft	https://www.iso.org/standard/75759.html
Process	ISO/ASTM PWI 52934	Additive manufacturing — Environmental health and safety — Standard guideline for hazard risk ranking and safety defense	Draft	https://committee.iso.org/sites/tc261/home/projects/ongoing/ongoing-1.html
Process	ISO/ASTM PWI 52934-1	Additive manufacturing — Process characteristics and performance — Part 1: Standard specification for directed energy deposition using wire and beam in aerospace applications	Draft	https://committee.iso.org/sites/tc261/home/projects/ongoing/ongoing-1.html
Process	ISO/ASTM PWI 52934-2	Additive manufacturing — Process characteristics and performance — Part 2: Standard specification for directed energy deposition using wire and arc in aerospace applications	Draft	https://committee.iso.org/sites/tc261/home/projects/ongoing/ongoing-1.html
Process	ISO/ASTM PWI 52934-3	Additive manufacturing — Process characteristics and performance — Part 3: Standard specification for directed energy deposition using laser blown powder in aerospace applications	Draft	https://committee.iso.org/sites/tc261/home/projects/ongoing/ongoing-1.html
Process	ISO/ASTM PWI 52944	Additive manufacturing — Process characteristics and performance — Standard specification for powder bed processes in aerospace applications	Draft	https://committee.iso.org/sites/tc261/home/projects/ongoing/ongoing-1.html
Process	ISO/ASTM PWI 52951	Data Packages for AM Parts	Draft	https://committee.iso.org/sites/tc261/home/projects/ongoing/ongoing-1.html
Process	ASTM WK65929	New Specification for Additive Manufacturing-Finished Part Properties and Post Processing - Additively Manufactured Spaceflight Hardware by Laser Beam Powder Bed Fusion In Metals	Draft	https://www.astm.org/workitem-wk65929
Process	ASTM WK65937	New Specification for Additive Manufacturing -- Space Application -- Flight Hardware made by Laser Beam Powder Bed Fusion Process	Draft	https://www.astm.org/workitem-wk65937
Process	ASTM WK66682	New Guide for Evaluating Post-processing and Characterization Techniques for AM Part Surfaces	Draft	https://www.astm.org/workitem-wk66682

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Process	ASTM WK71395	New Practice for Additive manufacturing -- accelerated quality inspection of build health for laser beam powder bed fusion process	Draft	https://www.astm.org/workitem-wk71395
Process	ASTM WK72391	New Guide for Additive manufacturing -- Environment, health and safety -- Standard guideline for use of metallic materials	Draft	https://www.astm.org/workitem-wk72391
Process	ASTM WK73227	New Guide for Additive Manufacturing -- Investigation for Additive Manufacturing (AM) Facility Safety Management	Draft	https://www.astm.org/workitem-wk73227
Process	ASTM WK73289	New Guide for In-Situ Monitoring of Metal Additively Manufactured Aerospace Parts	Draft	https://www.astm.org/workitem-wk73289
Process	ASTM WK74390	New Practice for Additive Manufacturing of Metals -- Data -- File structure for in-process monitoring of powder bed fusion	Draft	https://www.astm.org/workitem-wk74390
Process	ASTM WK74933	New Specification for Additive manufacturing of metals -- Environment, health and safety -- Part 1: Safety requirements for PBF-LB machines	Draft	https://www.astm.org/workitem-wk74933
Process	ASTM WK75184	New Guide for Additive Manufacturing of Metals -- Powder Bed Fusion -- Guidelines for Feedstock Recycling and Sampling Strategies	Draft	https://www.astm.org/workitem-wk75184
Process	ASTM WK75265	New Guide for Additive Manufacturing of Polymers -- Powder Bed Fusion -- Guidelines for Feedstock Recycling and Sampling Strategies	Draft	https://www.astm.org/workitem-wk75265
Process	ASTM WK77008	New Guide for Additive Manufacturing -- Laser Powder Bed Fusion -- Guide for Benchmarking of Powder Bed Density	Draft	https://www.astm.org/workitem-wk77008
Process	ASTM WK77236	New Specification for Additive manufacturing for aerospace -- Process characteristics and performance -- Part 2: Directed energy deposition using wire and arc	Draft	https://www.astm.org/workitem-wk77236
Process	ASTM WK78092	Practice for Additive Manufacturing -- Powder Bed Fusion -- Condition-defined Maintenance for Optical Systems. This is AM Coe project 2009 being developed in F42.01.	Draft	https://www.astm.org/workitem-wk78092
Process	ASTM WK78110	New Guide for Additive Manufacturing -- General Principles -- Development and Roadmapping of Additive Construction Standards	Draft	https://www.astm.org/workitem-wk78110
Process	ASTM WK78322	New Guide for Additive Manufacturing -- General Principles -- Guidelines for AM Security	Draft	https://www.astm.org/workitem-wk78322
Process	ASTM WK78378	New Specification for Additive Manufacturing for Automotive -- Qualification Principles -- Generic	Draft	https://www.astm.org/workitem-wk78378

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		Machine Evaluation and KPI Definition for PBF-LB/M Processes		
Process	SAE AMS7012A	Precipitation Hardenable Steel Alloy, Corrosion and Heat-Resistant Powder for Additive Manufacturing 16.0Cr - 4.0Ni - 4.0Cu - 0.30Nb	Draft	https://www.sae.org/standards/content/ams7012a
Process	SAE AMS7016	Laser-Powder Bed Fusion (L-PBF) Produced Parts, 17-4PH H1025 Alloy	Draft	https://www.sae.org/standards/content/ams7016
Process	SAE AMS7024	Inconel 718 L-PBF Material specification	Draft	https://www.sae.org/standards/content/ams7024
Process	SAE AMS7028	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Titanium Alloy, Ti-6Al-4V Stress Relieved, and Hot Isostatic Pressed	Draft	https://www.sae.org/standards/content/ams7028
Process	SAE AMS7029	Cold Metal Transfer Directed Energy Deposition (CMT-DED) Process	Draft	https://www.sae.org/standards/content/ams7029
Process	SAE AMS7030	Aluminum Alloy Powder 4.6Cu - 3.4Ti - 1.4B - 0.75Ag - 0.27Mg	Draft	https://www.sae.org/standards/content/ams7033
Process	SAE AMS7032	Additive Manufacturing Machine Qualification	Draft	https://www.sae.org/standards/content/ams7032
Process	SAE AMS7034	Hybrid Laser Arc Directed Energy Deposition	Draft	https://www.sae.org/standards/content/ams7034
Process	SAE AMS7036	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Steel, Corrosion and Heat Resistant 17Cr – 13Ni – 2.5Mo (316L), Hot Isostatic Pressed	Draft	https://www.sae.org/standards/content/ams7036
Process	SAE AMS7038	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Nickel Alloy, Corrosion and Heat-Resistant -52.5Ni - 19Cr - 3.0Mo - 5.1Cb (Nb) - 0.90Ti - 0.50Al - 18Fe Stress Relieved, Hot Isostatic Pressed	Draft	https://www.sae.org/standards/content/ams7038
Process	SAE AMS7039	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Steel, Corrosion and Heat Resistant 17Cr – 13Ni – 2.5Mo (316L), Stress Relief and Anneal	Draft	https://www.sae.org/standards/content/ams7039
Process	SAE AMS7100/1	Fused Filament Fabrication Process - Stratasys Fortus 900mc Plus, with Type 1, Class 1, Form 1, Grade 0, Natural Color Material	Draft	https://www.sae.org/standards/content/ams7100/1/
Process	SAE AMS7100/2	Fused Filament Fabrication – Markforged X7 with Onyx FR-A Type, Class, Grade, Black	Draft	https://www.sae.org/standards/content/ams7100/2
Process	SAE AMS7102	High Performance Laser Sintering Process for Thermoplastic Parts for Aerospace Applications	Draft	https://www.sae.org/standards/content/ams7102
Process	SAE AMS7104	Continuous Fiber Reinforced Fused Filament Fabrication	Draft	https://www.sae.org/standards/content/ams7104
Process	SAE AMS7104/1	Continuous Fiber Reinforced Fused Filament Fabrication Markforged	Draft	https://www.sae.org/standards/content/ams7104/1
Process	SAE ARP7044	Powder History Scoring Metric and Labeling Schema	Draft	https://www.sae.org/standards/content/arp7044/
Process	SAE GAAM-M20A	Aluminum Alloy Powder Template	Draft	https://www.sae.org/works/documentHome.do?docID=GAAM-M20A&inputPage=wIpSdOcDeTalIS&comtID=TEAAMSAM-M

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Process	SAE GAAM-M20B	Cobalt, Iron, or Nickel Alloy Powder Template	Draft	https://www.sae.org/works/documentHome.do?docID=GAAM-M20B&inputPage=wIpSdOcDeTallS&comtID=TEAAMSAM-M
Process	SAE GAAM-M20C	Titanium Powder Template	Draft	https://www.sae.org/works/documentHome.do?docID=GAAM-M20C&inputPage=wIpSdOcDeTallS&comtID=TEAAMSAM-M
Materials	ISO/ASTM 52903-1:2020	Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 1: Feedstock materials	Issued 04/2020	https://www.iso.org/standard/67290.html
Materials	ISO/ASTM 52907-19	Additive manufacturing — Feedstock materials — Methods to characterize metallic powders	Issued 10/2019	https://www.astm.org/f3382-19.html
Materials	ASTM F2924-14(2021)	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion	Issued 10/2021	https://www.astm.org/f2924-14r21.html
Materials	ASTM F3001-14(2021)	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion	Issued 10/2021	https://www.astm.org/f3001-14r21.html
Materials	ASTM F3049-14(2021)	Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes	Issued 10/2021	https://www.astm.org/f3049-14r21.html
Materials	ASTM F3055-14a(2021)	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion	Issued 10/2021	https://www.astm.org/f3055-14ar21.html
Materials	ASTM F3056-14(2021)	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion	Issued 10/2021	https://www.astm.org/f3056-14r21.html
Materials	ASTM F3302-18	Standard for Additive Manufacturing – Finished Part Properties – Standard Specification for Titanium Alloys via Powder Bed Fusion	Issued 02/2018	https://www.astm.org/f3302-18.html
Materials	ASTM F3318-18	Standard for Additive Manufacturing – Finished Part Properties – Specification for AlSi10Mg with Powder Bed Fusion – Laser Beam	Issued 08/2018	https://www.astm.org/f3318-18.html
Materials	SAE AMS7000A	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Nickel Alloy, Corrosion- and Heat-Resistant, 62Ni - 21.5Cr - 9.0Mo - 3.65Nb Stress Relieved, Hot Isostatic Pressed and Solution Annealed	Issued 05/2022	https://www.sae.org/standards/content/ams7000a
Materials	SAE AMS7001	Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 62Ni - 21.5Cr - 9.0Mo - 3.65Nb	Issued 06/2018	https://www.sae.org/standards/content/ams7001/
Materials	SAE AMS7002A	Process Requirements for Production of Metal Powder Feedstock for Use in Additive Manufacturing of Aerospace Parts	Issued 05/2022	https://www.sae.org/standards/content/ams7002a/
Materials	SAE AMS7003A	Laser Powder Bed Fusion Process	Issued 08/2022	https://www.sae.org/standards/content/ams7003a/
Materials	SAE AMS7004	Titanium Alloy Preforms from Plasma Arc Directed Energy Deposition Additive Manufacturing on Substrate Ti-6Al-4V Stress Relieved	Issued 1/2019	https://www.sae.org/standards/content/ams7004/

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Materials	SAE AMS7005	Wire Fed Plasma Arc Directed Energy Deposition Additive Manufacturing Process	Issued 01/2019	https://www.sae.org/standards/content/ams7005
Materials	SAE AMS7006	Nickel Alloy, Corrosion- and Heat-Resistant, Powder for Additive Manufacturing 52.5Ni - 19Cr - 3.0Mo - 5.1Cb (Nb) - 0.90Ti - 0.50Al - 18Fe	Issued 03/2022	https://www.sae.org/standards/content/ams7006/
Materials	SAE AMS7008	Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 47.5Ni - 22Cr - 1.5Co - 9.0Mo - 0.60W - 18.5Fe	Issued 3/2019	https://www.sae.org/standards/content/ams7008/
Materials	SAE AMS7012	Precipitation Hardenable Steel Alloy, Corrosion and Heat-Resistant Powder for Additive Manufacturing 16.0Cr - 4.0Ni - 4.0Cu - 0.30Nb	Issued 11/2019	https://www.sae.org/standards/content/ams7012/
Materials	SAE AMS7013	Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 60Ni - 22Cr - 2.0Mo - 14W - 0.35Al - 0.03La	Issued 1/2019	https://www.sae.org/standards/content/ams7013/
Materials	SAE AMS7014	Titanium Alloy, High Temperature Applications, Powder for Additive Manufacturing, Ti - 6.0Al - 2.0Sn - 4.0Zr - 2.0Mo	Issued 3/2019	https://www.sae.org/standards/content/ams7014/
Materials	SAE AMS7015	Titanium 6-Aluminum 4-Vanadium Powder for Additive Manufacturing AMS7015	Issued 04/2022	https://www.sae.org/standards/content/ams7015
Materials	SAE AMS7017	Titanium 6 - Aluminum 4 - Vanadium Powder for Additive Manufacturing, Extra Low Interstitial (ELI)	Issued 04/2022	https://www.sae.org/standards/content/ams7017/
Materials	SAE AMS7018	Aluminum Alloy Powder 10.0Si - 0.35Mg	Issued 5/2020	https://www.sae.org/standards/content/ams7018/
Materials	SAE AMS7020	Aluminum Alloy Powder 7.0Si - 0.55Mg - 0.12Ti	Issued 11/2021	https://www.sae.org/standards/content/ams7020/
Materials	SAE AMS7021	Precipitation Hardenable Steel Alloy, Corrosion and Heat Resistant, Powder for Additive Manufacturing, 15.0Cr - 4.5Ni - 3.5Cu - 0.30Nb	Issued 11/2020	https://www.sae.org/standards/content/ams7021/
Materials	SAE AMS7023	Gamma Titanium-Aluminide Powder for Additive Manufacturing Ti - 48Al - 2Nb - 2Cr	Issued 06/2021	https://www.sae.org/standards/content/ams7023/
Materials	SAE AMS7025	Metal Powder Feedstock Size Classifications	Issued 04/2021	https://www.sae.org/standards/content/ams7025/
Materials	SAE AMS7026	Titanium Ti-5553 (Ti - 5Al - 5Mo - 5V - 3Cr) Powder for Additive Manufacturing	Issued 07/2021	https://www.sae.org/standards/content/ams7026/
Materials	SAE AMS7031	Batch Processing Requirements for the Reuse of Used Powder in Additive Manufacturing of Aerospace Parts	Issued 03/2022	https://www.sae.org/standards/content/ams7031/
Materials	SAE AMS7033	Aluminum Alloy Powder 4.6Cu - 3.4Ti - 1.4B - 0.75Ag - 0.27Mg	Issued 06/2021	https://www.sae.org/standards/content/ams7033/
Materials	SAE AMS7035	Precipitation Hardenable Steel Alloy, Corrosion and Heat-Resistant, Powder for Binder Jet Additive Manufacturing, 16.0Cr - 4.0Ni - 4.0Cu - 0.30Nb	Issued 06/2021	https://www.sae.org/standards/content/ams7035/

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Materials	SAE AMS7037	Steel, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 17Cr - 13Ni - 2.5Mo (316L)	Issued 11/2021	https://www.sae.org/standards/content/ams7037
Materials	SAE AMS7100	Fused Filament Fabrication, Process Specification for	Issued 10/2019	https://www.sae.org/standards/content/ams7100/
Materials	SAE AMS7101/1	Fused Filament Fabrication, Type 1, Class 1, Form 1, Grade 0, Natural Color Material for	Issued 07/2022	https://www.sae.org/standards/content/ams7101/1/
Materials	ISO/ASTM DIS 52908	Additive manufacturing of metals — Finished Part properties — Post-processing, inspection and testing of parts produced by powder bed fusion	Draft	https://www.iso.org/standard/81779.html
Materials	ISO/ASTM DIS 52924	Additive manufacturing of polymers — Qualification principles — Classification of part properties	Draft	https://www.iso.org/standard/76909.html
Materials	ISO/ASTM DIS 52909	Additive manufacturing — Finished part properties — Orientation and location dependence of mechanical properties for metal powder bed fusion	Draft	https://www.iso.org/standard/74639.html
Materials	ASTM WK65929	Specification for Additive Manufacturing-Finished Part Properties and Post Processing - Additively Manufactured Spaceflight Hardware by Laser Beam Powder Bed Fusion In Metals	Draft	https://www.astm.org/workitem-wk65929
Materials	ASTM WK65937	New Specification for Additive Manufacturing -- Space Application -- Flight Hardware made by Laser Beam Powder Bed Fusion Process	Draft	https://www.astm.org/workitem-wk65937
Materials	ASTM WK66029	New Guide for Mechanical Testing of Polymer Additively Manufactured Materials	Draft	https://www.astm.org/workitem-wk66029
Materials	ASTM WK66030	New Guide for Quality Assessment of Metal Powder Feedstock Characterization Data for Additive Manufacturing	Draft	https://www.astm.org/workitem-wk66030
Materials	ASTM WK66637	New Specification for Additive Manufacturing -- Finished Part Properties -- Specification for 4340 Steel via Laser Beam Powder Bed Fusion for Transportation and Heavy Equipment Industries	Draft	https://www.astm.org/workitem-wk66637
Materials	ASTM WK67583	New Guide for Additive Manufacturing -- Feedstock Materials -- Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications	Draft	https://www.astm.org/workitem-wk67583
Materials	ASTM WK69730	New Specification for Additive Manufacturing -- Wire for Directed Energy Deposition (DED) Processes in Additive Manufacturing	Draft	https://www.astm.org/workitem-wk69730
Materials	ASTM WK70164	New Practice for Additive Manufacturing -- General Principles -- Part Classifications for Additive Manufactured Parts Used in Aviation	Draft	https://www.astm.org/workitem-wk70164
Materials	ASTM WK71391	New Guide for Additive Manufacturing -- Static Properties for Polymer AM (Continuation)	Draft	https://www.astm.org/workitem-wk71391

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Materials	ASTM WK71393	New Practice for Additive manufacturing -- assessment of powder spreadability for powder bed fusion (PBF) processes	Draft	https://www.astm.org/workitem-wk71393
Materials	ASTM WK71395	New Practice for Additive manufacturing -- accelerated quality inspection of build health for laser beam powder bed fusion process	Draft	https://www.astm.org/workitem-wk71395
Materials	ASTM WK73340	New Test Method for Additive Manufacturing -- Dynamic Properties -- Polymer Additive Manufacturing	Draft	https://www.astm.org/workitem-wk73340
Materials	ASTM WK74302	New Specification for Additive manufacturing for construction -- process characteristics and performance -- specification for manufactured polymeric UV cured structures for residential applications	Draft	https://www.astm.org/workitem-wk74302
Materials	ASTM WK74905	New Guide for Additive Manufacturing -- Feedstock -- Particle Shape Analysis by Optical Photography to Identify and Quantify the Agglomerates/Satellites in Metal Powder Feedstock	Draft	https://www.astm.org/workitem-wk74905
Materials	ASTM WK75158	New Practice for Additive Manufacturing -- Data -- Common exchange format for particle size analysis by light scattering	Draft	https://www.astm.org/workitem-wk75158
Materials	ASTM WK75265	New Guide for Additive Manufacturing of Polymers -- Powder Bed Fusion -- Guidelines for Feedstock Recycling and Sampling Strategies	Draft	https://www.astm.org/workitem-wk75265
Materials	ASTM WK75901	New Test Method for Additive Manufacturing -- Test Artifacts -- Miniature Tension Testing of Metallic Materials	Draft	https://www.astm.org/workitem-wk75901
Materials	ASTM WK76048	New Specification for Additive manufacturing -- Powder bed fusion -- Standard specification for maraging steel	Draft	https://www.astm.org/workitem-wk76048
Materials	ASTM WK77186	New Specification for Additive Manufacturing -- Finished Part Properties -- Specification for Niobium-Hafnium Alloy UNS R04295 via Laser Beam Powder Bed Fusion for Spaceflight Applications	Draft	https://www.astm.org/workitem-wk77186
Materials	ASTM WK78093	New Guide for Additive Manufacturing -- Feedstock Materials -- Guide for Testing Moisture Content in Powder Feedstock	Draft	https://www.astm.org/workitem-wk78093
Materials	ASTM WK78224	New Test Method for Additive Manufacturing -- Vat Photopolymerization -- Next Generation Tensile Test Method	Draft	https://www.astm.org/workitem-wk78224
Materials	SAE AMS7011	Electron Beam-Powder Bed Fusion (EB-PBF) Produced Parts, Titanium Alloy 6Al - 4V Hot Isostatically Pressed	Draft	https://www.sae.org/standards/content/ams7011/

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Materials	SAE AMS7012A	Precipitation Hardenable Steel Alloy, Corrosion and Heat-Resistant Powder for Additive Manufacturing 16.0Cr - 4.0Ni - 4.0Cu - 0.30Nb	Draft	https://www.sae.org/works/documentHome.do?docID=AMS7012A&inputPage=wIpSdOcDeTalIS&comtID=TEAAMSAM-M
Materials	SAE AMS7016	Laser-Powder Bed Fusion (L-PBF) Produced Parts, 17-4PH H1025 Alloy	Draft	https://www.sae.org/standards/content/ams7016
Materials	SAE AMS7024	Inconel 718 L-PBF Material specification	Draft	https://www.sae.org/standards/content/ams7024
Materials	SAE AMS7028	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Titanium Alloy, Ti-6Al-4V Stress Relieved, and Hot Isostatic Pressed	Draft	https://www.sae.org/standards/content/ams7028
Materials	SAE AMS7030	Aluminum Alloy Powder 4.6Cu - 3.4Ti - 1.4B - 0.75Ag - 0.27Mg	Draft	https://www.sae.org/standards/content/ams7033
Materials	SAE AMS7036	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Steel, Corrosion and Heat Resistant 17Cr – 13Ni – 2.5Mo (316L), Hot Isostatic Pressed	Draft	https://www.sae.org/standards/content/ams7036
Materials	SAE AMS7038	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Nickel Alloy, Corrosion and Heat-Resistant -52.5Ni - 19Cr - 3.0Mo - 5.1Cb (Nb) - 0.90Ti - 0.50Al - 18Fe Stress Relieved, Hot Isostatic Pressed	Draft	https://www.sae.org/standards/content/ams7038
Materials	SAE AMS7039	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Steel, Corrosion and Heat Resistant 17Cr – 13Ni – 2.5Mo (316L), Stress Relief and Anneal	Draft	https://www.sae.org/standards/content/ams7039
Materials	SAE AMS7045	Aluminum Alloy Powder, 5.3Zn – 3.3Mg - 1.7Zr – 1.6Cu (Composition Similar to 7A77.50)	Draft	https://www.sae.org/standards/content/ams7045
Materials	SAE AMS7046	Laser Powder Bed Fusion Produced Parts, Aluminum Alloy, 5.3Zn – 3.3Mg - 1.7Zr – 1.6Cu (Composition Similar to 7A77.60), SR + HIP + T7	Draft	https://www.sae.org/standards/content/ams7046/
Materials	SAE AMS7047	Low Alloy, Medium Carbon Steel Powder for Binder Jet Additive Manufacturing, 1.0Cr – 0.20Mo – 0.30C (Composition Similar to UNS G41300)	Draft	https://www.sae.org/standards/content/ams7047/
Materials	SAE AMS7048	Binder Jet Additive Manufacturing (BJAM) Produced Parts, Steel, 1.0Cr – 0.20Mo – 0.30C, As-Sintered (Composition Similar to UNS G41300)	Draft	https://www.sae.org/standards/content/ams7048/
Materials	SAE AMS7049	Binder Jet Additive Manufacturing (BJAM) Produced Parts, Steel, 1.0Cr – 0.20Mo – 0.30C, Austenitized, Quenched and Tempered (Composition Similar to UNS G41300)	Draft	https://www.sae.org/standards/content/ams7049/
Materials	SAE AMS7050	Binder Jet Additive Manufacturing (BJAM) Produced Parts, Steel, 1.0Cr – 0.20Mo – 0.30C, Hot Isostatic Pressed, Austenitized, Quenched and Tempered (Composition Similar to UNS G41300)	Draft	https://www.sae.org/standards/content/ams7050/

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Materials	SAE AMS7101/2	Fused Filament Fabrication Process- Markforged X7 with Onyx FR-A a Type 1 Form 1 PACF15FR15 filament	Draft	https://www.sae.org/standards/content/ams7101/2/
Materials	SAE AMS7103	Material for High Performance Laser Sintering	Draft	https://www.sae.org/works/documentHome.do?docID=AMS7103&inputPage=wIpSdOcDeTaIlS&comtID=TEAAMSAM-P
Materials	SAE AMS7104	Continuous Fiber Reinforced Fused Filament Fabrication	Draft	https://www.sae.org/standards/content/ams7104
Materials	SAE AMS7104/1	Continuous Fiber Reinforced Fused Filament Fabrication Markforged	Draft	https://www.sae.org/standards/content/ams7104/1
Materials	SAE AMS7105	ontinuous Carbon Fiber Reinforced Fused Filament Fabrication - Markforged	Draft	https://www.sae.org/standards/content/ams7105/
Materials	SAE AMS7105/1	Continuous Carbon Fiber Reinforced Fused Filament Fabrication, material Carbon Fiber FR-A	Draft	https://www.sae.org/standards/content/ams7105/1/
Materials	SAE GAAM-M20A	Aluminum Alloy Powder Template	Draft	https://www.sae.org/works/documentHome.do?docID=GAAM-M20A&inputPage=wIpSdOcDeTaIlS&comtID=TEAAMSAM-M
Materials	SAE GAAM-M20B	Cobalt, Iron, or Nickel Alloy Powder Template	Draft	https://www.sae.org/works/documentHome.do?docID=GAAM-M20B&inputPage=wIpSdOcDeTaIlS&comtID=TEAAMSAM-M
Materials	SAE GAAM-M20C	Titanium Powder Template	Draft	https://www.sae.org/works/documentHome.do?docID=GAAM-M20C&inputPage=wIpSdOcDeTaIlS&comtID=TEAAMSAM-M
Qualification and Certification	ISO/ASTM 52900:2021	Additive manufacturing — General principles — Fundamentals and vocabulary	Issued 11/2021	https://www.iso.org/standard/74514.html
Qualification and Certification	ISO/ASTM TR 52916:2022	Additive manufacturing for medical — Data — Optimized medical image data	Issued 1/2022	https://www.iso.org/standard/75143.html
Qualification and Certification	ISO/ASTM 52942:2020	Additive manufacturing — Qualification principles — Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications	Issued 08/2020	https://www.iso.org/standard/74949.html
Qualification and Certification	API STD 20S	Additively Manufactured Metallic Components for Use in the Petroleum and Natural Gas Industries, First Edition	Issued 10/2021	https://www.api.org/products-and-services/standards/important-standards-announcements/20s
Qualification and Certification	NASA-STD-6030	ADDITIVE MANUFACTURING REQUIREMENTS FOR SPACEFLIGHT SYSTEMS	Issued 04/2021	https://standards.nasa.gov/standard/nasa/nasa-std-6030
Qualification and Certification	AWS D20.1/D20.1M:2019	SPECIFICATION FOR FABRICATION OF METAL COMPONENTS USING ADDITIVE MANUFACTURING	Issued 12/2018	https://pubs.aws.org/p/1915/d201d201m2019-specification-for-fabrication-of-metal-components-using-additive-manufacturing
Qualification and Certification	ISO/ASTM DIS 52935	Additive manufacturing of metals – Qualification principles – Qualification of AM coordination personnel	Draft	https://www.iso.org/standard/79528.html
Qualification and Certification	ISO/ASTM DIS 52920	New Practice for Additive manufacturing -- Qualification principles -- Quality requirements for industrial additive manufacturing sites	Draft	https://www.iso.org/standard/76911.html

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Qualification and Certification	ISO/ASTM DIS 52925	Additive manufacturing of polymers — Feedstock materials — Qualification of materials for laser-based powder bed fusion of parts	Draft	https://www.iso.org/standard/76910.html
Qualification and Certification	ISO/ASTM DIS 52926-1	Additive Manufacturing of metals — Qualification principles — Part 1: General qualification of operators	Draft	https://www.iso.org/standard/76827.html
Qualification and Certification	ISO/ASTM DIS 52926-2	Additive Manufacturing of metals — Qualification principles — Part 2: Qualification of operators for PBF-LB	Draft	https://www.iso.org/standard/78529.html
Qualification and Certification	ISO/ASTM DIS 52926-3	Additive Manufacturing of metals — Qualification principles — Part 3: Qualification of operators for PBF-EB	Draft	https://www.iso.org/standard/78530.html
Qualification and Certification	ISO/ASTM DIS 52926-4	Additive Manufacturing of metals — Qualification principles — Part 4: Qualification of operators for DED-LB	Draft	https://www.iso.org/standard/78531.html
Qualification and Certification	ISO/ASTM DIS 52926-5	Additive Manufacturing of metals — Qualification principles — Part 5: Qualification of operators for DED-Arc	Draft	https://www.iso.org/standard/78532.html
Qualification and Certification	ISO/ASTM DIS 52936-1	Additive manufacturing of polymers — Powder bed fusion — Part 1: General principles and preparation of test specimens for PBF-LB	Draft	https://www.iso.org/standard/79529.html?browse=tc
Qualification and Certification	ISO/ASTM DIS 52937	Additive Manufacturing of metals — Qualification principles — Qualification of designers	Draft	https://www.iso.org/standard/79530.html
Qualification and Certification	ASTM WK65929	Specification for Additive Manufacturing-Finished Part Properties and Post Processing - Additively Manufactured Spaceflight Hardware by Laser Beam Powder Bed Fusion In Metals	Draft	https://www.astm.org/workitem-wk65929
Qualification and Certification	ASTM WK65937	New Specification for Additive Manufacturing -- Space Application -- Flight Hardware made by Laser Beam Powder Bed Fusion Process	Draft	https://www.astm.org/workitem-wk65937
Qualification and Certification	ASTM WK70164	New Practice for Additive Manufacturing -- General Principles -- Part Classifications for Additive Manufactured Parts Used in Aviation	Draft	https://www.astm.org/workitem-wk70164
Qualification and Certification	ASTM WK71376	New Guide for Additive manufacturing -- Qualification principles -- Part 2: Qualification of machine operators for metallic parts production for PBF-LB	Draft	https://www.astm.org/workitem-wk71376
Qualification and Certification	ASTM WK71377	New Guide for Additive manufacturing -- Qualification principles -- Part 3: Qualification of machine operators for metallic parts production for PBF-EB	Draft	https://www.astm.org/workitem-wk71377
Qualification and Certification	ASTM WK71378	New Guide for Additive manufacturing -- Qualification principles -- Part 4: Qualification of machine operators for metallic parts production for DED-LB	Draft	https://www.astm.org/workitem-wk71378

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Qualification and Certification	ASTM WK71379	New Guide for Additive manufacturing -- Qualification principles -- Part 5: Qualification of machine operators for metallic parts production for DED-Arc	Draft	https://www.astm.org/workitem-wk71379
Qualification and Certification	ASTM WK71616	New Specification for Additive manufacturing -- Qualification principles -- Part 2: Requirements for industrial additive manufacturing sites	Draft	https://www.astm.org/workitem-wk71616
Qualification and Certification	ASTM WK72659	New Guide for Guideline for Material Process Validation for Additive Manufacturing of Medical Devices	Draft	https://www.astm.org/workitem-wk72659
Qualification and Certification	ASTM WK73239	New Classification for Additive manufacturing -- Qualification principles -- Classification of part properties for additive manufacturing of polymer parts	Draft	https://www.astm.org/workitem-wk73239
Qualification and Certification	ASTM WK75329	New Practice for Nondestructive Testing (NDT), Part Quality, and Acceptability Levels of Additively Manufactured Laser Based Powder Bed Fusion Aerospace Components	Draft	https://www.astm.org/workitem-wk75329
Qualification and Certification	ASTM WK77614	New Specification for Additive Manufacturing for construction Qualification principles Structural and infrastructure elements	Draft	https://www.astm.org/workitem-wk77614
Qualification and Certification	SAE AS7040	Requirements for powder distributors	Draft	https://www.sae.org/standards/content/as7040/
Qualification and Certification	SAE AS7041	Distributor for AM build distributors Requirements	Draft	https://www.sae.org/standards/content/as7041/
Qualification and Certification	API STD 20T	Additively Manufactured Polymeric Components for Use in the Petroleum and Natural Gas Industries	Draft	https://mycommittees.api.org/standards/ecs/sc20/default.aspx
NDE	ISO/ASTM 52900:2021	Additive manufacturing — General principles — Fundamentals and vocabulary	Issued 11/2021	https://www.iso.org/standard/74514.html
NDE	ISO/ASTM 52902-19	Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems	Issued 08/2019	https://www.astm.org/f3345-19.html?a=
NDE	ASTM E3166-20e1	Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build	Issued 08/2021	https://www.astm.org/e3166-20e01.html
NDE	AWS D20.1/D20.1M:2019	SPECIFICATION FOR FABRICATION OF METAL COMPONENTS USING ADDITIVE MANUFACTURING	Issued 12/2018	https://pubs.aws.org/p/1915/d201d201m2019-specification-for-fabrication-of-metal-components-using-additive-manufacturing
NDE	ISO/ASTM 52905	Additive manufacturing of metals — Non-destructive testing and evaluation — Defect detection in parts	Draft	https://www.iso.org/standard/82539.html
NDE	ISO/ASTM 52906	Additive manufacturing — Non-destructive testing — Intentionally seeding flaws in metallic parts	Draft	https://www.iso.org/standard/75716.html
NDE	ASTM WK75329	New Practice for Nondestructive Testing (NDT), Part Quality, and Acceptability Levels of Additively	Draft	https://www.astm.org/workitem-wk75329

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		Manufactured Laser Based Powder Bed Fusion Aerospace Components		
NDE	ASTM WK75584	New Test Method for Additive Manufacturing Non-destructive testing and evaluation of fatigue cracks using tensioned computed tomography	Draft	https://www.astm.org/workitem-wk75584
NDE	ASTM WK69731	New Guide for Additive Manufacturing -- Non-Destructive Testing (NDT) for Use in Directed Energy Deposition (DED) Additive Manufacturing Processes	Draft	https://www.astm.org/workitem-wk69731
NDE	ASTM WK76038	New Test Method for Additive Manufacturing of Metals -- Non-destructive testing and evaluation -- Porosity Measurement with X-ray CT	Draft	https://www.astm.org/workitem-wk76038
NDE	ASTM WK78465	New Specification for Additive Manufacturing for Medical- Non-destructive Testing and Evaluation-Test Method for Evaluation of Porous Structures in Medical Implants via Computed Tomography Scanning	Draft	https://www.astm.org/workitem-wk78465
NDE	AMPP TR21522	Corrosion Testing for Additive Manufacturing	Draft	https://www.materialsperformance.com/news/2021/09/ampp-standards-committees-roll-out-new-projects
Maintenance and Repair	AWS D20.1/D20.1M:2019	SPECIFICATION FOR FABRICATION OF METAL COMPONENTS USING ADDITIVE MANUFACTURING	Issued 12/2018	https://pubs.aws.org/p/1915/d201d201m2019-specification-for-fabrication-of-metal-components-using-additive-manufacturing
Maintenance and Repair	SAE AMS7002A	Process Requirements for Production of Metal Powder Feedstock for Use in Additive Manufacturing of Aerospace Parts	Issued 05/2022	https://www.sae.org/standards/content/ams7002a/
Maintenance and Repair	SAE AMS7003A	Laser Powder Bed Fusion Process	Issued 08/2022	https://www.sae.org/standards/content/ams7003a/
Maintenance and Repair	SAE AMS7005	Wire Fed Plasma Arc Directed Energy Deposition Additive Manufacturing Process	Issued 01/2019	https://www.sae.org/standards/content/ams7005
Maintenance and Repair	SAE AMS7007	Electron Beam Powder Bed Fusion Process	Issued 07/2020	https://www.sae.org/standards/content/ams7007
Maintenance and Repair	SAE AMS7010A	Laser Directed Energy Deposition Additive Manufacturing Process (L-DED)	Issued 10/2021	https://www.sae.org/standards/content/ams7010a/
Maintenance and Repair	SAE AMS7022	Binder Jet Additive Manufacturing (BJAM) Process	Issued 11/2020	https://www.sae.org/standards/content/ams7022/
Maintenance and Repair	SAE AMS7027	Electron Beam Directed Energy Deposition-Wire Additive Manufacturing Process (EB-DED-Wire)	Issued 11/2020	https://www.sae.org/standards/content/ams7027/
Maintenance and Repair	SAE AMS7031	Batch Processing Requirements for the Reuse of Used Powder in Additive Manufacturing of Aerospace Parts	Issued 03/2022	https://www.sae.org/standards/content/ams7031/
Maintenance and Repair	PWG 5199.10-2019 (Printer Working Group)	IPP Authentication Methods v1.0	Issued 08/2019	https://ftp.pwg.org/pub/pwg/informational/bp-ippauth10-20190816-5199.10.pdf

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Maintenance and Repair	ASTM WK78322	New Guide for Additive Manufacturing -- General Principles -- Guidelines for AM Security	Draft	https://www.astm.org/workitem-wk78322
Maintenance and Repair	SAE AMS7029	Cold Metal Transfer Directed Energy Deposition (CMT-DED) Process	Draft	https://www.sae.org/standards/content/ams7029
Maintenance and Repair	SAE AMS7034	Hybrid Laser Arc Directed Energy Deposition	Draft	https://www.sae.org/standards/content/ams7034
Maintenance and Repair	SAE AS1390	Level of Repair Analysis (LORA)	Future Revision	https://www.sae.org/standards/content/as1390
Maintenance and Repair	SAE TA-STD-0017	Product Support Analysis	Future Revision	https://www.sae.org/standards/content/tastd0017a/