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Qualification Framework Evaluations, Status Quo, and Recommendations

September 2023

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Summary

The Advanced Materials and Manufacturing Technology (AMMT) program develops cross-cutting technologies in support of a broad range of nuclear reactor technologies and maintains U.S. leadership in materials and manufacturing technologies for nuclear energy applications. The overarching vision of AMMT is to accelerate the development, qualification, demonstration, and deployment of advanced materials and manufacturing technologies to enable reliable and economical nuclear energy. The acceleration of qualification processes is one of the key aspects and qualification processes for the nuclear industry is not necessarily equivalent or benchmarked against other industries.

A study was therefore undertaken and reported herein to obtain knowledge of the full concert of qualification processes or approaches from various industries. The AMMT program will use lessons learned from these industries, to further accelerate the adoption of advanced materials enabled by advanced manufacturing (AM) processes to the benefit of the nuclear industry (A detailed nuclear energy qualification roadmap is not of this work package's deliverables).

Although four agnostic qualification approaches—namely *statistical-based qualification, equivalency-based qualification, in situ data-based qualification, and model-based qualification*—are often described in literature, these approaches have not been fully validated for components fabricated by AM processes. Simultaneously, the integrating material and manufacturing as one integrated process, does require qualification protocols to ensure adequate basic isotropic mechanical properties (e.g., strength, elongation, fracture toughness) as well as acceptable response of the AM material to long term degradation mechanisms (e.g., creep, fatigue, thermal ageing, corrosion behavior and radiation tolerance). The unknown behaviors of AM products in many environments relevant to nuclear applications, stifled the acknowledgement of the benefits that AM can bring to the nuclear industry. However, the qualification methodologies applied by other industries already for AM products, can support the work that needs to be undertaken by the nuclear industry. It is therefore the AMMT programs vision, to develop a case study for AM adoption, following conventional approaches, however to concurrent evaluate and perform accelerated methodologies to demonstrate the advantages. Currently, many of these acceleration actions are not shown as an integrated data set, therefore it is not clearly visible to the designer or developer and therefor qualification of these new AM products, seems too daunting and high risk to implement.

Acceleration of qualification processes for AM products and systems are a topic of interest or concern of nearly all companies, industry types nationally as well as internationally. This study reveals that although there are many complimentary activities as well as similarities between the main reason for hesitancy, is the lack of case studies that the nuclear developers can understand as part of their risk analysis. Furthermore, the description of for qualification has often been heard as "qualification of new materials, or qualification of AM processes, however, seldom been considered as a holistic integrated process, which should be the next generation paradigm implemented for true acceleration. Therefore, multiple steps can be concurrent or even decreased.

The NRC current provides two distinct avenues for qualification of new materials and process. One avenue is a utility/user can work with the American Society of Mechanical Engineering to submit a Data Package and Code Case. Once the Code Case is approved, the U.S. Nuclear Regulatory Commission can adopt it under 50.55a and add additional conditions if warranted.

The other avenue is a utility/user can develop a Topical Report for a material/process and submit it directly to the Nuclear Regulatory Commission for approval.

A recommendation identified from the review of several industries was to conduct case studies of previous qualification processes. A potential for decreasing the duration and increasing the efficiency of the qualification process is to review planning and execution of previous efforts to evaluate:

- Lessons learned from actual material qualification processes, including efforts that achieved qualification and those that did not.
- Evaluate coordination and planning of original qualification process starting with initial plans prior to execution of activities.
  - Identify how process execution may have been optimized to reduce the time needed.
  - Identify tasks activities that were missing and overlooked from original plans.
  - Identify those tasks that were most misrepresented in establishing initial baseline schedule and resources. These will tend to be tasks/activities whose scope was initially underestimated and have the greatest uncertainty and potential risk.

Some specific recommendations for application to nuclear are provided:

- Recommendations from the automotive Industry to implement new products are 1) collaborative efforts, 2) increased communication, education, and training of the work force and within the industry, 3) simulation tool advancement (4) advanced forming and joining technologies.
- A recommendation that the nuclear energy community can learn from a U.S. Navy presentation among others are the material databases should address 1) performance, 2) production, 3) processing, and 4) research. Also, the maintenance of these databases is crucial so that the information can be available for generations and can be used for validation. However, it was clear that these databases are expensive to maintain and should be cross-cutting to be fully sustainable.
- To aid American Society of Mechanical Engineering coding of AM materials for future use in Gen-VI systems, a central database of feed powder quality (i.e., characterizing oxygen impurities) processing conditions, resulting microstructure, post-processing thermal treatment, mechanical properties, and the nuclear performance of these materials might be established. This would provide a systematic display of knowledge gaps and could help to enhance our understanding of the overall technology.
- Based on the detailed analysis of the MOST-AM national workshop at the University of Pittsburgh, the following conclusions can be made regarding current qualification challenges of AM fabricated products.
  - Mechanical properties and data management is important to many sectors for qualification practices.
  - The machine variability in the AM process, microstructural inconstancy, process parameter development remains the main roadblocks for the qualification process of AM products.
  - Although digital twin/machine learning can be useful tool for printing in an iterative design

- Regarding processes, the lack of better in situ monitoring or other advanced monitoring tools impede adaptation of optimized modeling guided printing.
- Modeling of AM products—mainly scaled up products and complex geometry—still need to be developed for accelerating the qualification process.

- Based on NASA's qualification framework, the following recommendations can be made:
  - Include the classification of parts depending on the level of consequence of the parts' failure, which would help in making parts potentially go through different, less strenuous qualification methods depending on that classification, potentially making it less time consuming.
  - Include the use of an Equipment and Facility Control Plan, which would allow for reliable AM part production through the consistent definition and implementation of equipment and facility controls.
  - Implement feedstock management, which is essential to safe and reliable AM processes, by providing requirements for storage and handling of AM materials, material lot control in AM machines, and blending operations.
  - Implement feedstock traceability, which is critical to tracking feedstock usage, life limits, and special usage requirements and enabling resolution of nonconformance involving feedstock.

This study includes summaries of multiple workshops hosted by U.S. Department of Energy Office of Nuclear Energy programs, international communities, or other industries, and although all the similarities are not fully interpreted and displayed, multiple complimentary actions were identified that the nuclear industry should consider.

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Acronyms and Abbreviations

3-D	three-dimensional
AM	advanced manufacturing
AMM	Advanced Materials and Manufacturing
AMMT	Advanced Materials and Manufacturing Technology
AMSC	America Makes & ANSI Additive Manufacturing Standardization Collaborative
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AMT	advanced manufacturing technology
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
EPRI	Electric Power Research Institute
CAR	Center for Automotive Research
DoD	U.S. Department of Defense
FAA	Federal Aviation Administration
GIF	Generation IV International Forum
HIP	hot isostatic pressing
IAEA	International Atomic Energy Agency
ICME	integrated computational material engineering
INL	Idaho National Laboratory
LPBF	laser powder bed fusion
LWR	Light Water Reactor
NASA	National Aeronautics and Space Administration
NEI	Nuclear Energy Institute
NRC	U.S. Nuclear Regulatory Commission
PNNL	Pacific Northwest National Laboratory
OEM	original equipment manufacturer
QMP	Qualified Material Process
R&D	research and development
SDO	standard development organizations
SS	Stainless steel
TF	Task Force
VVUQ	Verification, Validation, and Uncertainty Quantification

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1.0 Introduction

The Advanced Materials and Manufacturing Technology (AMMT) program develops cross-cutting technologies in support of a broad range of nuclear reactor technologies and maintains U.S. leadership in materials and manufacturing technologies for nuclear energy applications. The overarching vision of AMMT is to accelerate the development, qualification, demonstration, and deployment of advanced materials and manufacturing technologies to enable reliable and economical nuclear energy. The acceleration of qualification processes is one of the key aspects and qualification processes for the nuclear industry is not necessarily equivalent or benchmarked against other industries.

1.1 Objective

The objective of this work package is to obtain knowledge of the full concert of qualification processes, which will then provide a critical part of the knowledge base to enable the AMMT management team to provide a knowledge based and visionary qualifications strategy pertaining advanced material and manufacturing technologies. A detailed nuclear energy qualification roadmap is not part of this work package's deliverables.

1.2 Scope

It is envisaged that the following activities may help to reach the objectives, but this may change as information became available during the evaluation process:

- Review of other industries' qualification frameworks and identify emerging agnostic qualification strategies.
- Prepare a flow diagram of current U.S. Department of Energy Office of Nuclear Energy (DOE-NE) qualification processes, determining an integrated flow for a system qualification vs a material qualification.
- Review and summarize international nuclear industry qualification efforts, including topical workshops held by other organizations and/or DOE programs (e.g., the Advanced Materials and Manufacturing (AMM) and AMMT qualification workshops held in August and November 2021.
- Prepare a summary of current and planned activities under the codes and standards organizations (e.g., American Society of Mechanical Engineers [ASME], National Institute of Standards and Technology, American Society for Testing and Materials [ASTM] and others).
- Prepare a gap analysis and recommendations based on lessons learned from status quo, other industries and the envisage future activities for prioritization.
- Review and provide technical input and interpretation on the material score cards, identification of gaps from those score cards, advise on additional information to be examined. Interpretation and linkages will be developed in relation to the maturity level of the qualification data sets. This activity will ensure traceability of information from the onset of the work in early 2021 as well as the material score cards.

2.0 Qualification Processes: A Brief

2.1 Agnostics Qualification Approach Descriptions

Several qualification pathways have been proposed for advanced manufacturing (AM) materials, processes, and components [1, 2]. For example:

- *Statistical-based qualification* – This approach requires extensive testing and empirical modeling. With this approach, the uncertainty in the production of a particular component is understood and mitigated by massive testing during production. This approach is, however, not practical for qualifying AM components that have significant variabilities in processes. It also represents a high barrier for production of customized, low-volume components that expect to be the case for nuclear applications. It is extremely costly to re-qualify a process whenever any deviation occurs from the qualified procedure.
- *Equivalency-based qualification* – Qualification is achieved through moderate testing to demonstrate a new material or process is equivalent to a previously qualified material or process. However, the evaluation of AM materials must account for a broad range of characteristics of a material to assure that the material meets all of its expectations.
- *In situ data-based qualification* – This qualification approach heavily replies on in situ measurement data acquired during the manufacturing process. Layer-by-layer manufacturing makes it possible to inspect each layer during the build. Defects can be detected by in situ monitoring tools. For example, in situ infrared thermal imaging and optical imaging, and a part quality can be assured by in situ process monitoring and control. This process-informed qualification works the best with the model-based qualification approach.
- *Model-based qualification* – With a model-based qualification approach, a material's performance is demonstrated in a computer model and verified with a small amount of testing. This model-based qualification is based on a robust understanding of the processing-structure-property-performance relationships of a material in a nuclear reactor environment and with uncertainty quantification. For example, a process model can predict the local thermal histories and materials compositions; given the local composition and thermal history, a microstructure model can predict microstructure; a property model predicts strength of a material based on its composition and microstructure; a performance model predicts the behavior of a material in reactor environments.

2.2 Impact of Advanced Manufacturing on Qualification Processes

AM is of key interest to the nuclear industry as they enable the realization of complex designs, while improving the quality and safety of components, and reducing manufacturing time and cost. AM techniques have seen rapid development and deployment in many industries but their applications to nuclear power are still at an early stage. Potential applications will include the replacement of parts or component in existing plants as well as the procurement of new parts and structural components. Parts and components produced by AM may have nuclear safety functions and could form integral parts of the reactor pressure vessel, notably for small modular reactors. The deployment of structural material and nuclear core materials, manufactured through methods of advanced manufacturing in the nuclear industry, is challenged regarding the application of codes and standards as well as in obtaining regulatory acceptance. However, successful examples on AM qualification could serve as door opener for the wider integration of advanced manufacturing techniques into the global nuclear supply chain [3]. To allow for full deployment of AM in nuclear technology a substantial understanding of microstructure and property evolution during additive manufacturing and post-fabrication annealing is desirable to achieve reproducibility and to improve the technology to the point of gaining acceptance. The deployment of Gen-IV reactor technology and the associated demand for advanced materials can act as a booster for the adaptation of the ASME coded advanced AM materials in upcoming years [4].

Qualification of AM alloys is required to demonstrate that each prospective AM manufacturing process can deliver the required components in a reproducible way, and that both its properties and quality will comply with the demands applicable to the relevant nuclear safety classification. Over the last decade, the additive manufacturing process has been optimized to allow the production of alloys with equivalent properties to materials produced with traditional processes (e.g., forging, casting). Further research and development (R&D), however, are needed to clearly identify the methodology of AM qualification and the required test protocols to assure adequate product quality with highest accuracy. As result, qualification protocols must ensure adequate basic isotropic mechanical properties (e.g., strength, elongation, fracture toughness, pitting potential) as well as acceptable response of the AM material to long term degradation mechanisms (e.g., creep, fatigue, thermal ageing, and radiation tolerance). The qualification protocols will require an equally strict and extensive instructions to demonstrate the quality of the product, of its reproducibility of its AM fabrication process.

The use of components or material obtained from additive manufacturing for nuclear safety related equipment is not yet exhaustively regulated and some requirements exist for some AM technologies (e.g., welding, powder metallurgy/hot isostatic pressing), but all specificities of additive manufacturing have not been addressed. ASME is currently working to develop criteria for the qualification and acceptance of additive manufacturing components for pressure equipment [3]. Many parameters can affect the final quality of a product fabricated using additive manufacturing techniques. Qualifying processes are challenging as rules must be simultaneously generic whilst covering all aspects of process specific details and a large amount of experimental data are therefore required to substantiate the qualifications.

The chemical and mechanical properties of materials produced by advanced manufacturing at the point of manufacture have been well studied and characterized for alloys such as AM 316L, but additional knowledge regarding its long-term integrity is still needed. Further R&D must demonstrate that the components produced by additive manufacturing also satisfy requirements with regards to ageing and the degradation mechanisms they are subjected to during service in a nuclear environment.

Prospective pathways for AM components for nuclear application can be derived from vast experimental and computational information collected by the fabrication of AM 316 L stainless steel (SS) by laser powder bed fusion (LPBF) AM. In this regard, Hensley et al. [5] provide a comprehensive and consistent process flows with computational modeling, in situ measurements, ex situ characterization, and mechanical testing with sample material of simple and complex geometries. At this the crucial role of post-process hot isostatic pressing (HIP), and solution anneal treatment were also evaluated. After using HIP, the scatter in AM 316 L steel properties, within single and complex components, was minimized to further meet the requirement of existing industry standards. The qualification of AM components is displayed by the following flow sheet (Figure 1).

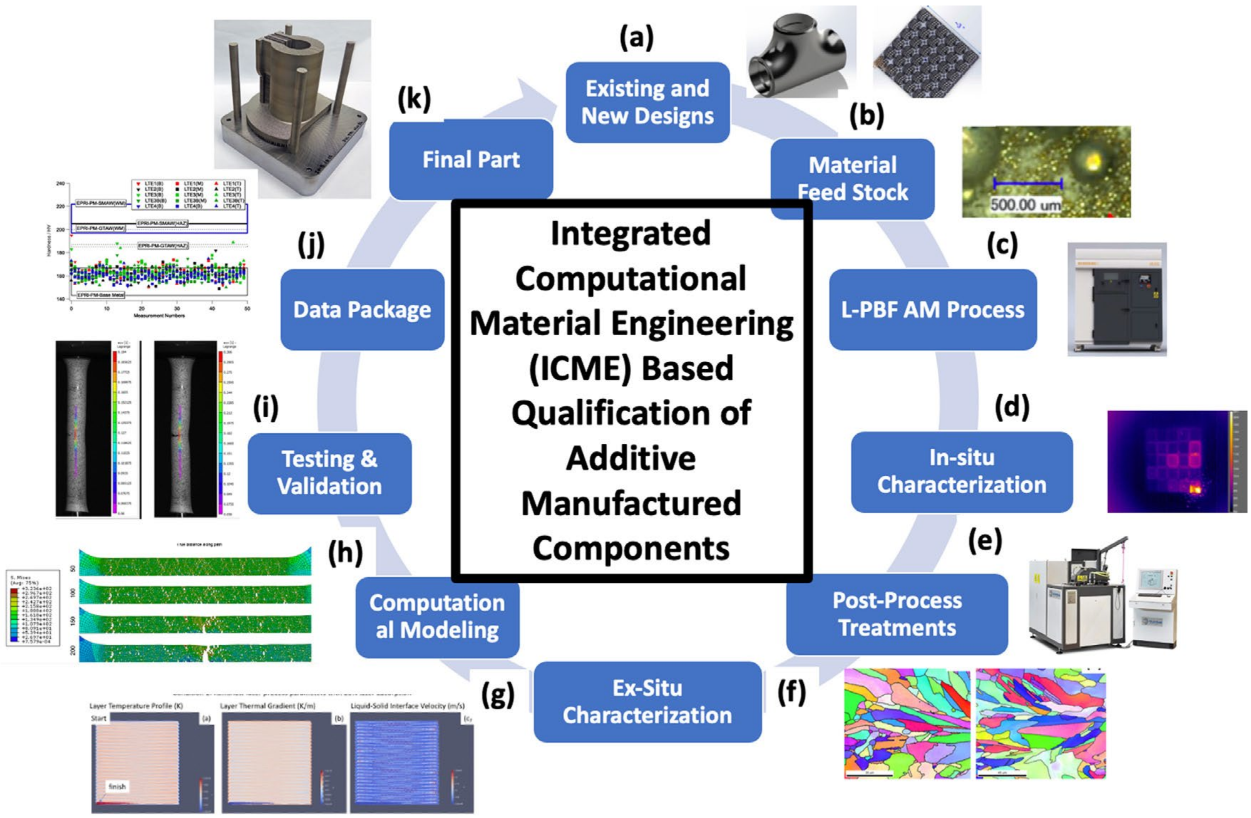

Figure 1. Part-Specific Qualification Methodology for Accelerated Deployment of Additive Manufacturing for Nuclear Applications by Hensley et al. [5]. (a) Revaluation of existing design based on traditional manufacturing. (b) Measurement of powder characteristics that is relevant to each component. (c) Selection of proper AM processing equipment relevant to application. (d) In situ characterization of surface and thermal signatures. (e) Post-process heat treatment. (f) Microstructure analyses and evaluate the heterogeneity. (g) Heat transfer. (h) Mechanics modeling. (i) Ex situ mechanical testing. (j) Development of data package. (k) Deployment.

This research paper published by Hensley et al. [5] valuates the feasibility of an integrated computational material engineering (ICME) approach by considering all aspects from start to finish in making an AM component. The proposed qualification methodologies by the authors integrate legacy knowledge from casting, welding, powder metallurgy, in situ and ex situ characterization and additive manufacturing literature.

Geometrical designing of components for AM for a given application is not trivial, because technical and business cases must be considered, as well as availability of infrastructure which includes high performance computational tools. Like traditional manufacturing, the properties, and characteristics of the incoming raw material (e.g., powder, wire, etc.) is crucial for product reliability during fabrication and service. The selection of the individual AM process is dictated by the scale and complexity of the geometry, required qualification, surface roughness, and the expected properties. In situ monitoring during the fabrication process (e.g., by X-ray scattering and imaging) and infrared thermal imaging might be an important aspect of AM qualification to ensure adequate fabrication conditions. Also in traditional manufacturing, components for nuclear applications often go through post-process treatments, such as solution annealing or normalizing, to arrive at defect free structure and homogenous properties. For parts and forms produced by AM methods post fabrication heat treatment and the HIP process might have to be applied to close the porosity and further to reduce the heterogeneities. Ex situ characterization will probably involve optical microscopy, scanning electron microscopy, hardness testing, tensile testing, fracture toughness, and crack propagation testing as integral part of traditional manufacturing. Integrated computational modeling that considers the geometry, thermo-mechanical history, and service performance are considered as an enabling tool by traditional manufacturing.

Advanced numerical techniques that are based on finite element or finite volume methods are useful for gaining insight into these phenomena at the 100-μm length scale of the melt pool is ill-suited for predicting engineering trends over full part cross-sections. Therefore, Plotkowski et al. [6] propose an alternative method that is based on a semi-analytical approach for predicting transient heat conduction during the powder bed metal additive manufacturing processes. The transient heat transfer effects, found in metal additive manufacturing, could be calculated using a semi-analytical heat conduction model [6]. It is shown that the transient effects of the scan strategy create significant variations in the melt pool geometry and solid-liquid interface velocity, especially as the thermal diffusivity of the material decreases and the pre-heat of the process increases.

Because of geometry and process dependent defect formation and microstructural heterogeneity during AM, various qualification pathways have to be considered [5]. The first pathway must consider the qualification based on eliminating of defects in the bulk. By using HIP and solution anneal treatment, the scatter in 316 L SS AM properties can be minimized within single and complex components by eliminating large porosities. The second pathway considered the application of integrated computational modeling based on process, microstructure, and deformation modeling. Heat transfer models predicted the spatial and temporal distribution of thermal gradients (10^4 to 10^8 K/m) and liquid-solid interface velocities (10^{-2} to 10^1 m/s). Under low liquid-solid velocity conditions, the microstructure may follow a solidification sequence typically seen in weld metals.

2.3 Traceability and Maturity Level of Materials Identified in the AMMT Program’s Material Score Cards

The consequence of the implementation of AM in support of nuclear technology, will be reduced construction costs by reduction energy for alloy fabrication requirements combined with savings of critical minerals [4]. The projected exponential annual growth of 2.37% in nuclear capacity requires additional 21 nuclear power stations build between 2049 and 2050 and a demand of 840,000 tons steel for establishing nuclear energy capacity. If all steel is manufactured by methods of advanced manufacturing, an energy saving of up to 39 PJ (Peta Joule) is achievable, which corresponds to the energy an average 1,000 MWe power plant produces annually (28 PJ with 90% availability). The prospective increase in mechanical strength and corrosion properties at similar elongation of AM material can translate to material savings of up to 30 % for a required design strength, if AM-alloys with reproducible mechanical properties can be reliably produced. Related cost savings can be a decisive economic factor for promoting deployment and sales, but also enhances sustainability of nuclear technology by significantly reducing the demands of critical minerals. If methods of advanced manufacturing could be attributed to material savings, the demand for critical minerals in nuclear technology would also decrease from about 840 kg/MWe (Gen-III+) to up to 588 kg/MWe.

AM of structural or core materials for future Gen-IV nuclear reactors will allow for fast prototyping and providing nuclear materials with superior mechanical properties and corrosion resistance. AM can be used as a tool to aid the development of Gen-IV reactor system and their deployment as carbon-free energy source of high availability. The materials scorecards developed in 2022 [30] provide overall technical readiness levels and detailed justification and traceability for the adoption of additively manufactured structural materials and ceramics for nuclear deployment: SS304, SS316, Incoloy 800H, Graphite C/C, Hastelloy N, Silicon Carbide (SiC), HT9, Inconel 617, and Inconel 718. These alloys and ceramics are selected for deployment of one or more of the following Gen-III+ or Gen-IV reactor systems: LWR, SFR, LFR, Micro-Reactor, VHTR, MSR and GFR, and an overview is provided in Table 1.

Table 1. Overview of Selected Materials for Use in Gen-III+ and Future Gen-IV Nuclear Reactors

	Gen-III+ and Gen-IV Nuclear Reactor					
Alloy	**LWR**	**SFR**	**MSR**	**GFR**	**VHTR**	**Micro-Reactor**
SS316	No	Yes	Yes	Yes	Yes	Yes
SS304	Yes	Yes	Yes	No	Yes	No
Incoloy 800H	No	No	Yes	No	Yes	No
Graphite C/C	No	No	Yes	Yes	Yes	No
Hastelloy N	No	Yes	Yes	No	No	No
SiC	No	No	Yes	Yes	Yes	Yes
HT9	No	Yes	Yes	No	No	Yes
Inconel 617	No	No	Yes	Yes	Yes	No
Inconel 718	No	No	No	Yes	Yes	Yes

While AM materials are being commercialized by industry, they have not yet been adopted within the nuclear industry for critical parts that are exposed to high temperatures, corrosive environments, high-radiation environments, and complex loading patterns. The understanding of materials properties in these conditions is limited. Unlike the conventional metal casting/forging process, AM generally creates a large temperature gradient within the significantly smaller melt pool, which results in abundant non-equilibrium heterogeneous microstructural features, including hierarchical boundary structures, columnar grain, sub-grain cellular dislocation structures, inhomogeneous element segregation and precipitation. Mechanical and nuclear properties of AM materials strongly depend on feed-powder and process-related parameters, and adequate guidelines and recommendations for fabricating nuclear-grade AM materials, hence technology-specific qualification guidelines, have yet to be established.

Advanced manufacturing is a powerful technology to aid the development of Gen-VI reactor system and their deployment as powerful carbon-free technology for primary energy and electric (secondary) energy production. Literature relevant to Gen-VI reactor systems was screened in 2022 to determine the overall technology readiness level of AM alloys and AM ceramics for their deployment in nuclear Gen-VI reactor systems [30]. The findings in this regard can be summarized as following:

- Additive manufacturing of austenitic steel grades SS316L and SS304 seems most promising for nuclear deployment and shows the highest levels of overall maturity and technical readiness.
- Martensitic/ferritic HT9 ranks high as well, even though fabrication-structure-property data on AM fabricated HT9 are far less available than those on austenitic steel grades.
- Advanced manufacturing SiC scores high because of a recent breakthrough in its fabrication route. The fabrication of AM ceramics is different from the fabrication of AM

alloys. Hybrid methods such as binder jet chemical vapor infiltration have recently shown their potential to fabricate dense and stochiometric ceramics. Advanced manufacturing SiC with acceptable quality was recently produced and in-core radiation testing of AM SiC is currently performed at Oak Ridge National Laboratory [37].

- Between Inconel Alloy 617 and Alloy 718, the overall maturity and readiness level of AM IN718 is somewhat higher compared with AM IN617. It is apparent, that readiness level of AM nickel-based alloys is far lower than those of the austenitic steel grades SS316 and SS304. The fabrication of crack-free high-performance Ni-based alloys using AM technology remains challenging because of their susceptibility to hot cracking.
- The technical maturity of AM Incoloy 800H for high temperature deployment is jeopardized by its affinity for carbide precipitation and sensitizing. The deployment of AM Alloy 800H for high temperature application is therefore limited and the overall score for Incoloy 800H is low.
- Fabricating nuclear grade graphite by AM is challenging. However, a novel process was developed by combining binder-jetting and sequential impregnation-drying-pyrolysis cycles. This process has the potential to fabricate graphite with properties acceptable for nuclear deployment.
- Hastelloy N ranks lowest in this comparison since data on AM Hastelloy N must yet become available. However, data on related AM Hastelloy X are available. AM Hastelloy X shows susceptibility for hot cracking, which could be mitigated by the addition of titanium carbide nano powders. However, Hastelloy N contains less chromium and more molybdenum than Hastelloy X and therefore its fabrication by AM is likely even more challenging than the fabrication of Hastelloy X. High concentration of refractory metals in AM alloys lead to phase segregation and solutionizing remains incomplete.

3.0 Qualification Frameworks of Other Industries

The aim of this section is to learn lessons from other industries' approaches on qualification methodologies and best practices. Although the nuclear industry has specific unique features related to nuclear safety requirements and unique technical challenges, relevant information from other industries can help already to implement practices that has been validated and applied to other safety critical parts. Therefore, this section will provide an overview of other industries' qualification frameworks and identify emerging agnostic qualification strategies.

3.1 National Aeronautics and Space Administration Qualification Framework

The National Aeronautics and Space Administration (NASA) currently has two standards that list requirements for additive manufacturing: 1) NASA-STD-6030, Additive Manufacturing Requirements for Spaceflight Systems [7], and 2) NASA-STD-6033, Additive Manufacturing Requirements for Equipment and Facilities Control [8]. Both standards became active on April 21, 2021.

3.1.1 NASA-STD-6030

NASA-STD-6030 is a technical standard that defines the minimum set of requirements for AM parts used for NASA crewed spaceflight systems. The standard covers the general and specific requirements for AM design, materials, processes, equipment, personnel, testing, and production. The standard also defines the concepts of Qualified Material Process (QMP), Qualified Part Process, and Material Processes Suite, which are essential for ensuring the reliability and performance of AM parts. The standard is organized into two categories: 1) foundational process control and 2) part production control. The standard is based on more than 10 years of research and development by NASA experts and collaborators from various disciplines and organizations. The standard is applicable to all NASA space program flight hardware, including crewed spaceflight hardware. NASA states that due to the complexity and uniqueness of space flight, it is unlikely that all the requirements in a NASA technical standard will apply and that it may be used by programs and projects to indicate requirements that are applicable or not applicable to help minimize costs. Of the requirements listed in the matrix, there are many that could be applicable to this industry. Specifically of interest to the nuclear industry, is the requirement [AMR-48]: A candidate material process shall share the following commonality criteria with an existing, approved QMP to enable the use of a Sub-QMP:

- Feedstock controls are identical.
- The AM build process definition is equivalent, meaning:
  - Same make of AM machine with equivalent configuration and build volume
  - Same make and model of printer head hardware
  - Same scheme for setting build path and assigning parameters
  - Same layer thickness.
- The post-AM process definition is identical.

The reasoning for this, is that the use of a Sub-QMP provides efficiencies by leveraging existing QMPs that are consistent based on machine and process commonality. Other requirements found in the standard's matrix could also be applied such as the classification of parts depending on the level of consequence of the parts' failure. The requirement matrices for both NASA-STD-6030 and NASA-STD-6033 provide the ASTM standards that any and all tests should be performed to. Going into detail for NASA's use of part classification can show how something like this can be useful for other industries.

3.1.1.1 Part Classification

In NASA-STD-6030, NASA assigns a primary classification to all AM parts. The three classes that they use are A, B, and C.

Class A parts are parts considered to have a high consequence of failure. If failure of the part leads to a catastrophic, critical, or safety hazard and/or the part is defined as mission critical by the program or project. NASA states that Class A parts shall not:

- Be made from polymeric materials
- Be fasteners
- Contain printed threads.

Class B parts are parts that are not designated as class A or C. Class B parts shall not:

- Be fasteners
- Contain printed threads.

Class C parts are those that are considered to have negligible consequence of failure, provided they meet all of the following criteria:

- Failure of the part does not lead to any form of hazardous condition.
- Failure of part does not eliminate a critical redundancy.
- Part does not serve as primary or secondary containment.
- Part does not serve as redundant structures for fail-safe criteria per NASA-STD-5019 [9], Fracture Control Requirements for Spaceflight Hardware.
- Part is not designated "Non-Hazardous Leak Before Burst" per NASA-STD-5019.
- Failure of part does not cause debris or contamination concerns, as defined by the Non-Fracture Critical Low-Release Mass classification per NASA-STD-5019, NASA-STD-6016 [10], and/or other project/program requirements.
- Failure of part causes only minor inconvenience to crew or operations.
- Failure of part does not alter structural margins or related evaluations on other hardware.
- Failure of part does not adversely affect other systems or operations.
- Failure of part does not affect minimum mission operations.

The standard also includes parts that are exempt of these classes, labeled as Exempt. An exempt part is classified as such if it meets all criteria for Class C and meets all of the following criteria:

- The part does not require any form of structural assessment.
- The part does not permanently interface to, or attach to, the launch vehicle, spacecraft, habitable module, or any subsystems thereof.
- Except for use in habitable crew spaces, the part does not provide any functionality or serve any purpose to the launch vehicle, spacecraft, or any subsystems thereof.

NASA lists a secondary classification for Class A and B parts, based on structural demand and AM risk. NASA provides tables that define these criteria found in Table 2 to Table 4.

Table 2. Structural Demand, Metallic AM Parts [7]

Analysis Input/Material Property	Criteria for Low Structural Demand
Load cases	Well-defined or bounded loads environment
Environmental degradation	Only due to temperature
Ultimate strength	Minimum margin[a] ≥0.3
Yield strength	Minimum margin[a] ≥0.2
Point strain	Local plastic strain <0.005
High cycle fatigue, improved surfaces	Cyclic stress range (including any required factors) ≤80% of applicable fatigue limit
High cycle fatigue, as-built surfaces	Cyclic stress range (including any required factors) ≤60% of applicable fatigue limit
Low cycle fatigue	No predicted cyclic plastic strain
Fracture mechanics life	20x life factor
Creep strain	No predicted creep strain

[a] Margin = [σ_{design}/($\sigma_{operation}$ × safety factor)] – 1

Table 3. Structural Demand, Polymeric AM Parts [7]

Analysis Input/Material Property	Criteria for Low Structural Demand
All Materials	
Load cases	Well-defined or bounded loads environment
Environmental Degradation	Only allowed due to temperature and moisture, if specific environmental performance data exist. Design environment temperature does not cross the *Tg.*
Fatigue	Cyclic stress range (including any required factors) ≤50% of applicable fatigue limit
Sustained stress/creep restrain	No sustained stress[†] and no predicted creep strain
Material with elongation at failure ≥3% in application environment	
Ultimate strength	Minimum margin* ≥0.5
Yield strength[‡]	Minimum margin* ≥0.3
Material with elongation failure <3% in application environment	
Ultimate strength[#]	Minimum margin* ≥2.0

[†]Includes assembly stress (tight snap fit connections, shrink fits, fastener preloads) and operational stress.
[‡]Yield strength defined by secant modulus to specified strain, by specified offset strain, or as otherwise defined by structural assessment requirements.
[#]Ultimate strength assessed against local maximum principal stress at stress concentrations (brittle material design rules) for low ductility materials.
*Margin = [σ_{design}/($\sigma_{operation}$ × safety factor)] – 1

Table 4. Assessment Criteria for Additive Manufacturing Risk [7]

	Metallic		Polymer			
	L-PBF	DED	L-PBF	Score For		
Additive Manufacturing Risk				Yes	No	Score
All surfaces and volumes can be reliably inspected, or the design permits adequate proof testing[a] based on the stress state?	X	X	X	0	5	
As-built surface can be fully removed on all fatigue-critical surfaces?[b]	X	X		0	3	
Surfaces interfacing with support structures are fully accessible and the as-built surface removed	X	X	X	0	3	
Structural walls or protrusions are the equivalent of ≥8 trace, (e.g., melt pool, bead, scan path) widths in cross section?	X		X	0	2	
Structural walls or protrusions are the equivalent of ≥2 trace, (e.g., melt pool, bead, scan path) widths in cross section?		X		0	2	
Critical regions of the part do not require support structure?	X	X	X	0	2	

[a] In the context of the assessment of AM risk, the adequacy of a proof test is determined by the degree to which the test meets its assigned objectives. For a workmanship proof test, at any given location in the part the proof test is considered adequate when the state of stress in the part during the proof test exceeds the states of stress in the part during operation by the required proof factor. If the proof test conditions do not fully replicate the operational environment, as is typically the case, the proof and operational stresses are compared using directional stress components with any needed corrections for environment. For the rare case of quantitative flaw screening by proof test as an anchor to fracture control requirements, the adequacy of the proof test is determined only by the ability of the applied proof test stress conditions to screen the critical initial flaw size for operation by causing failure, leak, or other clearly detectible damage to the part during the proof test. Just as in the workmanship proof test, the adequacy of a proof test for quantitative flaw screening is likely to vary throughout the part. Demonstrating the adequacy of a proof test for quantitative flaw screening is likely to vary throughout the part. Demonstrating the adequacy of a quantitative proof test is non-trivial and must be coordinated intently with the structures and fracture control requirements.

[b] Fatigue-critical surfaces are locations where fatigue analysis and surface condition assumptions influence the outcome of the structural assessment

3.1.2 NASA-STD-6033

NASA-STD-6033 is a NASA Technical Standard that outlines the requirements for equipment and facilities used in AM processes for NASA spacecraft systems [8]. It covers the production of AM parts for various hardware elements, including crewed and non-crewed spacecraft, launch vehicles, landers, and robotic systems. The standard assumes that the AM facility is already compliant with all applicable environmental, health, and safety regulations. The document provides guidelines for the control of AM equipment and associated facilities. It also emphasizes the importance of personnel training and qualification in ensuring the quality of AM parts. The standard requires the development and maintenance of an Equipment and Facility Control Plan (ECFP), which enforces requirements for qualification, maintenance, calibration activities, and other aspects related to AM machines and associated equipment. As with NASA-STD-6030, NASA-STD-6033 includes a Requirements Compliance Matrix that covers all the requirements listed out in the standard. Of the requirements listed in the matrix, there are many that can be used across industries, such as the need for an Equipment and Facility Control Plan, feedstock traceability, feedstock storage and handling, cleaning procedures for removal of residual feedstock, and others.

3.1.3 Recommendation Based on Review of NASA-STD-6030 and NASA-STD-6033

NASA-STD-6030 lists both Foundational Process Controls and Part Production Controls as two major pieces of their key products and processes for the standard. The foundational process controls take from both NASA-STD-6030 and NASA-STD-6033's requirements and are all used to help with the part production control requirements. (Equipment Control and Personnel Training are part of NASA-STD-6033.) The foundational process control requirements provide a basis for part design and production which is reliable. These requirements include:

- Qualification of manufacturing processes
- Equipment controls
- Personnel training
- Material property development.

The part production control requirements are typical of aerospace operations and include:

- Design and assessment controls
- Part production plans
- Preproduction article processes
- Relevant production controls.

Figure 2 and Figure 3 show a flow diagram made by NASA to represent the way the Foundational Process and Part Production Controls work together as well as a key to better understand the flow diagram.

The process indicated in Figure 2 shows how time consuming and intensive the qualification process can be. With trends in AM products changing constantly, the process that NASA has set up can perhaps be simplified, as there is a chance that multiple steps in NASA's approach may be performed at the same time to reduce time. A plan must be set into place to find parameters that can be changed to truly reduce the time of qualification. In the article "Path to Aircraft Certification for Additive Manufacturing with Stratasys F900" by Joseph Yang, one can see that this process can be simplified. Figure 4 is an example of a qualification or certification pathway that Yang suggests that can be used for other industries [11].

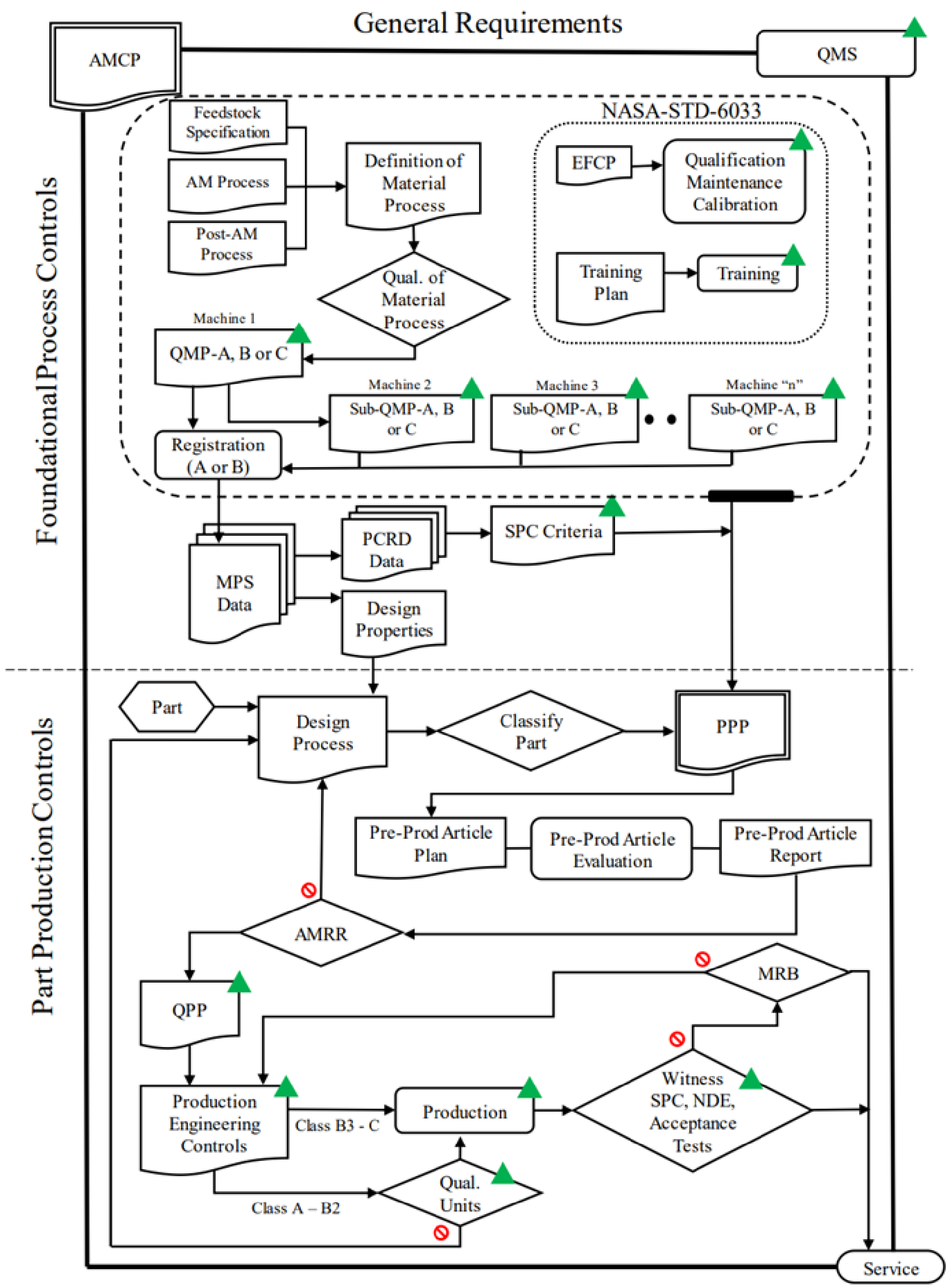

Figure 2. Key Products and Processes for NASA-STD-6030 [7].

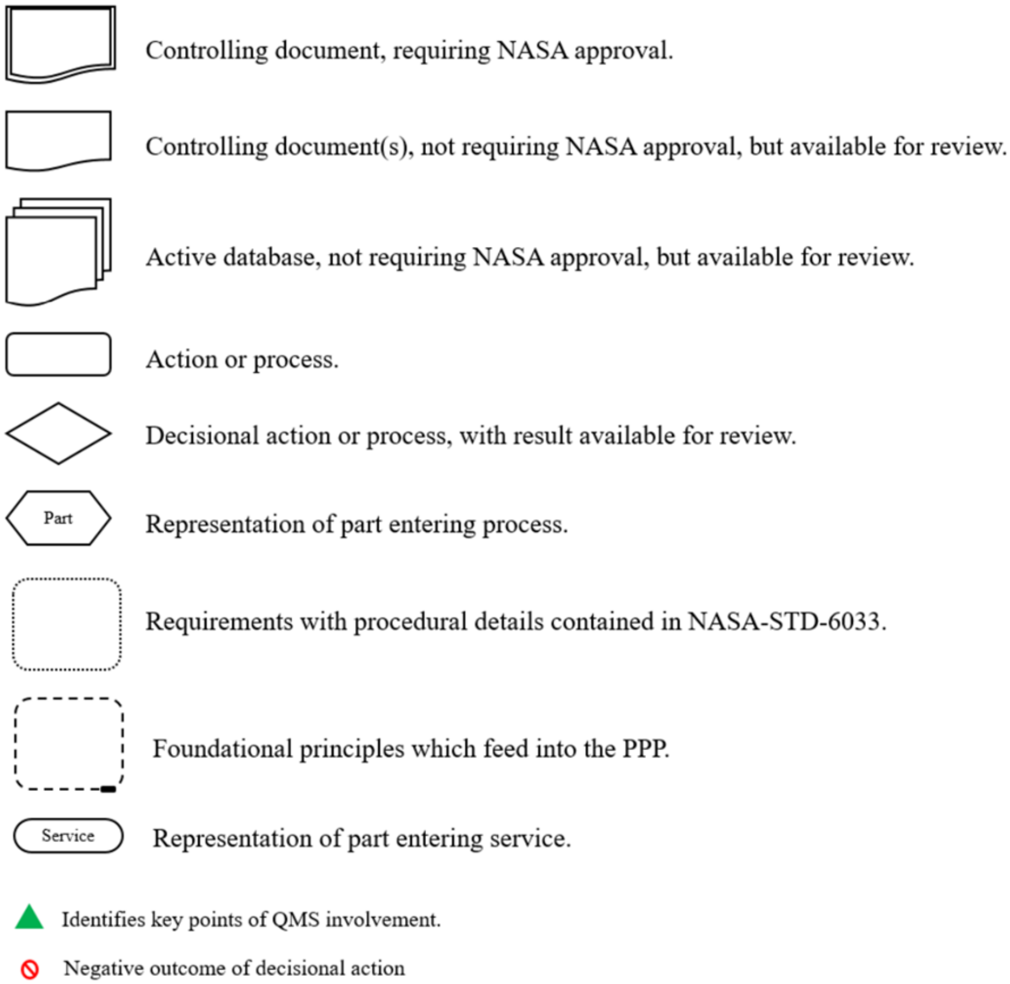

Figure 3. Symbol Legend for Key Products and Processes [7]

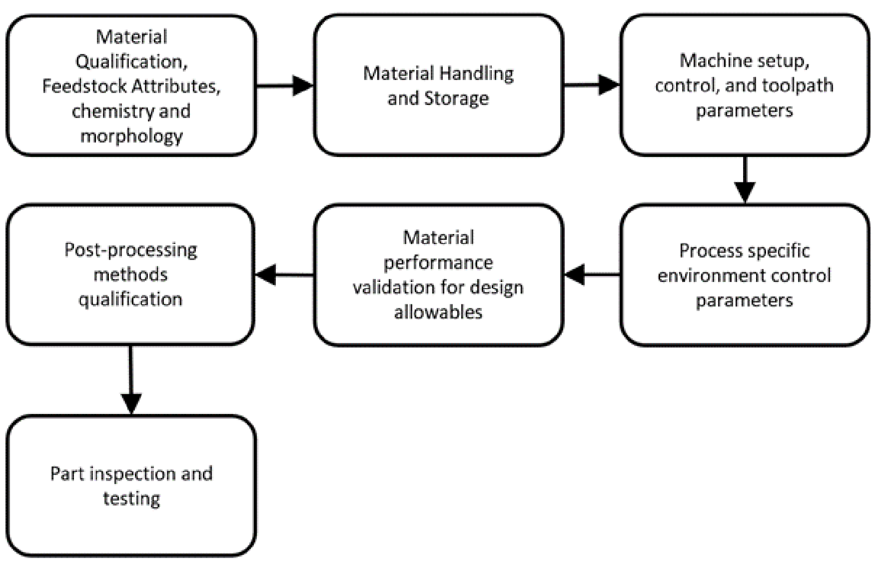

Figure 4. Simplified Pathway for Qualification [11]

3.2 Federal Aviation Administration Qualification Framework

The Federal Aviation Administration (FAA) has been working with various stakeholders, including industry, academia, and other regulatory agencies, to develop and implement a qualification framework for AM parts. The qualification framework is based on the following principles:

The FAA does not approve or certify AM technologies or processes, but rather the end products that are produced using AM. The FAA does not prescribe specific methods or standards for AM qualification, but rather provides guidance and best practices that can be adapted to different applications and scenarios. The FAA relies on a risk-based approach to determine the level of scrutiny and evidence required for AM qualification, depending on the criticality and complexity of the part and its intended use. The FAA encourages collaboration and knowledge sharing among the AM community to foster innovation and harmonization. The FAA's qualification framework for AM parts consists of four main elements:

- *Material Qualification* – This element involves establishing the material specifications, properties, and performance characteristics of the AM material, as well as the process parameters and controls that affect the material quality and consistency.
- *Design Allowable* – This element involves determining the design values and margins of safety for the AM part, based on statistical analysis of test data or validated models.
- *Part Qualification* – This element involves demonstrating that the AM part meets the design requirements and specifications, as well as the applicable airworthiness standards and regulations.
- *Production Approval* – This element involves obtaining the FAA's approval to produce the AM part in accordance with an approved quality system and a conformity inspection plan.

The FAA has published several documents and resources to assist the AM community in applying the qualification framework, such as:

- *2022 Joint FAA-EASA Additive Manufacturing Workshop* – This document contains the proceedings of a virtual workshop that was held in October 2022 to discuss the latest developments and challenges in AM qualification and certification.
- *FAA Report to Congress on Additive Manufacturing* – This document contains a report that was submitted to Congress in March 2020 to provide an overview of the use of AM parts in the civil aerospace industry and the FAA's efforts to monitor and mitigate the use of counterfeit AM parts.
- *Aerospace Industries Association Additive Manufacturing Best Practices Report* – This document contains a report that was developed by the Aerospace Industries Association in collaboration with the FAA to provide recommended guidance for certification of AM parts.
- *The Qualification of the Additively Manufactured Parts in the Aviation Industry* – This document contains a paper that was published in 2019 to provide a pathway and steps for qualification of AM parts.
- *Qualification for Additive Manufacturing Materials, Processes, and Parts* – This document contains a webpage that was created by the National Institute of Standards and Technology to provide information on various projects and activities related to AM qualification.

3.3 Automotive

The automotive industry material qualification practices were investigated because of the size of the industry, The need to address associated safety standards impacting the public, and the high frequency and rapid pace in which new products are introduced to the market. With new models being introduced yearly and generations/series of vehicle upgrades being introduced every 5 to 8 years, the automotive industry has significant experience with introducing new materials and applying materials to new applications. The Center for Automotive Research (CAR) identified in 2016 that the rate of material technology improvement (i.e., growth in use of lightweight materials) between 2007 and 2015 is 3.8%/year for passenger vehicles and 6.8%/year for body-on-frame vehicles [12].

The primary reason for new materials is associated with improving performance relative to crashworthiness, noise and vibration, cost of production, and fuel economy. The automotive industry considers the introduction of new materials to consist of three high-level processes: 1) development, 2) qualification, and 3) verification. Material development is the formulation of a material that previously did not exist. Material qualification is considered the process that occurs between a material supplier and a fabricator with the qualification process associated with determining/demonstrating a material meets a specified set of requirements. Material verification is the process of making sure the material is used appropriately. The following information regarding the automotive industry is focused on the defined qualification process and some on the verification process. The material development process is excluded from the following discussion. The discussion in Section 3.3.1 considers the current processes being implemented by the automotive industry. Section 3.3.1.8 summarizes practices being introduced for additive manufacturing. Section 3.3.2 summarizes methods and barriers associated with reducing the qualification and verification processes for introduction of new materials and new applications for existing materials identified through the industry review.

The automotive industry has estimated that the timeframe for material qualification is 18 to 20 months for metals and 5 to 7 months for plastics and polymer composites. Including development, the introduction of new materials into production lines is 3 to 7 years with material qualification occurring 2 to 3 years prior to the start of production.

3.3.1 Automotive Qualification Process

The automotive industry deals with advanced high-strength steels, aluminum, magnesium, plastics, and polymer composites. Higher end vehicle lines are also utilizing composite materials like carbon fiber. For introducing and qualifying new materials the automotive industry must consider the following.

- *Material performance for normal service and related cost benefit* – While a new material may provide improved performance, the cost of incorporating into production may far exceed actual benefits to the product.
- *Safety aspects relative to crashworthiness for critical structural components* – Qualification for such materials and components must consider functionality after extended service life of the vehicle.
- *Compatibility with interfacing materials and components* – Are there issues with component wear or corrosion due to interfacing materials/components.
  - Paint ability/color coating

- *Workability* – Will current manufacturing techniques of suppliers work with new material and is existing workforce skills/qualification suitable for application of material? Costs associated with retooling and retraining work force can be a major consideration for the introduction of new materials.
- *Material availability, production variability, certification of production* – High volume production requires versatile and secure supply chains for materials and components. Failure of the material supply chain due to unforeseen circumstances can lead to production delays resulting in both financial and market loss for an automotive company. For this reason, the evaluation of the robustness of the material and component supply chain is a high priority for qualification of new materials.
- *Repairability vs. replacement* – A significant fraction of the automotive industry is associated with replacement parts and repair for both service life maintenance and restoration following collisions. Future vehicle service, part replacement, and repair for extended life after vehicle production is a consideration in selecting and qualifying some materials for use.
- *Retirement/disposal of the material* – This is associated with the large volume waste stream created by vehicles at the end of their service life. Are there end-of-life considerations and regulations? Does improper disposal create labilities? The industry needs to be sure that new materials are not detrimental to the environment or public health. For that reason, recyclability is very important factor for material qualification. From a cost perspective, materials/components that are determined to be recyclable at the end of a vehicles service life may no longer be in demand by the automotive industry as new materials are introduced.

The qualification process for automotive industry includes establishing feasibility for both production and supporting extended service life. The automotive industry relies on a network of manufacturers, which requires coordination to assure fabricators can work with new materials based on manufacturing capabilities and experience and skill set of the work force. In addition, the large volume of production, the yearly update of vehicles models, and high frequency at which new materials are introduced increases the risk of deficiencies in anticipated component performance, which can result in costly recalls. A product recall is a request to return a product after a discovery of a safety issue or product defect (i.e., performance deficiency) that might endanger the consumer or put the maker/seller at risk of legal action. Several automakers in the past have invested billions of dollars to recall defect vehicles. The experience has forced the industry to implement stringent material qualification procedures to safeguard against future damages. Recalls can result with only a limited fraction of produced components exhibiting a deficiency. Therefore, the full variability of material and component performance needs to be understood for the qualification process.

Before describing the qualification process employed for the automotive industry by North American manufacturers, it is worth noting a comparison to the approach used by European manufacturers. Observations within the industry indicate that European manufacturers generally qualify the component/part and not the material. This is the result of European manufacturers working closer with individual suppliers compared to North American manufacturers. In comparison, North American manufacturers focus on qualifying the material. The opinion within in the industry appears to be that working collaboratively with component suppliers to qualify final products can aid in accelerating both the qualification process and the pace at which new material technologies (materials, fabrication techniques, etc.) are introduced within the industry. The qualification of the component is also speculated to allow for greater variability in material production as component design and production can provide compensation for material variability.

Figure 5 provides a schematic of the material qualification process for the automotive industry as determined from the authors' review of the industry. An initial basis for the process was obtained from the review conducted by CAR [13]. The qualification process is outlined below and is focused on material qualification. In some instances, the qualification process is focused on a material for a broader range of applications and the qualification process is focused on the characterization and assessment of just the material. For other applications, the material qualification is focused on a specific component application, and material qualification is heavily influenced by component fabrication and component performance. The outlined qualification process is based on industry practices which originated for traditional manufacturing methods (i.e., fabrication by subtraction of stock material) and material shaping/molding as for polymers. Section 3.3.1.821 summarizes practices emerging for additive manufacturing relative to the material evaluation, characterization, and testing process.

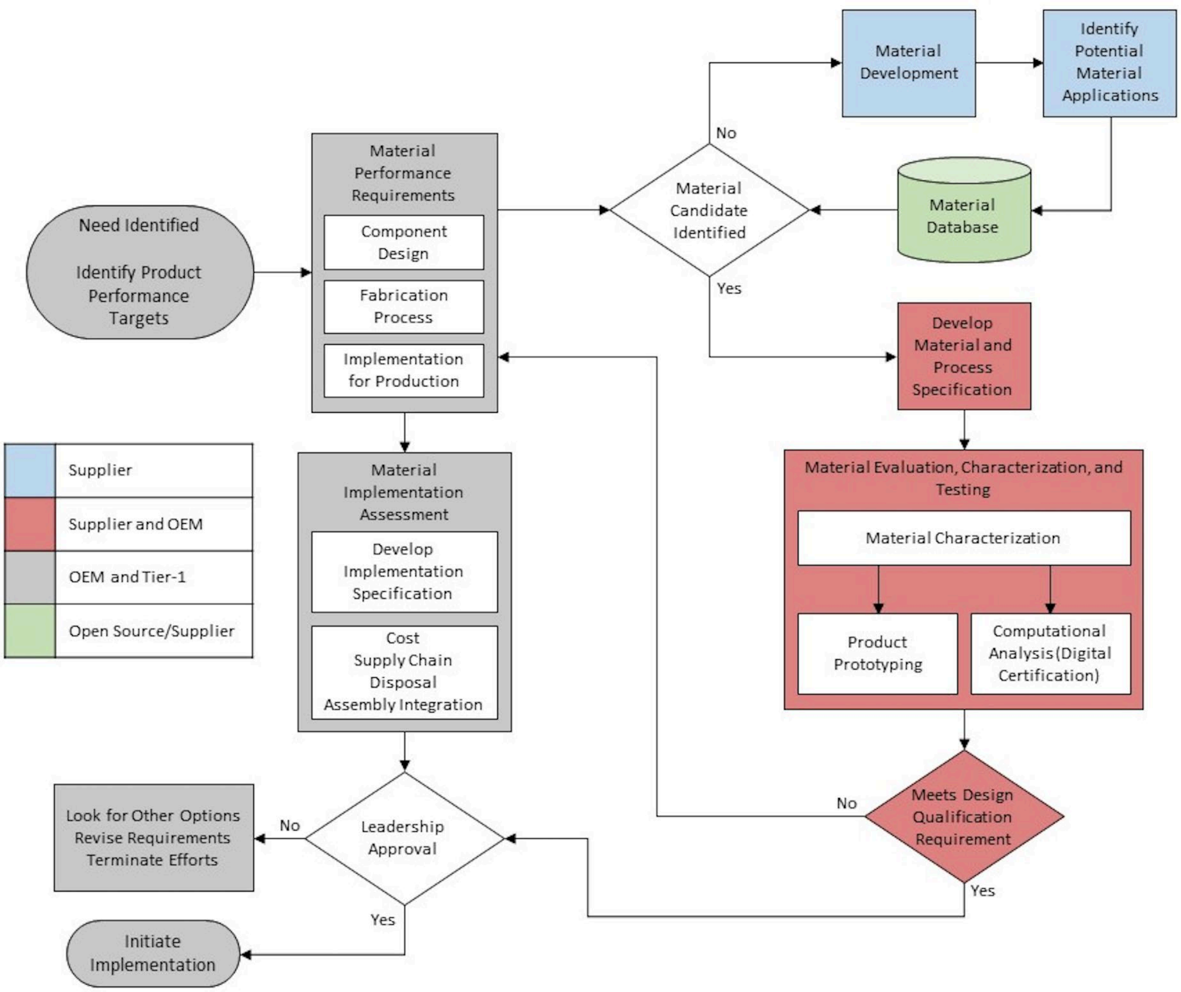

Figure 5. Depiction of Automotive Industry Qualification Process Developed from Review of Industry Practices

3.3.1.1 Determination of Material Need

Material qualification will usually stem from identifying a need or desire to incorporate a new material into the product (i.e., vehicle). However, material qualification needs can originate by changes in requirements/standards that require additional qualification for a material already in use for production. The range of motivations associated with a material need being identified will not be elaborated on here. However, within the automotive industry there are often cases where material needs are focused on finding a substitute material for weight or cost reduction. In such cases, the material is replacing an existing material with the same requirements for performance. Requirements exist and will need to be reviewed to account for changes associated with fabrication, assembly, or installation changes/issues. Material qualification will be focused on demonstrating equivalency.

3.3.1.2 Material Performance Requirements

Material performance requirements are generated by either the Tier-1 or original equipment manufacturer (OEM) depending on the one identifying the material need. The performance requirements define the target expectations for material behavior and performance. The requirements are developed for both application functions (i.e., component design) and fabrication needs, which are associated with the processing to which the material will be subjected. The material behavior/performance after fabrication and installation must satisfy the component design and application needs. The requirements provide both minimum and maximum performance properties.

For the automotive industry, in addition to the design and fabrication requirements, the performance requirements should address what will be referred to as implementation requirements. These requirements are associated with many of the considerations listed at the beginning of this section and include factors such as: material quantities that need to be supplied (supply chain considerations), material costs, recycle/disposal requirements.

3.3.1.3 Identifying Candidate Materials

The material requirements are used to identify candidate materials for consideration. The diagram in Figure 5 indicates that if no candidate materials are found, requirements may be presented to suppliers to develop a new candidate material. Within the industry, based on industry communication and observed trends, suppliers will also be proactive in identifying/proposing potential applications for existing materials or go so far as to develop a new material for consideration. In assessing candidate materials, automotive manufacturers will often consider applications within the industry. Automakers are reluctant to be first users of materials with no in-use failure mode data.

3.3.1.4 Material and Process Specification Development

The specification includes physically defining the material via standard material properties data. The use of standard test methods can be used to obtain a significant amount of the required data (e.g., stress strain curves, density, bendability). The specification will be dependent on the type of material (e.g., metal, polymer) and the material function or application. The grade of material can also influence the material specification such as assessment of microstructure dependent properties (e.g., high-grade heat-treated steels). Other factors that will influence the scope of the specification include fabrication methods, component application, and physical interfaces. The specification may also require material/component assessment relative to material history/exposure. Material properties required for material qualification include:

- *Physical properties* – Density, thermal expansion, heat capacity, thermal conductivity, Poisson's ratio, and tensile/compression/shear/bulk modulus
- *Static mechanical properties* – Tensile strength, compressive strength, shear strength, and bearing strength
- *Durability and damage tolerance properties* – Fatigue strength, notch sensitivity, crack growth, toughness, special design factors
- *Environmental effects* – Temperature, humidity, chemical resistance, wear, corrosion resistance, oxidation resistance
- *Manufacturability* – Castability, formability, deformation characteristics, weldability, machinability, assembly, chemical processing
- *Certification* – Material specification, process specification, approved supplier list, repair methods, and safety related specification(s).

Additional material properties required for polymers include:

- *Physical properties* – Thermal properties, differential scanning calorimetry, thermos gravimetric analysis, dynamic mechanical analysis
- *Static mechanical properties* – Impact strength, heat deflection temperature
- *Durability and damage tolerance properties* – Continuous-use temperature, creep, exposure to automotive fluids
- Environmental effects – Recyclability
- *Manufacturability* – Cycle time, mixed material joining
- *Certification* – Reparability.

Some companies have developed standardized specification depending on the material type (e.g., steels, aluminum). Most characterization testing is conducted by the material supplier, but fabricators will conduct tests for verification. For critical component tests and newer materials with limited or no other applications, third party independent laboratory testing, and certification will be specified.

The specification will address material sample requirements and the quantity for testing.

3.3.1.5 Material Evaluation, Characterization, and Testing

This stage of qualification is the essence of the process. Material characterization provides results that can be compared for equivalency to previously used materials and provide inputs for computational methods. The material evaluation is often carried out by the material suppliers or OEMs. Due to the expense associated with physical prototyping, the automotive industry relies heavily on computational analysis and subject matter expert evaluations for the initial stages/iterations referred to as digital certification. Figure 6 provides a schematic depicting the digital certification process.

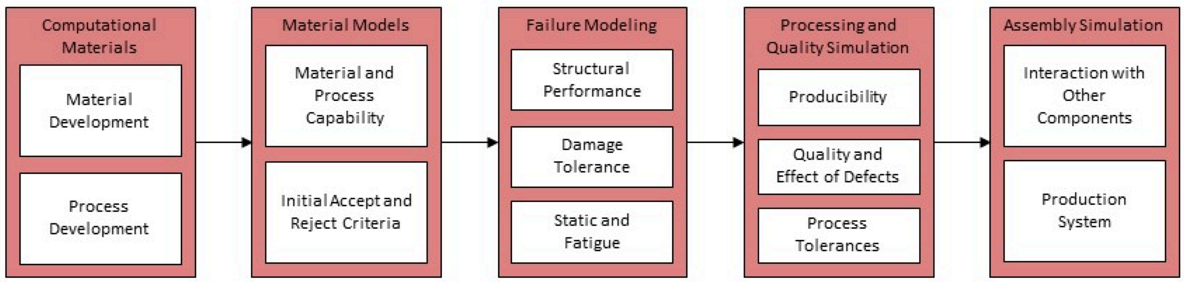

Figure 6. Digital Certification Process Employed within the Automotive Industry

Reliable models to computationally evaluate components made from newer lightweight material substitutes, including advanced aluminum alloys, ultra-high-strength steels, and advanced polymer composites, do not exist yet. Unique models are needed for various materials. For example, fracture modeling and crack propagation behavior are important aspects in the qualification of high- strength materials and subject matter experts claim existing models fail to accurately predict fracture in high strength materials. Simulation results do not compare well with physical test results for plastics and polymer composites. A contributing factor for the lack of comparison is that plastics and composites use different part manufacturing processes than metals. Accurate prediction of part performance requires both the material and associated fabrication process to be correlated/integrated for the models.

The results of this aspect of the qualification process are focused on determining whether the material is acceptable for both the fabrication and the service life functionality of the component.

3.3.1.6 Material Implementation Assessment

The implementation assessment is usually carried out by the organization that developed the material requirements (e.g., Tier-1 supplier, OEM) and an initial assessment is often conducted to support the identification of candidate materials. The assessment is focused on the logistical factors associated with incorporating the new material into the production process. Factors considered are those listed at the beginning of this section excluding those specific to the component performance relative to the design requirements.

3.3.1.7 Leadership Approval

Leadership approval consists of evaluating the results of both the material evaluation and characterization and the implementation assessment, which constitute technical and business factors. The decision process is expected to consider the material and component life cycle that includes design, product engineering, material procurement, tooling, production processes, surface finishing, assembly, marketing, and material disposal/recycling.

Failure for a material to qualify can result in identifying other materials or necessitate material development. However, failure to qualify due to implementation issues may mean efforts should focus on mitigating the limiting factors.

3.3.1.8 Development of Qualification Process for Additive Manufacturing

This section discusses issues created by additive manufacturing for the material evaluation, characterization, and testing activities depicted in Figure 5 and summarized in Section 3.3.1.

Additive manufacturing creates challenges for material qualification processes due to the nature of the process which consists of creating three-dimensional objects by the successive addition of material including applications for plastic, metal, ceramic, and composites. With a wide range of process applications, including both solid phase processing (material remains below melting point) and fusion processes (material reaches melting point temperature), components can be rendered in the real world for just about any shape that can be digitally created. The process makes additive manufacturing fundamentally different from traditional manufacturing methods, which starts with stock raw material and either uses molds and dyes to shape the raw material, or cuts and grinds away unwanted excess material from the stock material to create the desired result.

The advanced manufacturing processes start with a powder or wire feed and form the solid material continuum as the component is formed layer by layer throughout the manufacturing process. Therefore, no initial material continuum exists for which a stock material qualification can be applied as done for traditional processing methods. The material properties and microstructure of the initial powder or wire feed can undergo changes because of the processing/build up. In addition, while material properties on a microscale level may be the same for two completed components, the uniformity/density of the macro structure may be different for components made with different equipment or variations in process conditions.

Qualification is therefore a critical requirement for additively fabricated parts intending to replace qualified structural and machinery components. The method of processing for additive manufacturing makes it difficult or impossible to carry out material evaluation, characterization, and testing activities summarized in Section 3.3.1. Typically, no stock continuum material exists on which to perform baseline material characterization. The ability to apply computational methods for digital certification of processes is limited based on the current understanding of microscale physics for the range of additive manufacturing processes and the state of developed models applicable to computer simulations. Qualification refers to the requirements and verification that are tied to individual parts, machines, materials, and process parameters based on overall risk. It’s put into place to ensure the integrity of an application. As a result, qualification can be achieved by showcasing statistical equivalence based on testing many randomly selected parts across multiple builds and powder lots. Part qualification leverages the individual performance of a single part for a given material regardless of the machine on which it was built. However, for additive manufacturing, the basic material properties/characteristics as well as the uniformity of these properties can be highly dependent on the processing history of the component during a buildup.

Product certification and accreditation guidelines are in place for parts manufactured conventionally (e.g., casting, forging), whereas additive manufacturing components require a unique set of rules and certification schemes. With only a handful of standards focusing on inspection and certification for additive manufacturing products, fast adaptation to qualifying additive manufacturing parts depends on gathering evidence of processing history, process outcomes, and feedstock evaluation, amongst other sensor and manufacturing data. Revised approaches must be developed to assure and demonstrate that additive manufacturing components adhere to the same qualification and certification requirements as their conventional counterparts. Numerous methods could be conceived for achieving qualification and several approaches have been implemented for individual applications. An approach that appears to be emerging for additive manufacturing consists of defining three high-level phases for a qualification methodology that consist of installation, operational, and performance qualification phases.

The installation phase focuses on the critical aspects of the process equipment and ancillary system. The process equipment is evaluated based on factory acceptance testing (FAT) for gathering data on process equipment performance and site acceptance testing (SAT) after process equipment has been setup at a manufacturing site. Material build ups are obtained from FAT and SAT for specified range of operating conditions and then characterized and evaluated for material performance. The objective is to demonstrate final product acceptance as well as equivalency between FAT and SAT buildups. While custom buildups/test jobs can be specified, the installation phase lends itself to formulating both standardized buildups and corresponding characterization and performance evaluations for future equipment qualification.

The operational phase is focused on process controls required to maintain stable/consistent material performance and demonstrate that specified material requirements can meet acceptance criteria. Test jobs are built with static or dynamic coupons to demonstrate acceptance and reproducibility as well as providing the baseline for application design. The test jobs are defined/designed focusing on demonstrating the desired component/product requirements will be satisfied. During this phase, component design/dimensions and process conditions can be varied to obtain data for evaluating/establishing trends in performance relative to design and process parameters. The result of such testing provides feedback to the design process and could be used to create a performance data base for a fabricator.

The performance phase focuses on a finalized/correlated part-specific design, process parameters, job layout/configuration, and post processing procedures that produce the desired product with the desired consistency in performance. First article evaluations are utilized to meet certification requirements. For the automotive industry, the volume of production allows the approach to be used for determining process capabilities and implementing strategies for statistical process control to achieve a greater degree of robustness and optimization.

The approach is intended to initially qualify the process/equipment to assure the desired material properties are obtained. The approach allows for characterization data to be fed back to the design process. The strategy is to reduce repeated testing of individual components, which can result in an iterative design process, and shorten the qualification timeline. The application of results for each qualification phase can be thought as becoming narrower and narrower with progression from installation through performance qualification. The installation phase provides a qualification of equipment that can be applied to a range of applications and for parts that may not initially be conceived at the time this qualification phase is conducted. Data obtained from the qualification phases may also be valuable in developing a digital approach to certification with time. For specific components or modification to a component only the performance phase would need to be repeated with previous installation and operational qualifications being applicable.

3.3.2 Recommendations Identified from Review of Automotive Industry

Recommendations for faster instruction of new materials based on the evaluation of the automotive industry qualification process and needs in the automotive industry are summarized below based on those identified by CAR [13].

3.3.2.1 Collaborative Efforts

Standardization of testing requirements based on material types to aid in developing a streamlined material qualification process. The standardization can consider material production methods, fabrication techniques, and material applications. This would allow a standardized process but can streamline process based on production and application factors (i.e., only execute the applicable portion of the standard). Future efforts to expand the application of a material need only address those portions of the standard not previously addressed. Standardization in testing protocols that improve the understanding of material behavior related to failure modes such as corrosion, fatigue, wear, creep, and crack propagation is also needed. The standardization of test protocols for these factors would improve the understanding and interpretation of test results needed for qualification to be achieved.

In addition to standardization of the process, the establishment of a centralized database of material results obtained via the standardized methods could optimize material selections and provide an incremental process for qualification of a material to expanded applications. The centralized database also could provide a method by which additional suppliers could qualify material production aiding in reducing supply chain risks.

Material suppliers and parts manufacturers/suppliers should consider cost-sharing for development and qualification of new materials and associated fabrication techniques. CARS assessment identified industry coordination was essential to help accelerate innovation and associated material qualification.

Industry collaboration would allow for the communication (and possible funding) of innovation challenges and needs. If end user anticipated needs are communicated earlier, than development efforts can be focused on future targets and potential solutions introduced for evaluation and use closer to when the market need exists.

3.3.2.2 Increased Communication, Education, and Training of the Work Force and Within the Industry

Better education and socializing of the qualification process between engineering, manufacturing, material suppliers, and procurement workers would improve communication of needs, requirements, and assessments associated with the qualification process. Improvement in education and socializing of the process aids in supporting the standardization of the process discussed above.

Improved education for engineering and overall workforce to be capable of defining and executing qualification plans as well as developing material models and applications was identified as an industry need. Continuous education programs and workshops on new material technologies can improve general understanding of the qualification process, may reduce the intimidation factor associated with using new materials, and could boost enthusiasm for identifying and employing new materials.

Showcasing applications of new materials using industry and government funding can provide a reference for engineers when considering the application of alternative materials to improve product performance (including cost of production, achieving weight limit targets).

3.3.2.3 Simulation Tool Advancement

Design and testing of materials are highly dependent on experimentation and characterization testing, which can be time consuming, iterative, and expensive. The potential exists to replace a portion of this testing, especially initial iterations, with computational tools. However, current simulation capabilities are found/considered to be deficient in functionality and accuracy. Accuracy in predicting the material behavior from computer simulations could greatly reduce both the cost and time duration associated with material qualification. Industry and government funding to develop, verify, and validate multi-phenomenon modeling tools for material performance is recommended. The objective of development efforts would be to ultimately integrate the multi-phenomenon models with the design analysis tools. Such an effort would include identifying the material characterization/assessments required to establish model inputs for predicting material performance.

3.3.2.4 Advanced Forming and Joining Technologies

Introduction of new materials within the automotive industry is highly dependent on advancements in forming technologies. Short cycle times (>1 min per part) are required due to the high production volumes. Advancements in forming technologies such as additive manufacturing to reduce cycle times greatly influences that ability/rate at which new materials can be accepted for mass production operations. In addition, mixed-material production operations require the joining of dissimilar materials. Industry and government funding to advance forming and mechanical joining technologies increases capability of manufacturing operations to select from a wider range of new materials. Such industry and government funding should include increasing the understanding for the basic physics associated with joining dissimilar materials using techniques such as solid phase processing, which also benefit the development of simulation tools discussed above.

To accompany advancements in forming and joinery technologies, efforts should be funded for improving non-destructive examination techniques to assess the integrity of manufactured components using newer materials especially plastics and polymer composites. With respect to materials, qualification and applications of new materials becomes less complex/simpler if the integrity of material/component can be verified after production and while in service compared to the predictive nature of relying only on the design process and control/verification of the fabrication process.

3.4 Navy

Limited outreach as part of this work scope occur to the U.S. Navy community, with a presentation delivered by Dr. Charles Fischer on June 22, 2023, at PNNL [14]. The title of the presentation was “Insertion of ICME into Process Simulation for Shipbuilding: Summary of Presentation.”

The title of Fisher’s presentation indicates that the primary subject of discussion for this presentation is the application of ICME for the purpose of improving shipbuilding processes, but the scope of his talk is considerably wider than this one topic. In actuality, the subject of Fisher’s presentation concerns itself with the use of ICME methods to decrease the time and cost of material insertion for various purposes within the U.S. Navy, not only shipbuilding.

Fisher discusses numerous naval applications for ICME approaches, most of which are associated with either welding, metal additive manufacturing, or alloy design. The naval applications of additive manufacturing innovations, as Fisher explains, is considerable. Additive manufacturing provides considerable geometric and design freedom for the fabrication of metallic components but, as Fisher points out, can and is being used for the purpose of replicating components, many of which either cannot be directly replaced or experience undesirable lead times for replacement. Therefore, if it is possible to verify and validate the serviceability of additively manufactured components, replacing these components will become more cost efficient, and the supply chains designed to replace them will become more agile.

Fisher asserts that the primary challenge to achieving this vision is access to useful data. By leveraging existing data from experimentation and modeling, much of the workload for exploratory investigation is removed. For example, CALPHAD databases can significantly reduce the time required for alloy design by predicting the stable phases for different sets of compositions and conditions. Similarly, analysis through multiphysics simulations can provide volumes of data that are burdensome or unfeasible to produce experimentally, let alone repeat. For this reason, the Naval Surface Warfare Center, Carderock Division, and U.S. Naval Research Laboratory have been aiming to produce an “Agile Manufacturing ICME Toolkit”. The stated goals of this program were to 1) increase technical expertise with ICME tools, 2) improve ICME-based infrastructure, and 3) significantly decrease the time and cost for inserting materials and processes. This toolkit would also benefit from the existing HyperThought data management platform. Fisher describes several projects that are in progress in conjunction with this effort. These include an effort to develop a stainless steel whose welded microstructure has high strength and high toughness with low magnetic permeability.

An overview of historical attempts to develop materials information databases were provided and some perspectives were offered on what lead them to be successful, or not successful. He discusses four efforts within the Navy since 1985 that have attempted in some capacity to collect materials data in this way. All of these efforts failed in some way, typically due to loss of funding or scope creep within the programs that maintained them. Fisher argues, essentially, that the HyperThought data management platform, and “Internet of Things” approach, will be more resilient to these types of issues due to its interconnectivity with other sources and repositories of information.

Fisher also notes several times that companies and professional societies, such as ANSYS-GRANTA, ASM, and Citrine, have excellent access to data that have persisted for decades and have, in some cases he mentions, preserved information from these different attempts to create databases. There is a need for connectivity and accessibility of this data, but the way how institutions maintain the data and platforms, influence the resilience of these platforms and therefor the accessibility of the data. The American Society of Materials is the preeminent materials information society. Access to this kind of information impacts the bottom line for ANSYS and Citrine. Stating that the issue is "long-term funding" or "scope" kind of loses the forest for the trees.

Fisher also discussed several categories of materials information: performance, production, processing, and research data. The distinction between each of these subcategories is the purpose for creating and the availability of the information. Performance data, according to Fisher, is generated in numerous iterations to ensure statistical significance. Materials research data, however, typically comes in a wide variety of formats and in each case is only generated on time. Meanwhile, material production data, which is associated with the physical act of fabrication of components, can be rigorously collected, but is often considered proprietary information and therefore is not typically easy to access. Finally, materials processing data relates to investigations of how processing can impact the properties and performance of the final component. Therefore, the data collected is usually sparser. In each case, Fisher discusses several organizations that store these types of information.

The last segment of Fisher’s presentation discusses attempts to establish digital twin prototypes across the U.S. Navy related to shipbuilding. Fisher points out that the processing for designing ship hulls and predicting their deterioration over time typically starts with the assumption that the formed hull of the ship is stress-free material, but this is not correct. Residual stresses created during fabrication cause detrimental effects that significantly decrease the service lifetime of the hull. Fisher notes that a digital twin approach in which simulations track the impact of the actual service may be able to overcome this problem. He provides an example in which a digital twin of a four-pass weld simulated with SYSWELD software was able to predict comparable strain states to those measured at the CHESS Synchrotron. Fisher foresees a future in which these types of integrated sources of information also will be able to provide estimations of uncertainty for predictions from materials models, using the example of how the yield stress of an alloy may change with temperature depending on its composition.

In summary, Fisher’s presentation discussed what appears to be an expanding program to manage materials information in such a way as to make it accessible for ICME related efforts within the Navy, primarily with a focus on additive manufacturing and alloy design of naval components. Fisher believes that making material data available through an “internet of things” approach will enable to Navy to qualify and deploy new materials and processes for deployment more rapidly.

A recommendation that the nuclear energy community can learn from this presentation amongst others are the material databases should address 1) performance, 2) production, 3) processing, and 4) research. Also, the maintenance of these databases is crucial so that the information can be available for generations and can be used for validation. However, it was clear that these databases are expensive to maintain and should be cross-cutting to be fully sustainable.

4.0 Nuclear Energy Qualification Processes

Nuclear applications and component qualification are dependent on the licensing body; for example, a U.S. Nuclear Regulatory Commission (NRC) public site or a DOE site. It is important to fully understand NRC qualification process and expectations.

4.1 Current Standards for Materials and Component Qualification and the Regulatory Process

The following description is a summary (prepared by David Gandy) of presentations provided during the workshop from multiple presenters:

The NRC current provides two distinct avenues for qualification of new materials and process:

- A utility/user can work with ASME to submit a Data Package and Code Case. Once the Code Case is approved, the NRC can adopt it under 50.55a and add additional conditions where it is warranted.
- A utility/user can develop a Topical Report for a material/process and submit it directly to the NRC for approval.

ASME BPV-II provides a standardized approach for approval of a new material under Mandatory Appendix 5—Guidelines on the Approval of New Materials under ASME BPVC. The approach can be used today for qualification of new materials in product forms of castings, forgings, wrought alloys, and powder metallurgy-hot isostatic press alloys.

ASME BPV-III is currently working to incorporate three AMM processes via a Task Group on Advanced Manufacturing. These include:

- Powder Metallurgy-Hot Isostatic Pressing (PM-HIP)
- Directed Energy Deposition—Gas Metal Arc Additive Manufacturing (DED-GMAAW)
- Laser Powder Bed Fusion Additive Manufacturing (LPBF-AM)

ASME BPV-III Div. 5 provides the rules that govern components and materials used in high temperature reactors. Required testing for qualification on a new material is provided in Div. 5, Appendix HBB-Y – Guidelines for Design Data Needs for New Materials. Div. 5 is also very interested in new approaches for qualification of new alloys which can be used in high temperature service. It was also noted that the NRC recently published a draft regulatory guideline for Section III, Div. 5: https://www.nrc.gov/docs/ML2109/ML21091A276.pdf [nrc.gov]

In addition to the above AMMs, the NRC is also focused on providing guidance for the following applications:

- Electron Beam Welding
- Cold Spray

ASME recently formed a Working Group on Non-metallic Materials to assess AM and develop new standards and guidance documents as they pertain to non-metallics.

ASTM F42 on Additive Manufacturing is focused on developing assessment methodologies for AM that are based on defect tolerant approaches wherein inspection of a component is used to limit the size of a defect. A number of standards are currently being developed by ASTM that focus on various stages of the AM process including feedstocks, testing, NDT/process monitoring.

Suggested pathways for qualification of new alloys are described below:

- To gain experience with the AM process (or other new AMMs), it was suggested that DOE works with utilities to insert components into "pressure retaining" operation within secondary systems. Additionally, experience could also be gained via fossil, HRSG, or other systems.
- AM components will be more difficult to inspect than convention product forms: forgings, wrought, and PM-HIP. They may be easier to inspect than castings, however. It was suggested that industry focus on developing new inspection methods such as Computer-Aided Tomography to address thicker section AM products. It was also suggested that an Acceptance Guideline for non-destructive evaluation (NDE) be developed.
- ASME Div. 5 already provides an avenue to qualify materials wherein materials can be placed into service with test data that may not span the entire expected life of the component. In this approach, a user will submit the data out to a certain number of hours of operation, put a component in service using the material, and then continue to develop data in parallel with the service operation. This approach will allow a user to gain service experience while maintaining safe operation within the bounds of the current test data and ASME acceptance of that material.

4.2 Nuclear Fuel Qualification

In March 2022, NRC published public guidance for fuel qualification for advanced reactors (NUREG-2246). This guidance includes the Regulatory Basis and Guidance References and Fuel Qualification Assessment Framework [15].

Additionally, NUREG-0800 [16] provides a Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: Light Water Reactor (LWR) Edition

- Section 4.2, Revision 3, "Fuel System Design," lists acceptance criteria that the NRC staff considers in a licensing review for a LWR fuel system.
- Section 4.3: fuel assemblies, control systems, and reactor core.
- Section 4.4: thermal margins, corrosion products (crud), and hydraulic loads under Standard Review Plan Section 4.4.
- Section 6.3: design bases for the emergency core cooling system, including General Design Criteria and emergency core cooling system acceptance criteria.
- Chapter 15: postulated fuel failures resulting from overheating of cladding, overheating of fuel pellets, excessive fuel enthalpy, pellet/cladding interaction, and bursting.

The methodology proposed by Oelrich [17] for the accelerated fuel qualification process, as shown in Figure 7, integrates data across technical platforms to confirm fuel design compliance with requirements. Success hinges on producing fuel test specimens that match conversion requirements and are commercially viable, representing the fabrication process accurately.

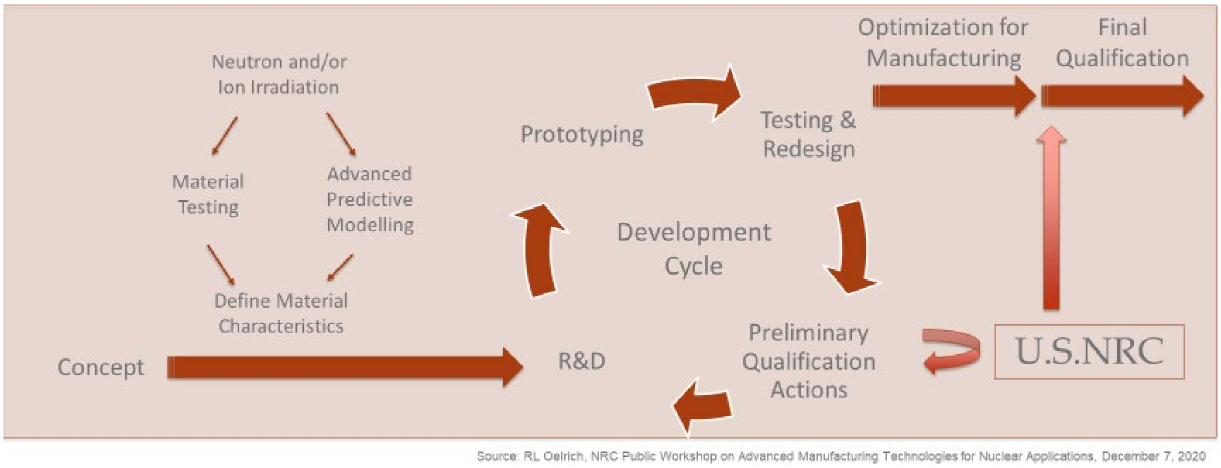

Figure 7. Accelerated Framework for Nuclear Fuel Qualification [17]

After submitting Qualification Report, ongoing interaction with the NRC is expected for responding to information requests. Additionally, NUREG-2246 has considerable guidance on accelerated fuel qualification processes as shown in Figure 8.

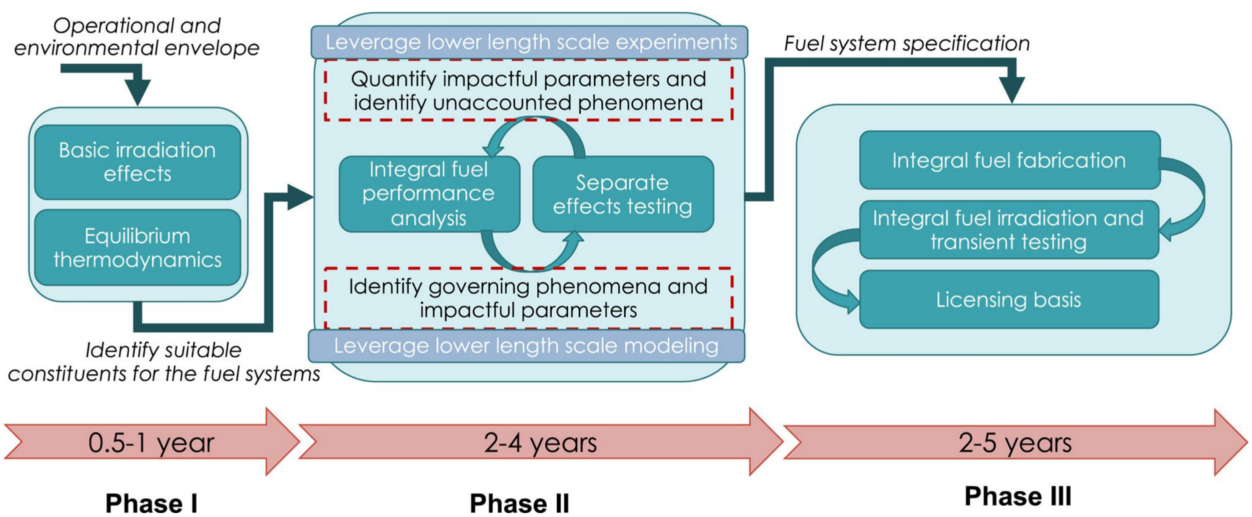

Figure 8. Guidance on Accelerated Fuel Qualification Processes from NUREG-2246 [15]

4.3 Nuclear Materials and Component Qualification Process

The growing demand for clean and sustainable electricity, coupled with the need to reduce greenhouse gas emissions, has renewed interest in nuclear power as a viable energy source. However, the development of new nuclear reactors, especially advanced reactor concepts, presents several challenges, particularly in the realm of materials and processes [18, 19, 20]. The following areas are critical for successful development of fuel for qualification and deployment of new materials and processes:

- *Materials and Process Development* [18, 21]– Advanced reactor designs often operate at higher temperatures, pressures, and radiation levels than traditional reactors. This necessitates the development of new materials that can withstand these extreme conditions while maintaining structural integrity and safety. Materials research is crucial for ensuring the long-term viability and safety of these reactors. The materials used in nuclear reactors are exposed to intense radiation which can cause structural changes and degradation in material properties over time. Research is needed to create materials that are more resistant to irradiation, which will extend the operational life of reactor components and reduce maintenance costs. Nuclear reactor materials must have excellent mechanical properties to withstand the stresses and strains they experience during operation. Additionally, they should be highly corrosion-resistant to ensure the long-term integrity of the reactor. Developing materials with improved mechanical and corrosion properties is essential.

- *Cost Considerations* – While advanced materials may offer improved performance, they must also be cost-effective. Balancing performance, safety, and cost is a significant challenge in the development and adoption of new materials and processes for nuclear reactors.
- *Qualification and Testing* – Before these new materials and processes can be used in nuclear reactors, they must undergo rigorous qualification and testing procedures. This includes evaluating their performance under simulated reactor conditions to ensure safety and reliability. Establishing these qualification protocols is a critical step in accelerating the adoption of new materials and processes. For the regulatory approval process the International Atomic Energy Agency (IAEA) provides guidance on the selection of materials for use in nuclear facilities, taking into consideration factors such as radiation resistance, corrosion resistance, and mechanical properties. Recommendations are often provided in documents and technical publications. Nuclear reactors are subject to strict regulatory oversight to ensure safety. Any new materials or processes must meet these regulatory requirements. Collaboration between industry, research institutions, and regulatory bodies is essential to define the standards and procedures necessary for the approval of advanced materials and processes.
- *Quality Assurance* – NRC and IAEA standards include requirements for quality assurance and quality control in nuclear applications. These standards emphasize the importance of maintaining high-quality standards in the design, construction, and operation of nuclear facilities, which includes materials and processes.
- *Safety Evaluation* – The NRC requires licensees to demonstrate that any new materials or processes do not compromise the safety of nuclear facilities. This includes evaluating the impact on reactor safety, structural integrity, radiation protection, and environmental safety. The IAEA publishes a series of safety standards that cover various aspects of nuclear safety, including those related to materials and processes. These standards offer recommendations and guidance for ensuring the safety of nuclear facilities and operations.

Figure 9 describes the critical steps that capture stages 1–5 for qualification of nuclear materials components and parts.

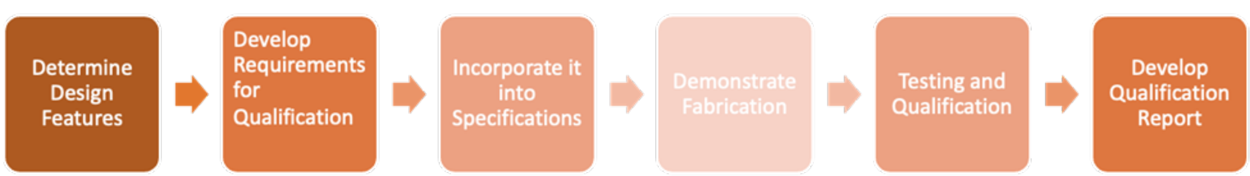

Figure 9. Critical Steps Needed to Qualify New Materials

1. Radiation Protection: The IAEA offers guidance on radiation protection, including the use of shielding materials and personal protective equipment to minimize radiation exposure to workers and the public.
2. Waste Management: Guidelines for the management and disposal of radioactive waste, which may include materials used in nuclear applications, are provided by the IAEA. Proper handling and disposal of nuclear materials are critical for environmental and public safety.
3. Transportation Safety: The IAEA has set standards and recommendations for the safe transportation of nuclear materials, including packaging requirements and transportation procedures [22].
4. Emergency Preparedness and Response: The IAEA provides guidance on emergency preparedness and response for nuclear and radiological incidents, which can involve materials used in nuclear applications.
5. Security: While primarily focused on safety, the IAEA also offers guidance on nuclear security, including the protection of nuclear materials against theft, sabotage, and unauthorized access.
6. Public Perception: The acceptance of nuclear power, including advanced reactor concepts, depends on public perception of safety and environmental impact. Demonstrating the safety and reliability of new materials and processes is crucial to gaining public trust.

4.4 International Qualification Efforts

DOE-NE has nominated two representatives (Mark Messner (Argonne National Laboratory) and Isabella van Rooyen (Pacific Northwest National Laboratory [PNNL]) on the Generation IV International Forum (GIF) Advanced Manufacturing Materials Engineering (AMME) Task Force (TF). An interim AMME TF was formed to investigate whether collaborative R&D could be used to enable such advances to reduce the time to deployment of Gen IV advanced reactor systems [23].

The initial primary aim of this TF was to undertake a feasibility assessment for a GIF crosscutting activity in AMME by.

- Assessing the interest of both research institutions and nuclear companies within GIF countries in a crosscutting activity in GIF supporting advanced materials and manufacturing solutions to a High Technology Readiness Level.
- Developing and applying a flexible and accessible approach with clearly identified mechanisms for directly involving leading and advanced nuclear reactor companies from GIF countries.
- Developing a priority list of R&D areas and initiatives.
- Delivering a white paper discussing the identifying merits and difficulties of such cooperation on this topic and identifying potential ways forward.

The activities of this AMME TF are summarized in Figure 10 and the overall recommendation of the first 2020 workshop was that collaborative activities should be actively encouraged in three main areas:

- Qualification
  - Codes and standards development
  - New qualification modalities (e.g., real time process qualification)
  - An increased need for component testing
- Demonstration and deployment
  - Materials property database structure and content
  - Specific component testing
  - Round robin activities (e.g., generic intermediate heat exchanger) component
- Design and modelling
  - Collect experience and experimental data (feed data-driven methods).
  - Share practices for inspection and design optimization.
  - Resolve modelling and simulation benchmark problems.

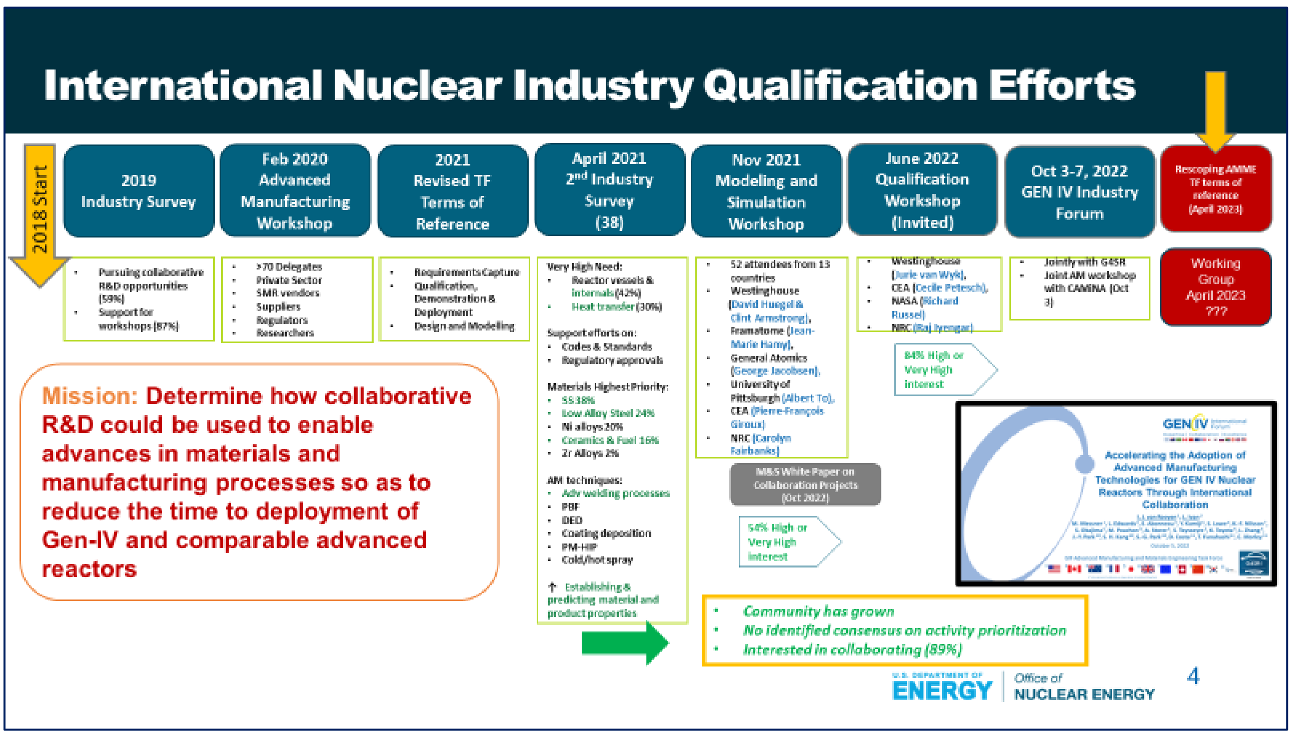

Figure 10. AMME TF GIF Activities for Advanced Manufacturing Processes to be Adopted by Industry

To enable the GIF-AMME-TF to act on the high impact actions identified during subsequent workshops held in 2021, potential collaborative projects were identified, and key activities are proposed. These are [24]:

- Demonstrate machine learning
  - Identify existing datasets for use in training/validating models

    - Demonstrate machine learning and to correlate processing history to material structure
- Identify and promote common and/or open-source software
    - Develop and disseminate benchmark problems for applying models to accelerate material qualification
    - Identify and review past modeling efforts
    - Develop new benchmark problems
- Identify key ranges of operating parameters for models to target (temperature, stress, fluence, etc.).

The AMME-TF held its most recent, in person, workshop on October 3, 2022, as part of the 4th International Conference on Generation IV and Small Reactors and the GIF Industry Forum 2022. Consequently, this workshop was jointly held by the GIF AMME-TF and the Canadian Advanced Manufacturing in Nuclear Alliance. The focus of the workshop, which had approximately 40 attendees, was to explore paths to qualifying advanced manufacturing components for use in Gen IV reactors. The morning session of the in-person workshop consisted of plenary talks by four speakers focusing on qualification pathways for advanced manufactured components covering the same ground as in the June virtual workshop. This was followed by a panel discussion.

Based on this successful outcome of all the activities of the AMME TF, a new working group has been motivated to enable to act on these suggestions. A new term of reference is being developed for final approval by the GIF Policy group chair during October 2023, after on approval, specific projects by the participating countries can be implemented.

In addition to the GIF activities, interaction and interface meetings with IAEA and the United Kingdom Advanced Materials Research Center occurred as well as the material development community during the SMINS-6 international workshop [25-27].

4.5 National Efforts

This section provides some insight of activities nationally, but it is not fully comprehensive for all the domains. Nearly every industry sector is currently working on some level of activity to either qualify new advanced manufacturing components and/or replace obsolete parts with AM products and therefore aiming to accelerate the qualification processes. In Section 4.5.1, an overview will be provided of qualification process evaluation that was initiated under the AMM program in 2021, which was later integrated as one of the three programs to form the AMMT program.

4.5.1 AMM-GAIN-Electric Power Research Institute (EPRI)-National Energy Institute (NEI) Workshops

4.5.1.1 August 24–25, 2021 Workshop

The following write up, was prepared as part of the AMM programs September 2021 newsletter, although it was not issued due to the integration of this program within AMMT. However, this information collected during this workshop was beneficial for the subsequent activities under the AMMT program.

The AMM-GAIN-EPRI-NEI Qualification Virtual Workshop was held August 24–25, 2021, in support of the AMM program of DOE-NE led by Dirk Cairns Gallimore (DOE-NE AMM federal Program Manager) and Isabella van Rooyen (National Technical Director).

The purpose of the workshop was to discuss development of an integrated approach to the AMM qualification process for materials, components, and reactor systems. The objectives were:

- Understand current qualification processes for nuclear applications.
- Identify nuclear industry needs in product, properties, and performance requirements.
- Identify supply chain needs and supply qualification gaps.

From the initial draft of the purpose statement to securing the last presenter, the workshop is the culmination of a 6-month planning effort. As shown below, the planning team was a multi-level, diverse group that contributed to varying areas of expertise and insight. [Lori Braase (GAIN program manager); Everett Redmond (NEI/GAIN); Andrew Sowder (EPRI/GAIN); Teresa Krynicki (GAIN admin); Holly Powell (GAIN project coordinator); Donna Kemp-Spangler (GAIN communications, Dirk Cairns-Gallimore (DOE-NE federal program manager); Isabella van Rooyen (INL/AMM National Technical Director), Cindy Carroll (INL/AMM admin); Marc Albert (EPRI); David Gandy (EPRI); John Carpenter (LANL); Jason Christensen (INL/AMM Regulatory); Ryan deHoff (ORNL/TCR); Ram Devanathan (PNNL); Ed Herderick (The Ohio State University [OSU]); Hillary Lane (NEI); Kun Mo (ANL)]

The workshop opened with presentations from Lori Braase (GAIN/INL), Dirk Cairns Gallimore (DOE-NE AMM Federal Program Manager) and Isabella van Rooyen (National Technical Director AMM program/INL) to set the stage for the interactions and needs. Figure 11 describes schematically the envisioned interactions to reach an informed and executable roadmap to prioritize, improve, and accelerate qualification processes.

The rest of the first day of the workshop was dedicated to presentations and discussion sessions on the current status quo on using standards for qualification and regulatory processes (moderator David Gandy, EPRI), and the role of digital threads and modeling in qualification (moderators Ram Devanathan, PNNL, and Ed Herderick, Oregon State University).

The second day started with overviews from Everett Redmond (NEI/GAIN) and Andrew Sowder (EPRI/GAIN) followed by sessions on supply-chain opportunities (Moderator Marc Albert, EPRI); Lessons learned (Moderator Ed Herderick, OSU), and Nuclear Industry feedback (Moderator Hilary Lane, NEI). The workshop was closed for an open brainstorming session to gain insight on the approach and topics for the second workshop to gain further industry participation (moderated by Isabella van Rooyen, AMM/INL), Lori Braase (GAIN/INL), and Dirk Cairns Gallimore (DOE-NE).

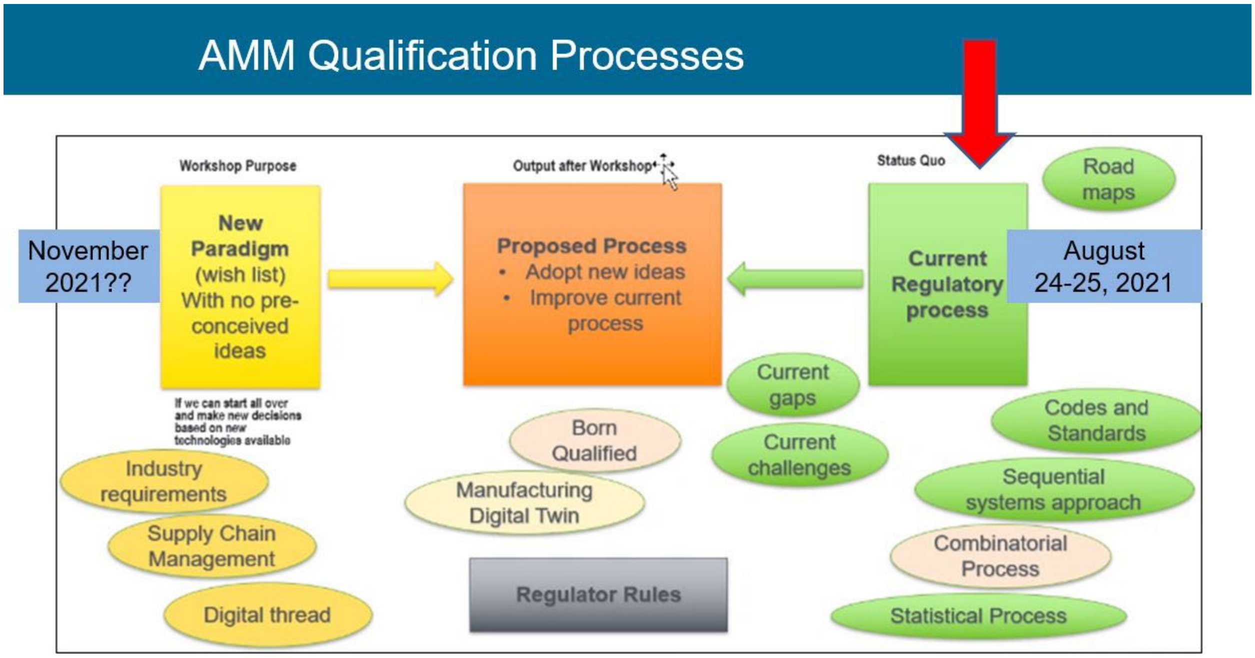

Figure 11. Schematic Presentation of the Envisioned Interactions to Reach an Informed and Executable Roadmap to Prioritize, Improve, and Accelerate Qualification Processes [28]

Workshop session summaries are captured below:

"Current Standards for Materials and Component Qualification, and the Regulatory Process"

The summary of work presented during this workshop is already described in section 4.1 of this report.

"Digital Threads and Modeling (Databases of Properties)"

The session on digital threads and modeling highlighted the essential role of data-driven approaches to reduce variability, assure reliability, and accelerate adoption of components produced by AM. The envisioned digital platform will connect design, real-time sensor output, modeling and simulation, metrology, material testing, microstructural data, scaled testing in simulated environments, machine learning, and instrument control. An enormous amount of data would need to be collected from sources including real-time process monitoring, calibration, and postprocessing. These data will need to be collected, curated, and made available in a central database. Standardized data models and data handling need to be put in place across the entire lifecycle, from design through manufacturing and service until component retirement. Traceability and pedigree of the data along this chain will be critical to adoption of AM. The data must be recorded and reported with relevant metadata to be of value to the community.

Given that data are considered an asset by participating organizations and that much of the available data exists in silos, there must be a greater willingness in the community to share data. Such data sharing is increasingly common in the aerospace community, and it should be adopted by the nuclear energy community as a best practice. The DOE national laboratories have a critical role in collecting, curating, and disseminating data in a manner that complies with export-control requirements.

“Supply Chain Opportunities and Challenges”

Organizations at varying levels of the supply chain are considering implementation of AMMs in their designs and products. This decision would be driven by economics, alternative supply chains, and ability (or lack thereof) to fully realize the design and supply benefits of AMMs. Precursors to reduce risk in implementation must be addressed to accelerate deployment, including codes and standards (or equivalent data), knowledge through the entire supply chain, and demonstrations. The primary challenges discussed in relation to AMM deployment include the need for NDE techniques to characterize unique AMMs and rapid improvement of some technologies. Collaboration and demonstrations to gain operating experience and lower risk of implementation is key in accelerating AMM deployment.

The following opportunities were identified:

- Collaboration between designers and purchasers with suppliers and manufacturers could ensure a robust supply chain.
- Proposed qualification approaches include “bracketed or bounding” process parameters like the proposed Section IX Code Case 3020.
- Installing components in test loops and operation with sensors for monitoring can provide real-time evaluation of components providing operation experience and confidence in deployment and operation lifetimes.

“Lessons Learned – Success Stories – Accomplishments”

Key points from this session were:

- Define the effects of defects to accelerate introduction of components, identify critical length scales and geometries of defects that affect relevant properties, and tie to the right inspection methods to ensure high probability of defect detection in parts that will be fielded.
- Data-driven approaches are key to reducing variability and assuring reliability. This includes real-time data collection, data management, and machine learning and analysis.

David Huegel from Westinghouse shared the following lessons learned:

- “While we had a number of hurdles to clear along the way, I think overall we had the right approach. We properly vetted potential AM vendors, we informed the NRC continually, we selected an appropriate part for demonstrating the process, etc.”

David expanded further on other key areas that can help other developers:

- In vetting vendors, the focus needs to be on the quality system, controls, and documentation and that there are “… AM vendors who in general are not knowledgeable as to what would be required for nuclear applications.”
- The importance of including a utility earlier in the manufacturing process will substantially decrease the time to get the AM product tested in a reactor.

“Nuclear Industry / End User Feedback and AMM Needs”

The following takeaways were identified:

- Advanced reactor developers are interested in pursuing a wide range of AMM applications and demonstrations, but the long-term benefit must be realized.
- The existing commercial fleet has seen two successful first-of-a-kind deployments in the fuel assembly space. More related deployments are in the pipeline (i.e., debris filters, tie plates).
- This question is posed to utilities: Can we pursue AMM deployments on the secondary side (i.e., pumps, valves, etc.)?
- Utilities continue to rely upon cold spray as a reliable mitigation strategy.
- AMM will inevitably evolve faster than the regulatory framework making technology-agnostic guidance vital.

"AMM Qualification Workshop – Part II: Brainstorming Sessions – November 4, 2021"

Main feedback received:

- Participants found the workshop valuable.
- Follow-up workshops on this topic need to continue sooner rather than later.
- A face-to-face meeting for breakout sessions for futuristic views are preferred.

Conclusion:

The workshop was well-attended by 130 participants from all over the world. Developers, suppliers, regulators, and researchers were all represented. If you would like to download the full presentations, please visit https://gain.inl.gov/SitePages/Workshops.aspx.

4.5.1.2 November 2021 Workshop

The GAIN-EPRI-NEI Advanced Materials and Manufacturing Technologies (AMMT) virtual workshop (99 total attendees) was held on November 4, 2021 (Figure 12 shows the envisaged impact of the workshop), to engage the nuclear industry in discussions on advanced manufacturing codes, standards, demonstrations, and advanced techniques to accelerate commercialization.

This was a follow-on event from the successful August 24–25, 2021, GAIN-EPRI-NEI AMM Qualification Workshop, which identified key industry and stakeholder challenges and needs.

The AMMT Workshop accomplished their objectives to:

- Understand applications of machine learning and digital twin tools through collaboration with codes and standards' entities
- Define "uncertainty," including measurements for uncertainty and how it can be minimized
- Identify cross-cutting demonstration or benchmarking products or projects that are suitable for industry.

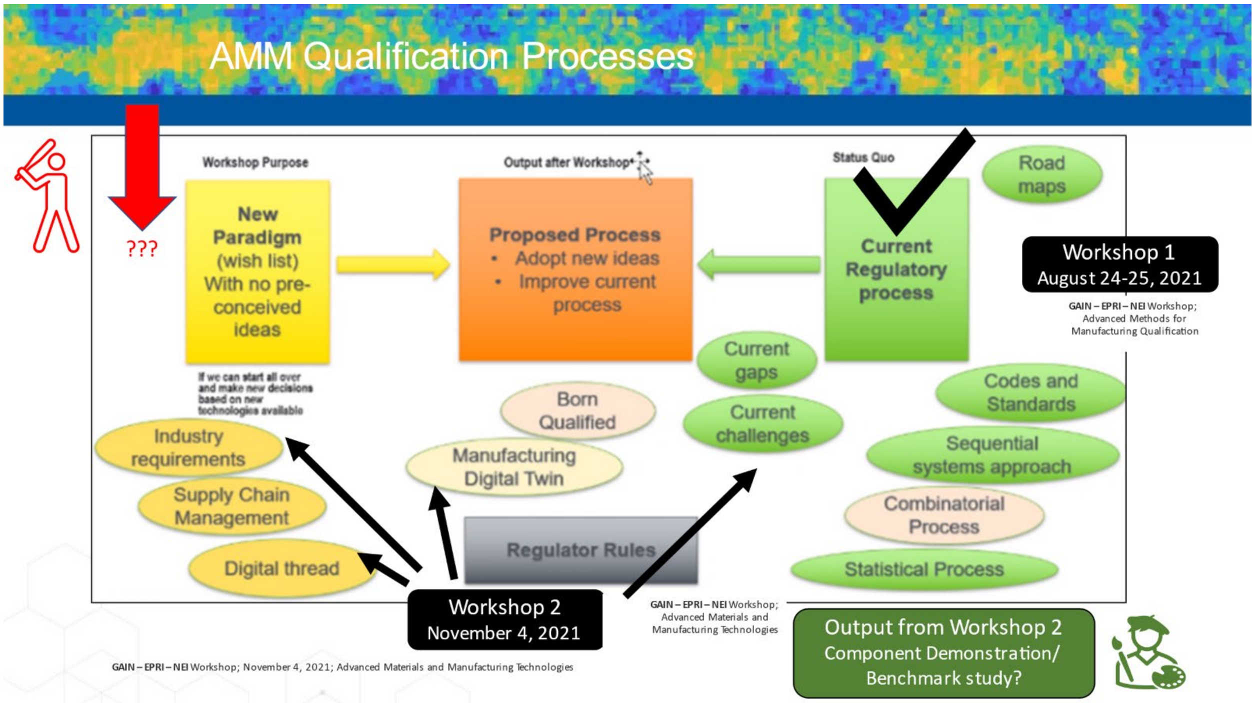

Figure 12. AMM Workshop 2 Flow Chart

Dr Ram Devanathan (PNNL) was moderator of the first group discussion on activities to support machine learning and digital twins. Josh Kaizer from NRC delivered a presentation titled "ASME VVUQ – Activities to Support Machine Learning and Digital Twins." The speaker provided a historical view of numerical modeling. He then described the work of the ASME Verification, Validation, and Uncertainty Quantification (VVUQ) in the Computational Modeling and Simulation Standards Committee in fostering the development of standards and procedures for assessing and quantifying the accuracy and credibility of computational models and simulations. The speaker presented the timeline of ASME VVUQ subcommittees culminating in VVUQ70. This subcommittee develops standards and procedures for machine learning algorithms applied to mechanistic and process modeling. The speaker discussed the importance of defining consistent terminology. Explainability of the machine learning model is not a focus at this stage.

The group discussion that followed addressed the following areas covered by the talk:

- One should not give up on machine learning because it appears in some instances to be a black box. VVUQ activities can serve to increase the credibility and acceptance of machine learning even in traditional industries like the nuclear industry.
- An excessive emphasis on interpretability may detract from adoption of useful machine learning models. Such models can be verified using high fidelity data. Placing excessive emphasis on interpretability will prevent us from taking advantage of useful models.
- To increase adoption of machine learning and digital twins there is a role for a centralized database not just for codes and standards but also terminology and best practices.
- It is possible to use model-based engineering to ensure consistency, but the details could not be fleshed out in the limited time available for the discussion.

Dr Curtis Smith (INL) was moderator of the second group discussion on uncertainty quantification. The technical presentation by Josh Kaizer summarized the current status of the ASME VVUQ activities, focusing on formalizing this technical area. Discussion for the rationale in the name change of the V&V Committee (to VVUQ) was discussed. It was noted that the standard on The Role of Uncertainty Quantification in Verification and Validation of Computational Solid Mechanics Models has been approved by the Standards Committee and is out for review. Resources to the VVUQ Committee page, associated journal, May 2022 Symposium, and LinkedIn group were provided.

The group discussion touched on several areas, including:

- Is the focus on uncertainty quantification more on a statistical treatment (which are known well) or more on fundamental drivers of uncertainty? A comment was made that for some processes, it is important to know what parameters are contributing to the highest variability and therefore the uncertainty.
- How machine learning approaches work could be better understood. A comment was made pointing to a blog with additional information on uncertainty quantification and deep learning (https://www.inovex.de/de/blog/uncertainty-quantification-deep-learning/).
- Discussion was held on the fact that we are learning from other communities. For example, biologists have a "protein folding" benchmark challenge problem that has resulted in advances in machine learning. These types of challenge problems may be useful in the nuclear community. The NASA modeling and simulation standard was also mentioned as a resource, and the genesis of that document (from the verification and validation community) were discussed.
- There was a question on the tie between uncertainty quantification and machine learning/digital twin. The synergies between these two areas were discussed.
- Finally, a comment was submitted but not discussed:
  - “Human brains "Sees" in patterns, but computers operate in pixels, that's one reason for failures of facial recognition or classification (cat vs dog). But I wonder in the nuclear engineering: what types of images will you be looking at? Can we hope that "recognition" of those images will be reliable?

4.5.2 DOE Program Activities

As mentioned previously, the AMMT program has three major goals namely to 1) to develop advanced materials and manufacturing technologies that have cross-reactor impacts, 2) to establish a comprehensive framework for rapid qualification of new materials made by advanced manufacturing, and 3) to accelerate commercialization of new materials and manufacturing technologies through demonstration and deployment. These goals will be achieved through three program elements: 1) Development, Qualification, and Demonstration; 2) Capability Development, and 3) Transformative Research; Collaborative Research and Development [29].

The AMMT program has incorporated a workplan to develop a novel, new qualification framework that will be based on the understanding of the processing-structure-property-performance relationships of reactor materials and integrate materials development, advanced manufacturing, and environmental effects. This new qualification framework will capitalize on the wealth of digital manufacturing data and employ an ICME methodology and machine learning/artificial intelligence tools, in concert with accelerated testing and high-throughput characterization techniques. LPBF 316 SS is selected as a test case based on the results of the material scorecards [30]. The new qualification framework will be demonstrated initially through establishing a Code case for LPBF 316H SS in the ASME Code. Experience gained in qualifying LPBF-316H SS will benefit the expansion/application of the framework to other manufacturing technologies and materials systems.

The outcome and lessons learned from this workplan, will be contributing towards the AMMT program's new qualification framework development.

4.5.3 MOST workshop

The goal of this workshop was to gain a better understanding in the current practice for additive manufacturing qualification in the industry, especially the role of modeling and simulation (Agenda in Figure 13). The workshop included of 10 presentations to share beneficial overviews and insights of the challenges from different perspectives in qualifying and adopting AM in industry. The participants represented various industries, including 19% nuclear, academia and government as shown in Figure 14.

AM Qualification Workshop, MOST-AM Consortium, University of Pittsburgh, April 13, 2023

AGENDA, MOST-AM Consortium, University of Pittsburgh, April 13, 2023

8:00 – 8:30 am	**Registration/Breakfast/ Networking**
8:30 – 9:15 am	Welcome & Update Albert To with Wei Xiong
9:15 – 9:30 am	Ramesh Subramanian (Siemens Energy)
9:30 – 9:45 am	Isabella van Rooyen (Pacific Northwest National Lab)
9:45 – 10:00 am	Scott Parent (Ansys)
10:00 – 10:15 am	Networking Break
10:15 – 12:15 pm	Qualification Workshop Moderated by Chris Robinson
12:15 – 1:30 pm	Lunch and Tour of the Ansys AMRL (1-1:30pm)

1:30 – 1:55 pm	John Wilczynski (America Makes)
1:55 – 2:20 pm	Ryan Fishel (3D Systems)
2:20 – 2:45 pm	Rob Martinsen (nLight)
2:45 – 3:15 pm	Networking Break
3:15 – 3:40 pm	John Barnes and Tom Bockius (Metal Powder Works)
3:40 – 4:05 pm	Anthony Mott (Wabtec)
4:05 – 4:30 pm	Michael Schmitt (HAMR Industries)
4:30 – 4:45 pm	Closing Remarks

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Figure 13. Agenda for the MOST-AM Consortium, University of Pittsburgh, April 13, 2023

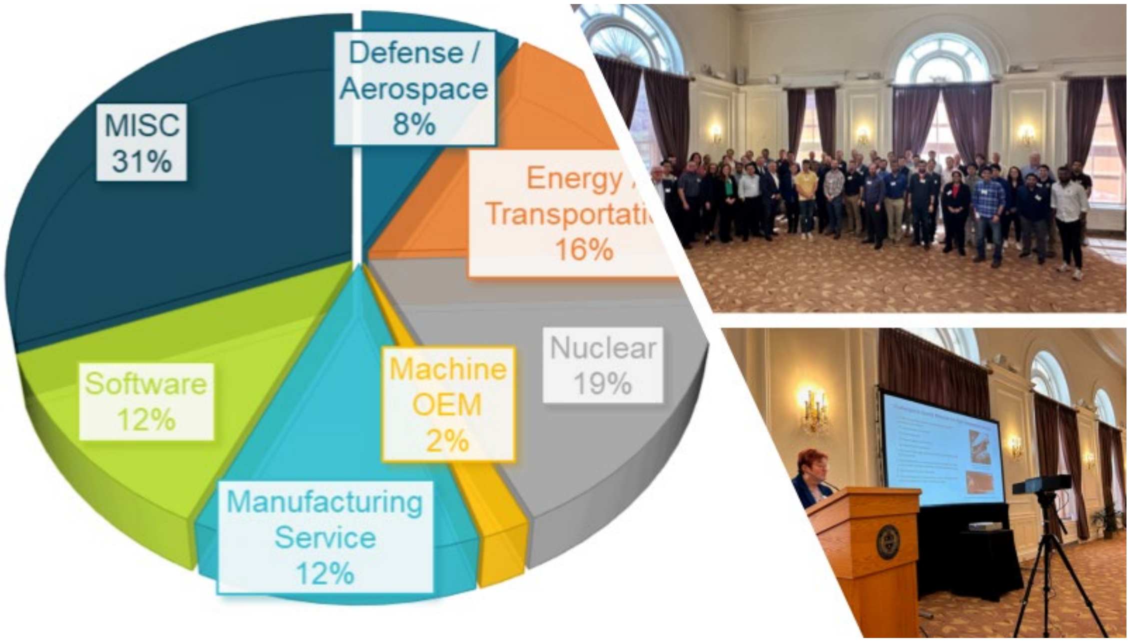

Figure 14. Workshop was attended by 55 participants from industry, government laboratories, and academia.

The workshop participants were divided into five breakout groups by industries. They were asked to discuss and answer the five questions shown below:

1. What qualification activities does your company perform? Common practices?
2. What are the most difficult areas of qualification?
3. How does process monitoring fit in with simulation/qualification?
4. What is the top priority modeling needs with respect to qualification and in general?
5. How are test artifacts being used for qualification?

Initially at the workshop, five challenges (one from each workshop group) were identified as part of the outcome of the workshop, although more detailed report were prepared by the workshop team by the University of Pittsburgh team under leadership of Professor Albert To [31]. Three delegates (Ayoub Soulami, Mohan Nartu, Isabella van Rooyen) from the AMMT program participated in the workshop and presented a presentation at the workshop. The initial five challenges identified by the closure of the workshop were:

1. Process variability and dimensional stability are the most difficult challenge to qualification (e.g., between machines, within a part, among different part geometries, and different locations on build plates).
2. Qualification is application-specific and oftentimes no standard exists. There is difficulty with scaling material properties from test coupons to actual parts.
3. An AM database is not widely available and data sharing is still limited.
4. In situ monitoring is helpful for qualification; however, we need to find a good way to relate monitoring data to variance in microstructure and material properties.
5. A modeling tool to predict properties and performance of actual parts based on test coupons while capturing location-specific process variability is needed.

As part of this study, a re-imagining and interpretation was performed based of the delegates' notes, lessons learned as well as the outcomes report. This re-imagined outcome shows the main challenges associated with these questions, as discussed in this workshop (Table 5 and Figure 15 to Figure 19).

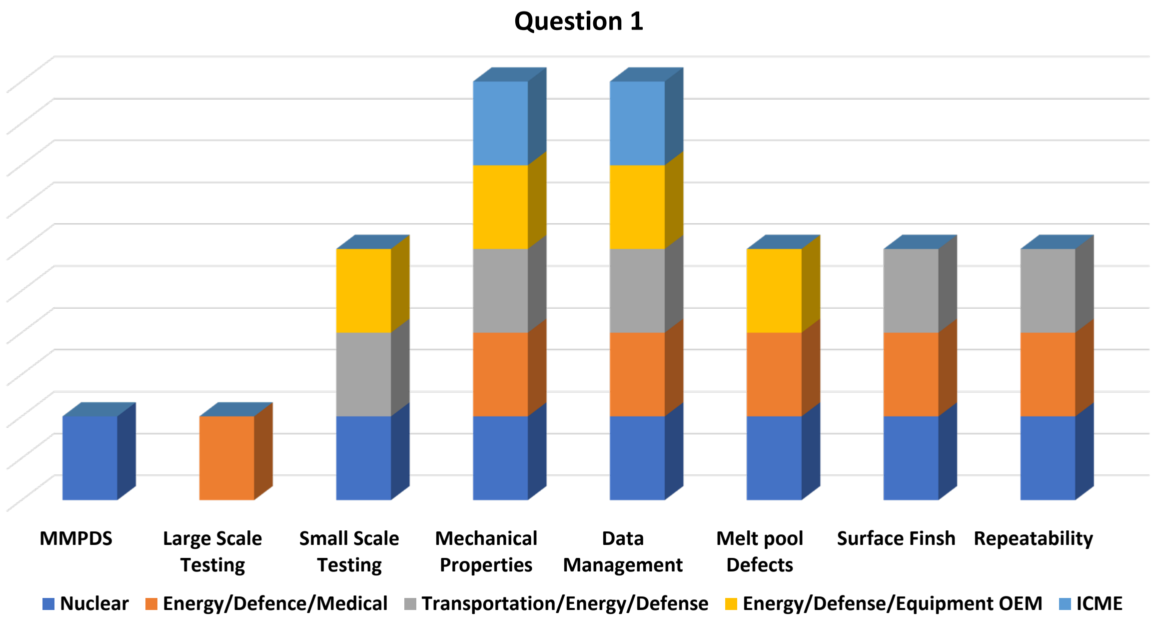

Figure 15. Distribution of Challenges Related To Question 1 and Their Relevance to Different Groups

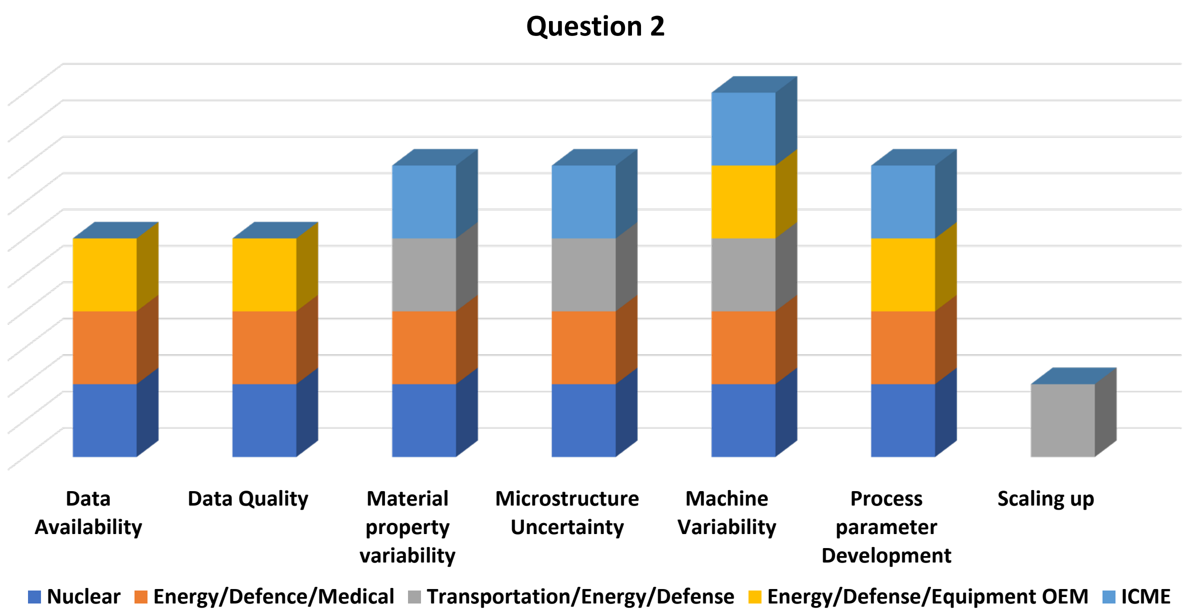

Figure 16. Distribution of Challenges Related to Question 2 and Their Relevance to Different Groups

Table 5. Re-Imagining and Interpretation of Workshop Outcomes as the Five Questions and Associated Challenges for Qualification of AM Materials. (MMPDS: Metallic Materials Properties Development and Standardization)

	Challenges							
Question 1	MMPDS	Large Scale Testing	Small Scale Testing	Mechanical Properties	Data Management	Melt pool Defects	Surface Finish	Repeatability
Question 2	Data Availability	Data Quality	Material property variability	Microstructure Uncertainty	Machine Variability	Process parameter Development		
Question 3	Processing Monitoring challenges	In-situ Monitoring	Digital Twin Machine Learning	Lack of Monitoring tools				
Question 4	Digital twin	Modeling on AM product	Modeling on Scaled up product	Modeling of Complex Geometry				
Question 5	Tensile and Density cube Test	Irradiation Behavior	Shape Effect	High Temperature Behavior	Mechanical Testing			

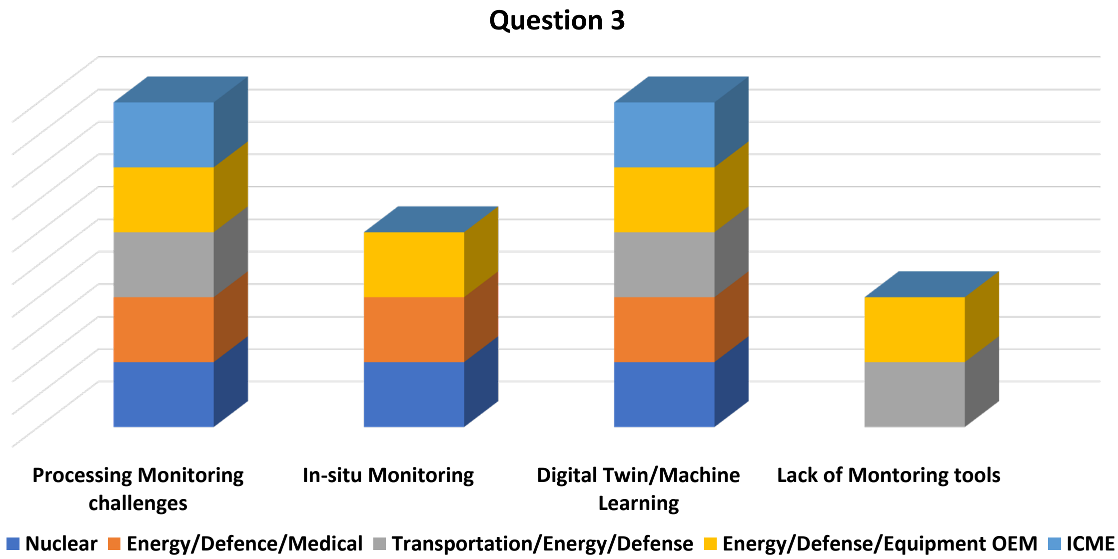

Figure 17. Distribution of Challenges Related to Question 3 and Their Relevance to Different Groups

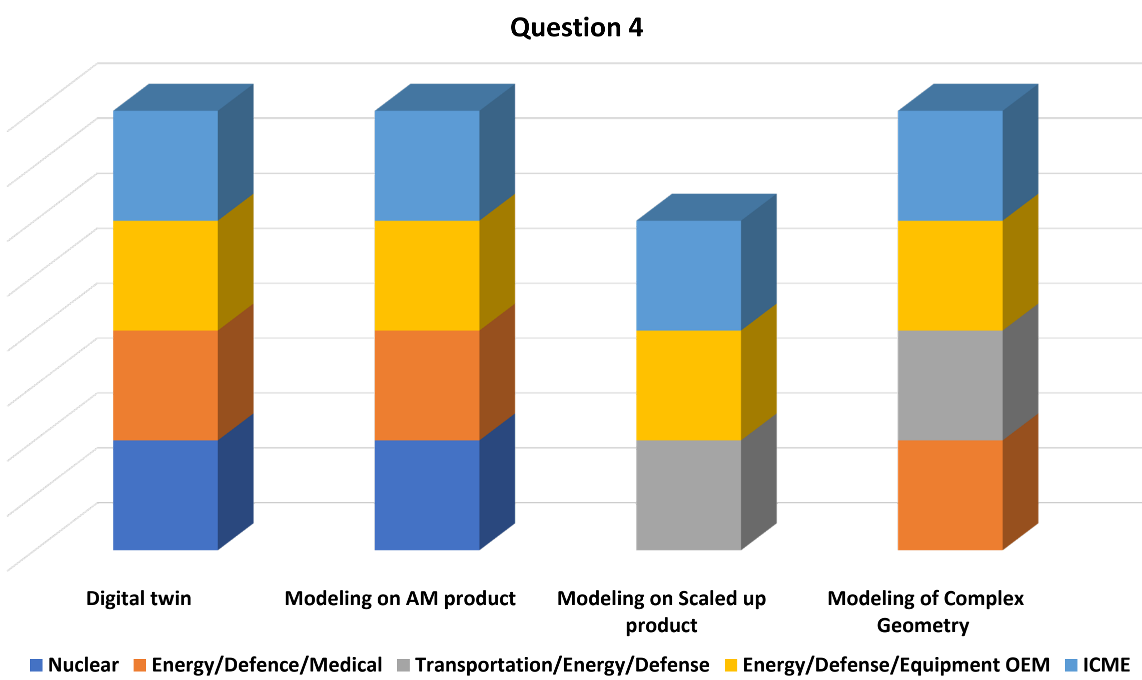

Figure 18. Distribution of Challenges Related to Question 4 and Their Relevance to Different Groups

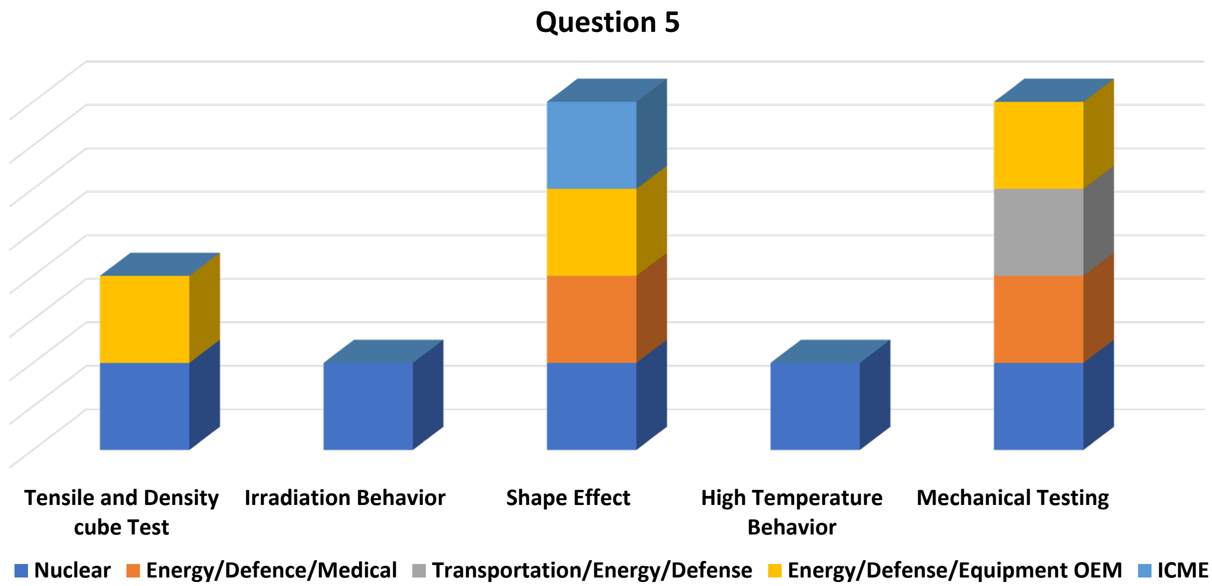

Figure 19. Distribution of Challenges Related to Question 5 and Their Relevance to Different Groups

Based on the detailed analysis of the workshop, the following conclusions can be made regarding current qualification challenges of AM fabricated products:

- Mechanical properties and data management is important to many sectors for qualification practices.
- The machine variability in the AM process, microstructural inconstancy, process parameter development remains the main roadblocks for the qualification process of AM products.
- Although digital twin/machine learning can be useful tool for printing in an iterative design
- Process, the lack of better in situ monitoring or other advanced monitoring tool slow down the adaptation of optimized modeling guided printing.
- Modeling on AM products mainly scaled up products and complex geometry still need to be developed for accelerating the qualification process.

4.5.4 Topical Workshops and Conferences

4.5.4.1 NRC Workshop on Advanced Manufacturing Technologies (AMTs) for Nuclear Applications

During December 7–10, 2020, the NRC hosted the “Workshop on Advanced Manufacturing Technologies for Nuclear Applications” [32]. This public workshop was intended to broadly address potential industry use of AMTs, including the replacement/repair of components in operating nuclear power plants and in the initial construction of small modular and advanced reactors. AMTs are defined by the NRC as those techniques and material processing methods that have not been traditionally used or formally standardized/codified by the nuclear industry.

The primary objectives of the workshop were to do the following:

- Discuss ongoing activities related to AMTs, including nuclear industry implementation plans, codes and standards activities, research findings, and regulatory approaches in other industries
- Inform the public of the NRC's activities and approach to approving the use of AMTs
- Determine, with input from nuclear industry stakeholders and other technical organizations, areas where the NRC should focus to ensure the safe implementation of AMTs.

To support the objectives of the workshop, the NRC staff organized the following seven sessions:

- Session 1: Practical Experience Related to Implementing AMTs
- Session 2: Plans and Priorities for AMT Implementation in Commercial Nuclear Applications
- Session 3: Performance Characteristics of AMT-Fabricated Components
- Session 4: Approaches to Component Qualification and Aging Management
- Session 5: Codes and Standards Activities and Developments
- Session 6: Regulatory Approaches for AMTs
- Session 7: Research and Development of AMTs.

These sessions were intended to broadly cover the range of AMT topics, emphasizing practical experience with and the application of AMTs. The staff solicited presentations from a range of national and international organizations, including vendors, utilities, EPRI, NEI, the U.S. Department of Defense (DoD), DOE (including its national laboratories), the National Institute of Standards and Technology, NASA, regulators (other U.S. government and international), and universities. About 280 individuals from 80 organizations in 10 countries attended the workshop. Sessions 4 through 6 provide the most relevant material associated with the scope of this report. Presentations are publicly available from NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications, Part II – Workshop Slides [33].

4.5.4.2 MILAM 2023

Military programs held a variety of open workshops and summits discussing AM processes and related topics to accelerate utilizing AM benefits for the military industry. This includes aircraft applications, supply chain, logistic solution due to AM, qualification, techniques, equipment etc. as an example. A PNNL delegate participated in one such summit, namely MILAM2023 in February 2023 at Tampa, Florida, to gain more knowledge on the lessons learned in the military space that is open to the public. Below is a summary of information gained:

- The need to design for AM to fabricate model/small aircraft parts for better understanding prior to the application.
- Logistics: Key for warfare
  - AM to help solve the supply chain issues for better logistics
  - Three-dimensional (3-D) printed modular/multipurpose structures
  - Drone drop mechanism assembly
  - Helmets mounted with night vision google power supply

  - Space logistics (a new area)
- 3-D printed parts currently used by DoD; AM reduces the lead times by 83%
  - Valve on USS Harry S. Truman (CVN-75) aircraft carrier
  - F110 sump cover in F-16 Fighting Falcon fighter jet
  - Horizontal stabilizer panel
  - M249 site spanner wrench (apparently first AM part approved for DoD)
- AM can be efficient and cost saving as machine assemblies with fewer and lighter parts can be manufactured obviating welding and riveting of structures.
- AM avoids bonding/riveting and hence the non-conformances.
- State of AM in DoD
  - 1,780 items in production (mostly plastic)
  - End use parts (74%)
  - Tools (20%)
  - Quality of life (6%)
  - Primary benefits: reduced lead times and part cost
- Game changers for DoD
  - 3-D printing of energetic materials (deployed in space)
  - Bio-manufacturing
  - Hypersonics
  - High temperature and propulsion standards
  - Spare parts for warfare
  - Maintenance tools
  - 3-D printed unmanned air vehicles
  - Rapidly 3-D printed concrete structures for security
  - 3-D printed engines
  - 3-D printed biscuits/nutrition
- Due to the availability of various commercial AM techniques, developing a single qualification process is a challenge.
  - The respective OEM manufacturers to certify the AM parts for use by DoD
- Defense Logistics Agency makes policies for AM parts for DoD
  - Joint Additive Manufacturing Model Exchange contains all the information regarding qualification and testing of AM materials
- Developing families of applications by implementing AM ecosystem help to get the support and effective supply chain
- Centralized AM infrastructure for best synergies: AM Centre of Excellence

- Panel discussions (Master Sergeant Carlos Gill, Tech. Sergeant Chris, Sergeant Mitchell and Specialist Andrew):
  - Two-to-three-week lead time for certain non-critical parts
  - AM significantly reduces the man hours.
  - AM can potentially avoid errors in subtractive manufacturing.
  - If any step in the subtractive manufacturing goes wrong, the whole part must be scrapped.
  - Production capacity is not a factor as the demand for specific parts is not significant.
  - Most aircrafts/machinery are decades old, and there is no access to the models or parts in some cases.
- OEM (currently plastic) must qualify the AM parts. The military can then use the same protocol to manufacture or repair the parts in in-house fabrication shops as needed.
  - Currently only a handful of basic tools that are 3-D printed in the in-house facility and used without proper qualification.
  - All critical parts require qualification.
- Galvanic corrosion at rivetted joints (dissimilar metal interfaces) is a potential issue.
- Panel Discussions (Lt. Col. Gary Goff, Charlotte M. Gerhart, Troy Dawson Josh Brost):
  - A lot more risk in involved when certifying an AM part for the first time.
    - Conducting multiple parallel tests to qualify the AM part
  - Key advantages of AM:
    - Avoids multiple parts
    - Few monolithic parts
    - Avoids human errors in secondary post processing
    - Saves labor
    - Rapid iteration cycle
    - Model rockets can be rapidly developed and tested
    - Rapid learning from mistakes and new innovations
    - Scaling up; printing large structures
    - Printing anywhere
    - 3-D printing in space
- Boeing uses 3-D printed aluminum and titanium
- Relativity space uses 3-D printed Inconel 625 and Inconel 718
- Relativity Space is 3-D printing 85% of the parts in their rockets.
- Lessons learned on AM certification and qualification: DETAILS MATTER
  - Process defects

- Microstructure control
- Chemistry control
- Resultant property scatter
- Part to part and Batch to batch and Machine to machine variability
- Powder handling and re-use
- Geometry control
- Surface finish

- A detailed slide was presented on “Digital Manufacturing Data Vault” as in Figure 20. The biggest lesson learned for the AMMT team is the importance that was placed on the ***accessibility and interoperability***.

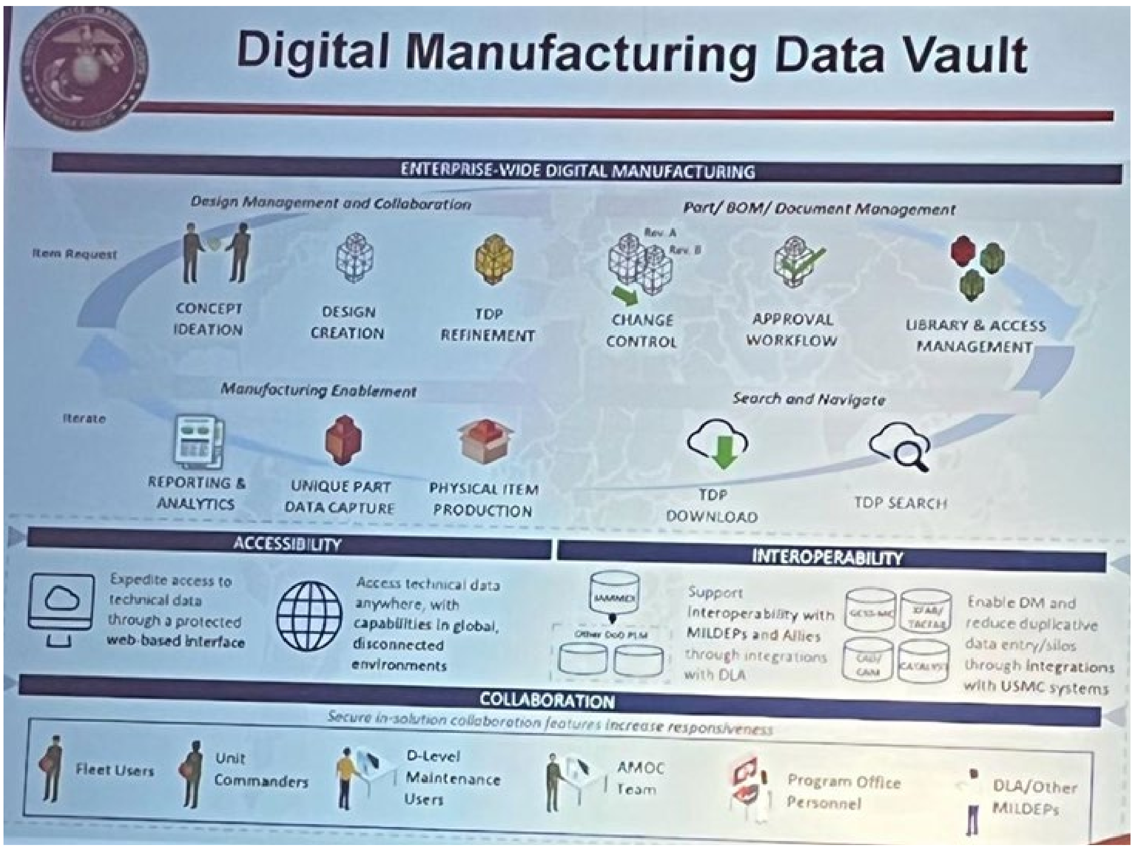

Figure 20. Digital Manufacturing Data Vault

- The application of AM in the construction was also discussed.This is a topic for DOE NE that was highlighted also previously as part of the previous AMM program as well as the Fission Battery webinar series in 2021 [34]

4.5.5 EPRI: High-Temperature Applications

EPRI has many activities related to material and product readiness for adoption in the market and this section does not provide all the information.

We highlight one aspect that EPRI deemed additionally important, namely that EPRI notes that other industries using ASME code design practices for construction and plant operation, have experienced significant challenges in directly applying code compliant specifications to high-temperature components. While the challenges of material variability can be addressed by taking into account potential variability of properties and using “lower bound” data from the code allowable, EPRI believes that a more effective solution is to identify the metallurgical factors that can affect key time dependent properties and to provide guidance in materials procurement for their avoidance. This practice is employed by current fabricators and operators of power generating reactors who have learned by experience to enhance their purchasing specifications with limitations over and above those required for code compliance. EPRI expects that ARs will be more efficiently deployed and operated for reasonable times if these challenges are investigated up front.

To avoid such downstream problems in high-temperature reactors, knowledge is required to increase confidence in the long-term performance for materials selection in designs for advanced reactors:

- Reducing the uncertainties associated with these materials is vital to the long-term performance of the candidate reactor designs.
- Because advanced reactors rely upon time-dependent material properties, the effects of material processing and microstructural variabilities on the creep and creep fatigue behaviors of candidate high temperature alloys need to be determined to minimize the risk of in-service degradation and any loss of plant robustness and reliability.
- For components operating in high-temperature and high-pressure conditions, the elastic stresses that develop seek to relax in a time-dependent manner. Testing of materials at high temperatures to determine their time-dependent mechanical responses, therefore, is a key component of ASME code considerations. However, the crucial creep and stress relaxation testing activities are most often conducted under simplified uniform and uniaxial conditions. In most structures under real-world conditions, relaxation will be greatest at local stress concentrations, for example, at holes, changes in section thickness, or weld geometry. For alloys that exhibit good high-temperature ductility, localized stress relaxation can take place without significant damage. However, many high-strength creep-resistant alloys considered for high-temperature service applications exhibit limited ductility and can be susceptible to excessive damage at stress concentrations. Such materials are said to be “creep-notch sensitive.”

4.5.6 America Makes

In March 2016, America Makes and the American National Standards Institute (ANSI) collaborated to create the America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC). AMSC's purpose was to coordinate and accelerate the development of additive manufacturing standards, supporting the growth of the AM industry. America Makes is a prominent public-private partnership for AM technology, while ANSI oversees voluntary standards in the United States.

The AMSC Standardization Roadmap for Additive Manufacturing, Version 3.0, was developed with the support of approximately 300 individuals from 150 public- and private-sector organizations, including U.S. federal government agencies, national laboratories, standard development organizations (SDOs), industry, academia, and others. This collaborative effort aimed to address key safety, performance, and quality issues in additive manufacturing technologies. The development of the AMSC Standardization Roadmap for Additive Manufacturing, Version 3.0 involved a comprehensive approach that encompassed the entire life cycle of producing an additive manufacturing part. This approach was organized into nine working groups, each focusing on specific aspects of the AM process and its associated standards [35]. Following is a breakdown of these working groups:

- *Design* – This group likely focused on standards related to the initial design phase of AM, ensuring that designs are compatible with AM processes and meet required specifications.
- *Precursor Materials* – This group concentrated on standards for the materials used in AM, including raw materials and powders, to ensure their quality, consistency, and suitability for AM processes.
- *Process Control* – Process control is crucial in AM to maintain consistency and quality. This group likely addressed standards related to monitoring and controlling the AM process itself.
- *Post-Processing* – After the AM part is built, post-processing steps may be necessary to improve surface finish, mechanical properties, or other characteristics. This working group likely dealt with standards for these post-processing steps.
- *Finished Materials Properties* – Standards related to the properties and characteristics of the finished AM parts, including mechanical properties, surface finish, and dimensional accuracy.
- *Qualification and Certification* – This group likely focused on standards for qualifying and certifying AM parts and processes to ensure they meet industry and regulatory requirements.
- *Nondestructive Evaluation* – NDE methods are essential for inspecting AM parts without causing damage. This working group likely addressed standards for NDE techniques specific to AM.
- *Maintenance and Repair* – Standards related to the maintenance and repair of AM equipment and parts, ensuring the long-term reliability of AM systems.
- *Data* – The data working group likely dealt with standards for data management and exchange throughout the entire AM life cycle, ensuring consistency and compatibility of data across different stages.

By organizing the roadmap into these nine working groups, the AMSC aimed to comprehensively address the various aspects of AM standardization, from design to post-production testing, qualification, and maintenance. This holistic approach helped assure that the quality and reliability of AM parts and processes, fostering growth and innovation in the field. The roadmap represents the culmination of work since September 2022, during which time the AMSC identified these issues, assessed relevant existing standards, and determined gaps in the standards landscape. A "gap" in this context signifies the absence of a standard or specification to address a specific AM-related issue.

Key points from the roadmap include:

- *Prioritized Timeframes* – The document provides prioritized timeframes for when standards development work should take place. It categorizes 141 identified gaps or recommendations into three priority levels: 54 high priority, 64 medium priority, and 23 low priority. Additionally, in 91 cases, it suggests that further pre-standardization R&D are required.

- *Identified Responsible Parties* – The roadmap also identifies the standard development organizations (SDOs) or other entities that may be capable of developing the required standards or conducting the necessary R&D to fill the identified gaps.
- *Tracking Progress* – The AMSC plans to continue monitoring the progress made by SDOs in addressing the roadmap's gaps and recommendations. This suggests an ongoing commitment to advancing standardization in additive manufacturing.

In summary, the AMSC Standardization Roadmap for Additive Manufacturing, Version 3.0 is the result of extensive collaboration among various stakeholders. It provides a clear roadmap for addressing critical issues in additive manufacturing through the development of standards and research, with an emphasis on prioritization and ongoing progress tracking.

4.6 Applications of Advanced materials and manufacturing processes in current reactors

AM products were already successfully qualified and used in reactor applications recently, although not in-reactor core applications. Also, the replacements parts were not safety critical, and therefore did not need a new verification from the NRC. Figure 21 provides three examples of AM products in current nuclear plants. These applications will help demonstrating the use of AM products for future use. Below more applications are listed.

- Coated cladding in pressurized water reactors and boiling water reactors are introducing new coating technologies (e.g., cold spray, physical vapor deposition)
  - Framatome chromium-coated M5® into Vogtle 2
  - Westinghouse chromium-coated rods in Byron 2
  - GNF Armor-coated zirconium at Plant Hatch
- Chromia Doped Fuel Pellets for higher density and performance require new blending techniques
- Additive Manufactured components are now being introduced into commercial LWRs
  - Pressurized water reactor thimble plug assembly installed at Exelon’s Byron Unit 1
  - Boiling water reactor channel fasteners at Brown’s Ferry.

GE Armor-Coated Cladding
Source: Power Magazine April 1, 2018

Westinghouse – PBF Thimble Plug
Source: World Nuclear News May 5, 2020

Framatome/TVA/ORNL TCR – AM Channel Fasteners
Source: ORNL Press Release October 19, 2020

Figure 21: Three Examples of AM Products in Current Nuclear Reactors

5.0 Codes and Standards Organization Activities Related to Additive Manufacturing

Multiple organizations (ASTM, ISO, ASME, AWS, NIST etc.) are working on standards relevant to AM processes, testing etc. This section is providing already some information; however, it is not fully comprehensive and merits more work.

5.1 Existing Standards for AM materials for Nuclear Applications

There are multiple relevant standards that already exist for AM materials for nuclear applications and those are listed below:

- ASME PTB-13-2021: Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing, ASME BPVC Section II Materials, Parts A, B, C and D; ASME, 2 Park Avenue, New York, New York 10016
- Report Number 3002018273, ICME and In-Situ Process Monitoring for Rapid Qualification of Components Made by Laser-based Powder Bed Additive Manufacturing Processes for Nuclear Structural Applications, September 2020, EPRI, 3420 Hillview Avenue, Palo Alto, California 94304-1338
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- ASTM A1080-19, Standard Practice for Hot Isostatic Pressing of Steel, Stainless Steel, and Related Alloy Castings, ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, Pennsylvania 19428-2959
- ISO/ASTM 52907-19, Additive Manufacturing – Feedstock Materials – Methods to Characterize Metallic Powders, International Organization for Standardization (ISO), Central Secretariat, Cheminde Blandonnet 8, Case Postale 401, 1214 Vernier, Geneva, Switzerland
- AWS D20.1-19 Specification for Fabrication of Metal Components Using Additive Manufacturing:2019, American Welding Society (AWS), 8669 NW 36 Street, No. 130, Miami, Florida 33166
- ASTM E2586-19, Standard Practice for Calculating and Using Basic Statistics, ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, Pennsylvania 19428-2959
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- ASTM E18-20, Standard Test Methods for Rockwell Hardness of Metallic Materials; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, Pennsylvania 19428-2959
- ASTM E92-17, Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, Pennsylvania 19428-2959
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5.2 ASME Codes and Standards for Additive Manufacturing Processes

This section provides a summary of current ASME efforts and activities focused on developing standards for additive manufacturing and AM and is a summary of a presentation provided David Gandy. The information provided was obtained from a review of the presentation “ASME Codes and Standards for Additive Processes,” prepared by David W. Gandy of EPRI) for presentation by Frank Gift of EPRI in April 2023 [36]. The goal of ASME is to have AM requirements in ASME Construction Codes and product standards with the 2025 editions with code cases preceding the 2025 edition. In pursuit of these goals, ASME has drafted two code cases for additive manufacturing.

- “AM Construction of Pressure Equipment using the Direct Energy Deposition Process with Wire Feedstock,” which covers gas metal arc and electron beam welding processes.
- “AM Construction of Pressure Equipment using the PBF AM Process,” which includes laser and electron beam energy sources.

For the code case applications, the maximum temperature shall be at least 50°F (25°C) colder than the temperature at which time-dependent material properties govern.

The defined criteria for PBF and direct DED provide the needed requirements for the materials, design, fabrication, examination, inspection, tasting and quality control. Table 6 provides a listing of the topics used to define the criteria for both PBF and DED.

Table 6. Topic Listings for Defining PBF and DED Criteria

PBF Criteria	DED Criteria
Scope	Scope
Additive manufacturing specification	Additive manufacturing specification
Materials	Materials
Thermal treatment	Thermal treatment
Powder requirements	Design requirements
Design requirements	Welding qualification
PBF procedure	Procedure qualification builds
Procedure qualification builds	Production builds
Production builds	Chemical composition testing
Chemical composition testing	Mechanical property testing
Mechanical property testing	Metallographic evaluation
Metallographic evaluation	Referenced standards
Referenced standards	Definitions
Definitions	Records
Records	Quality program
Quality program	

The BPTCS/BNCS Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment is a special appointed group appointed by the ASME board to develop AM guidelines currently consisting of:

- PBF-AM – PTB-13 "Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing" was published in Pressure Technology Book
- DED-AM – Draft

The special committee supports code activities and Code Cases across various Book Standards Committees. In addition, the committee is working with Section II on how to specify allowable stress values for AM materials. An outstanding question to be addressed is determining how ASME Section II, Part D should be used to determine the allowable stress values for weld metals. Associated efforts require determining how base metal property data for the allowable stress values form ASME Section II, Part D should be applied to AM deposited metal. Weld metal data is needed to evaluate the trends for tensile properties between deposited weld metal and base metal below the time dependent regime.

The chemical composition for DED and PDF components can be different as the PBF powder particles are fabricated from source material, which matches the alloy composition of the ASME material specification. By comparison, the chemical composition for DED material conforms to the ASME filler material specification. In addition, the rate of heat input and associated cooling rate, which are AM process dependent, control the final tensile properties. Examples of Tensile properties for weld metal and DED equipment builds are provided in Figure 23.

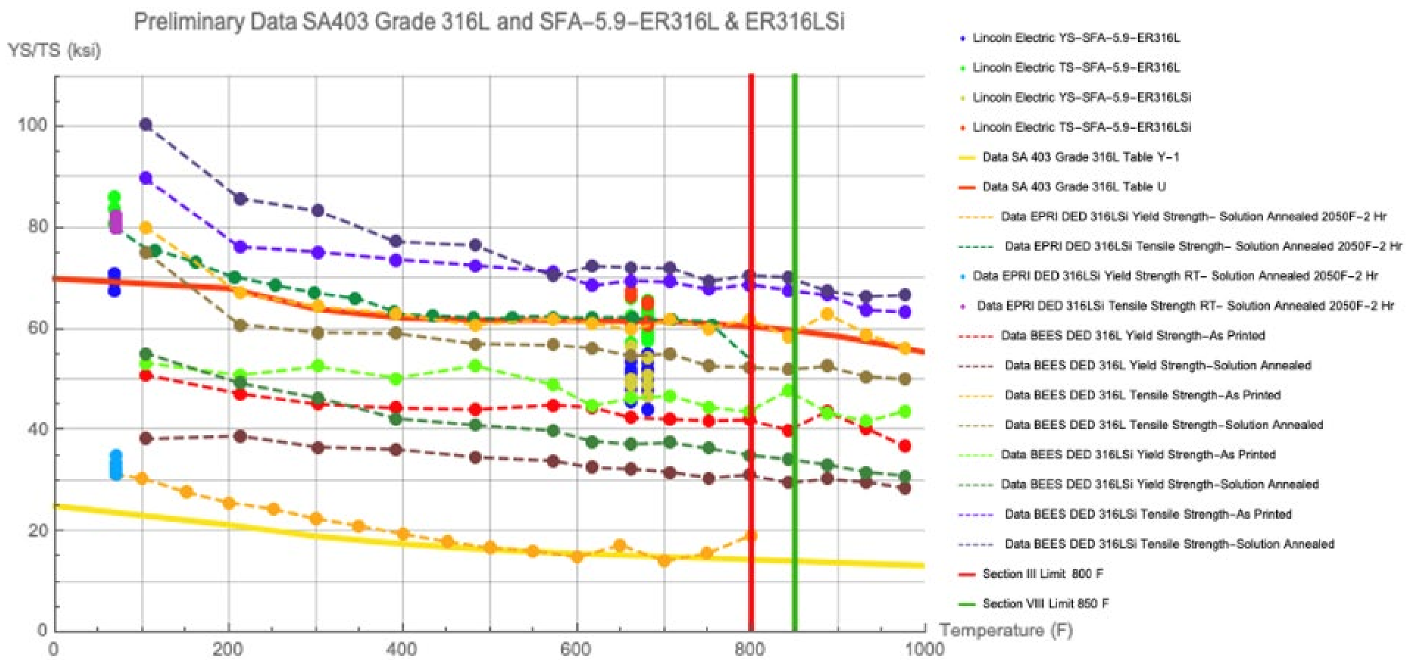

Figure 22. Comparison of Tensile Properties for 316L Weld Metal and 316LSi Filler Materials Used for DED Equipment Builds [36]

Sample data for the bracketed weld qualification used for AM material property qualification is presented in Figure 24.

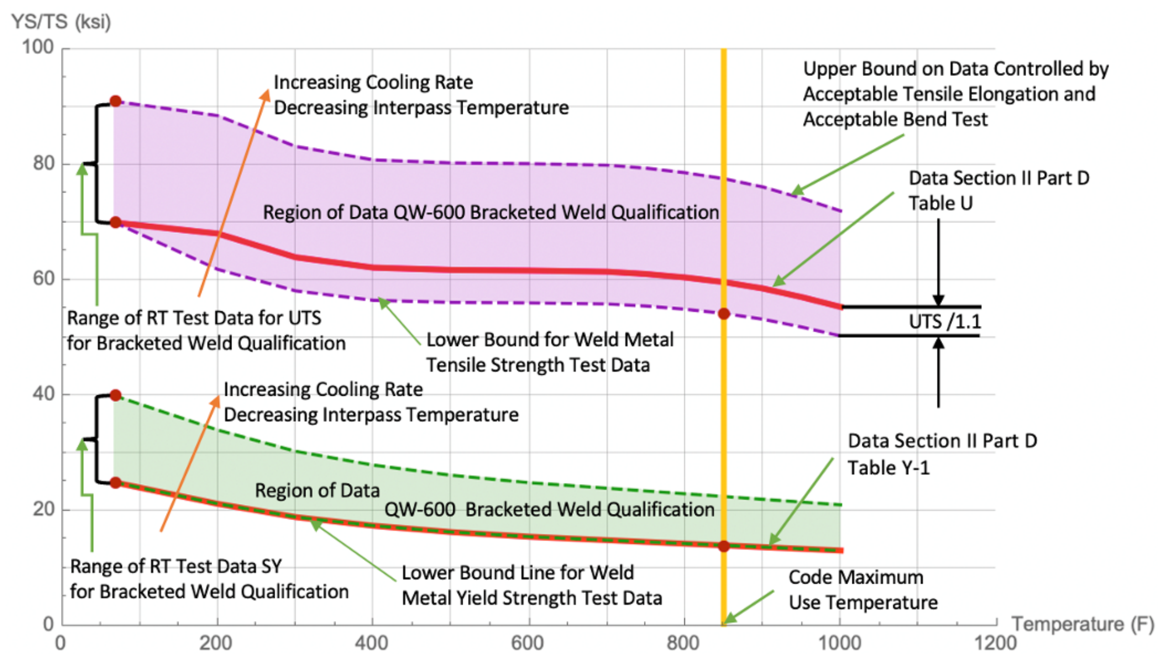

Figure 23. Sample Data for Bracketing the Weld Qualification Used for AM Material Property Qualification [36]

Material performance/properties to be considered include PBF fatigue evaluation. Figure 25 presents welded joint fatigue curve data for PBF fatigue evaluation that consists of 295 load-controlled test and 22 test specimen types/geometries that resulted in over 400 conditions (i.e., data points) being analyzed.

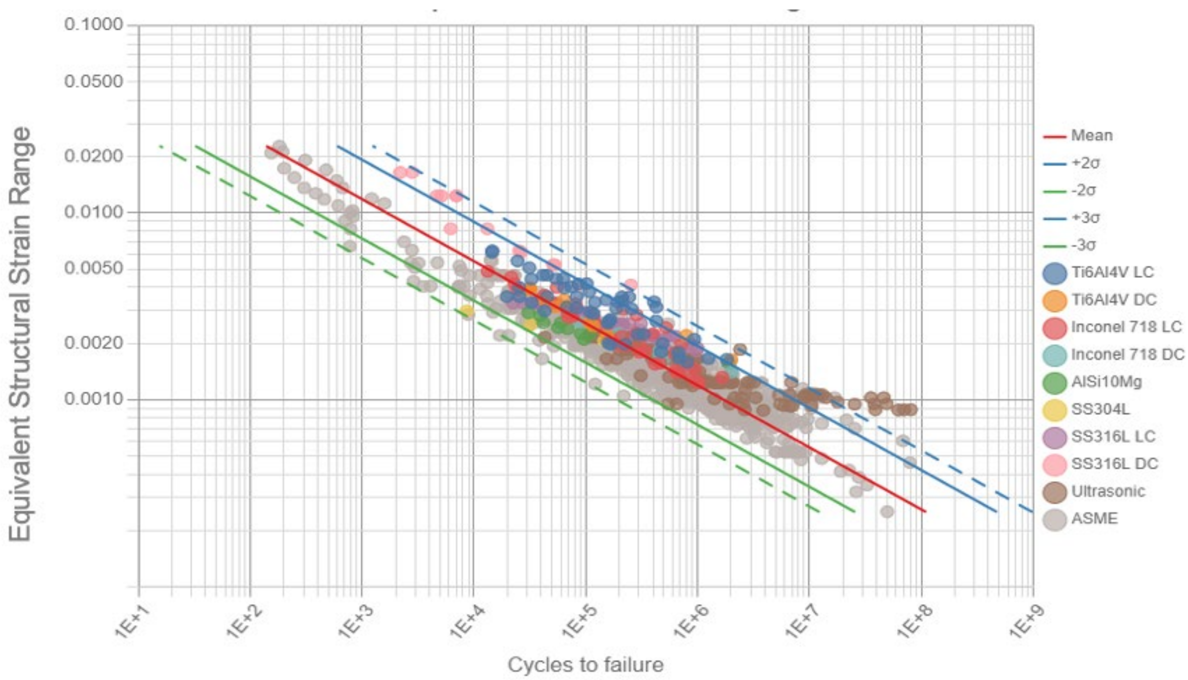

Figure 24. Equivalent Structural Strain Range vs. Cycles to Failure for PBF Fatigue Evaluation. Welded Joint Fatigue Curve Data Obtained from 295 Load-Controlled Test and 22 Test Specimen Types/Geometries [36]

Current key ASME activities related to additive manufacturing include:

- ASME Section 1
  - Approved the Code Case for AM of PR parts using the PBF AM Process. The code case follows the recommendation of PTB-13
  - Opened record 21-1702 for a Code Case using DED-AM, however no action to date.
- Section II
  - Currently includes specific filler metals under Part C that are invoked by other Standards Books for welding activities. Committee's intention is to use same specifications for DED-AM applications.
- Section VIII
  - Opened Record 21-241 for a Code Case for development on electron beam DED-AM for titanium product forms.
- Section IX
  - Approved Code Case 3020 for the qualification of Gas Metal Arc AM (GMA-AM) Procedures.

- Approved qualification rules for wire-additive welding as a new Article QW-600 (Includes incorporation of Code Case 3020).
- Applied a bracket qualification approach to:
  - Qualify the lowest and highest cooling rates that will be applied for AM production.
  - Qualify thin and thick sections if both will be used in AM production.
  - Results are compared back to the "corresponding materials specification."

The task group on Advanced Manufacturing for Nuclear Applications (Section III) is chartered with developing, clarifying, and prescribing rules for the fabrication and stamping of items manufactured by techniques including powder metallurgy / hot isostatic pressing (HIP); powder bed-additive manufacturing; DED-additive manufacturing/wire; cold-spray deposition/cladding; and diode laser cladding.

Key ASME activities related to advanced manufacturing, which includes additive manufacturing, for Section III consist of:

- PM/HIP
  - Record 21-2331 was approved. The requirements for PM/HIP apply to Division 1 items.
  - The resulting structure will be used to incorporate other advanced manufacturing processes into Division 1 mandatory appendices. Currently only 316L SS has been incorporated.
- DED/Wire
  - The task group on Advanced Manufacturing for Nuclear Applications is collaborating with the BPTCS/BNCS Special Committee to develop the new Code Case for wire DED additive manufacturing.
  - Test results have been obtained but not provided. The task group is currently waiting on transmittal of test results and direction from the special committee.
- 2025 Publication Cycle Tasks
  - Record 22-1499: Mandatory appendix requirements were expanded for Advanced Manufacturing to incorporate additional AM process methods for Section III Div. 1 Items.
  - LPBF Code Case Ballot 22-18, Record 20-254 Closed. A new DRAFT Code Case that parallels PTB-13 wording will be opened soon.
    - Future 2025 Edition task group work product is being targeted to reference and incorporate PTB-13 principles that have been adapted to Section III requirements.

The responsibilities within the ASME Code that have relevance to advanced manufacturing consist of:

- Section 1 – Boilers
- Section II – Material properties
- Section III – Nuclear applications

  - Division 1 – Construction of nuclear components – Class 1, 2, ,3 and core components.
  - Division 2 – Construction of nuclear components – Concrete containments
  - Division 5 – construction of nuclear components – high temperature reactors.
- Section V – Nondestructive examination (NDE)
- Section VIII – construction of pressure vessels (mostly non-nuclear)
- Section IX – Welding, brazing, and fusing
- Section XI – Inspection of nuclear components
- B31.1 and B31.3 – Power piping and process piping, respectively
- B16.5 – Piping flanges and fittings, which includes valves, flanges, fittings, etc.

5.3 ASME based Qualification Processes for GEN-IV Reactor AM Components and Systems

Promoting ASME qualification as a base for AM components and systems for nuclear deployment must address some technical issues listed below. Future R&D on AM materials for nuclear deployment should entertain parametric studies to gain quantitative knowledge on the impact of feedstock, process parameter, and post-fabrication treatment on AM properties and performance.

- Impact of microstructural anisotropy on properties and performance
- Validation of process repeatability and variation in total density
- Test protocols for qualification and certification only exist in fragments.
- Surface finish specifications and allowable flaw densities are not yet defined.
- Lack of overall AM fabrication standards
- NDE methods for complex defects and part geometry are needed.
- Non-destructive testing methods to provide multimodal property measurements should be developed.
- Potential increase of component fatigue failure rates.

There are foreseeable challenges for the implementation of AM material in the nuclear industry as compared with other industries. Component validation against established qualified materials and manufacturing processes is probably the greatest hurdle. Currently, AM methods can result in components having increased performance uncertainty, which is undesirable in the nuclear industry. However, it is expected that the AM process will result in suitable material with structure and strength that are acceptable by the national code organizations and regulators.

Another challenge is to obtain the appropriate microstructure to achieve the desired mechanical performance of AM components. During the layer-by-layer deposition process, the material undergoes melting, solidification, and thermal cycling. This induces a liquid-to-solid phase transformation, as well as solid-state transformations. Therefore, the as-built microstructure of the component often provides heterogeneous microstructures with anisotropic mechanical properties on a macroscopic length scale. To overcome these challenges, the common practice is to use suitable post-fabrication heat treatment protocols, with or without HIP, for the as-built part. These post-fabrication heat treatments further change the microstructure according to its composition segregation level, phases, and grain structure (morphology and texture). Therefore, to achieve the desired properties for nuclear application, it is necessary to better understand the phase transformations during the formation of the as-built microstructure.

Hence, it is recommended to develop time-temperature-transformation diagrams for AM fabricated steels and alloys in order to optimize solutionizing, control the formation of carbides (MC, M23C6), γ'/γ'', G-phase, and ordered Laves phases, minimize the content of δ-ferrite (in austenitic alloys), homogenize microstructure and thus achieve normalization, and ultimately an isotropic behavior of physio-mechanical properties similar of those of the related wrought material. In the meantime, it seems judicious to avoid ASME qualification for AM materials, to allow their enhanced deployment within this decade and without undergoing lengthy testing of mechanical and nuclear properties. Heat treatment will certainly deplete some properties of AM materials which are superior compared with the wrought material, such as mechanical strength, resistance to grain boundary embrittlement and intergranular corrosion, as well as corrosion resistance.

Information on radiation tolerance of AM built alloys are only sparsely available and a campaign on the performance of AM alloys regarding void swelling, radiation-induced precipitation (RIP) and radiation-induced segregation might be necessary to allow for a full deployment of AM materials in nuclear reactor systems. However, the objective is to provide AM fabricated material which would satisfy the ASME requirements like the wrought counterpart. This will promote the fast deployment of AM fabricated steels, alloys, and ceramics in the nuclear arena within this decade. We conclude that AM SS316L and AM SS304 are shown as the most promising candidates for reaching this goal.

To aid ASME coding of AM materials for future use in Gen-VI systems, a central database of feed powder quality (oxygen impurities) processing conditions, resulting microstructure, post processing thermal treatment, mechanical properties, and the nuclear performance of these materials might be established. This will provide a systematic display of knowledge gaps and could help to enhance our understanding of the overall technology.

6.0 Gap-analysis and Recommendations

The Advanced Materials and Manufacturing Technology (AMMT) program develops cross-cutting technologies in support of a broad range of nuclear reactor technologies and maintains U.S. leadership in materials and manufacturing technologies for nuclear energy applications. The overarching vision of AMMT is to accelerate the development, qualification, demonstration, and deployment of advanced materials and manufacturing technologies to enable reliable and economical nuclear energy. The acceleration of qualification processes is one of the key aspects and qualification processes for the nuclear industry is not necessarily equivalent or benchmarked against other industries.

A study was therefore undertaken and reported herein to obtain knowledge of the full concert of qualification processes or approaches from various industries. The AMMT program will use lessons learned from these industries, to further accelerate the adoption of advanced materials enabled by advanced manufacturing (AM) processes to the benefit of the nuclear industry (A detailed nuclear energy qualification roadmap is not of this work package's deliverables).

Although four agnostic qualification approaches—namely *statistical-based qualification, equivalency-based qualification, in situ data-based qualification, and model-based qualification*—are often described in literature, these approaches have not been fully validated for components fabricated by AM processes. Simultaneously, the integrating material and manufacturing as one integrated process, does require qualification protocols to ensure adequate basic isotropic mechanical properties (e.g., strength, elongation, fracture toughness) as well as acceptable response of the AM material to long term degradation mechanisms (e.g., creep, fatigue, thermal ageing, corrosion behavior and radiation tolerance). The unknown behaviors of AM products in many environments relevant to nuclear applications, stifled the acknowledgement of the benefits that AM can bring to the nuclear industry. However, the qualification methodologies applied by other industries already for AM products, can support the work that needs to be undertaken by the nuclear industry. It is therefore the AMMT programs vision, to develop a case study for AM adoption, following conventional approaches, however to concurrent evaluate and perform accelerated methodologies to demonstrate the advantages. Currently, many of these acceleration actions are not shown as an integrated data set, therefore it is not clearly visible to the designer or developer and therefor qualification of these new AM products, seems too daunting and high risk to implement.

Acceleration of qualification processes for AM products and systems are a topic of interest or concern of nearly all companies, industry types nationally as well as internationally. This study reveals that although there are many complimentary activities as well as similarities between the main reason for hesitancy, is the lack of case studies that the nuclear developers can understand as part of their risk analysis. Furthermore, the description of for qualification has often been heard as "qualification of new materials, or qualification of AM processes, however, seldom been considered as a holistic integrated process, which should be the next generation paradigm implemented for true acceleration. Therefore, multiple steps can be concurrent or even decreased.

The NRC current provides two distinct avenues for qualification of new materials and process. One avenue is a utility/user can work with the American Society of Mechanical Engineering to submit a Data Package and Code Case. Once the Code Case is approved, the U.S. Nuclear Regulatory Commission can adopt it under 50.55a and add additional conditions if warranted. The other avenue is a utility/user can develop a Topical Report for a material/process and submit it directly to the Nuclear Regulatory Commission for approval.

A recommendation identified from the review of several industries was to conduct case studies of previous qualification processes. A potential for decreasing the duration and increasing the efficiency of the qualification process is to review planning and execution of previous efforts to evaluate:

- Lessons learned from actual material qualification processes, including efforts that achieved qualification and those that did not.
- Evaluate coordination and planning of original qualification process starting with initial plans prior to execution of activities.
  - Identify how process execution may have been optimized to reduce the time needed.
  - Identify tasks activities that were missing and overlooked from original plans.
  - Identify those tasks that were most misrepresented in establishing initial baseline schedule and resources. These will tend to be tasks/activities whose scope was initially underestimated and have the greatest uncertainty and potential risk.

Some specific recommendations for application to nuclear are provided:

- Recommendations from the automotive Industry to implement new products are 1) collaborative efforts, 2) increased communication, education, and training of the work force and within the industry, 3) simulation tool advancement (4) advanced forming and joining technologies.
- A recommendation that the nuclear energy community can learn from a U.S. Navy presentation among others are the material databases should address 1) performance, 2) production, 3) processing, and 4) research. Also, the maintenance of these databases is crucial so that the information can be available for generations and can be used for validation. However, it was clear that these databases are expensive to maintain and should be cross-cutting to be fully sustainable.
- To aid American Society of Mechanical Engineering coding of AM materials for future use in Gen-VI systems, a central database of feed powder quality (i.e., characterizing oxygen impurities) processing conditions, resulting microstructure, post-processing thermal treatment, mechanical properties, and the nuclear performance of these materials might be established. This would provide a systematic display of knowledge gaps and could help to enhance our understanding of the overall technology.
- Based on the detailed analysis of the MOST-AM national workshop at the University of Pittsburgh, the following conclusions can be made regarding current qualification challenges of AM fabricated products.
  - Mechanical properties and data management is important to many sectors for qualification practices.
  - The machine variability in the AM process, microstructural inconstancy, process parameter development remains the main roadblocks for the qualification process of AM products.
  - Although digital twin/machine learning can be useful tool for printing in an iterative design
  - Regarding processes, the lack of better in situ monitoring or other advanced monitoring tools impede adaptation of optimized modeling guided printing.

  - Modeling of AM products—mainly scaled up products and complex geometry—still need to be developed for accelerating the qualification process.
- Based on NASA's qualification framework, the following recommendations can be made:
  - Include the classification of parts depending on the level of consequence of the parts' failure, which would help in making parts potentially go through different, less strenuous qualification methods depending on that classification, potentially making it less time consuming.
  - Include the use of an Equipment and Facility Control Plan, which would allow for reliable AM part production through the consistent definition and implementation of equipment and facility controls.
  - Implement feedstock management, which is essential to safe and reliable AM processes, by providing requirements for storage and handling of AM materials, material lot control in AM machines, and blending operations.
  - Implement feedstock traceability, which is critical to tracking feedstock usage, life limits, and special usage requirements and enabling resolution of nonconformance involving feedstock.

This study includes summaries of multiple workshops hosted by U.S. Department of Energy Office of Nuclear Energy programs, international communities, or other industries, and although all the similarities are not fully interpreted and displayed, multiple complimentary actions were identified that the nuclear industry should consider.

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