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

Advanced Materials and Manufacturing Technologies (AMMT)

2022 Roadmap

September 2022

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Department of Energy Office of Nuclear Energy Advanced Materials and Manufacturing Technologies (AMMT) 2022 Roadmap

by
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Executive Summary

The Advanced Materials and Manufacturing Technologies (AMMT) program will develop cross-cutting technologies in support of current fleet and next-generation advanced nuclear reactor technologies and maintain U.S. leadership in materials and manufacturing technologies for nuclear energy applications. The overarching vision of the AMMT program is to accelerate the development, qualification, demonstration, and deployment of advanced materials and manufacturing technologies to enable reliable and economical nuclear energy. This roadmap identifies key research needs, challenges, and opportunities; outlines strategic research priorities; and provides a detailed five-year plan to realize the mission and vision of the AMMT program.

The major goals of the AMMT program are (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:

- *Development, Qualification, and Demonstration*

This is the core program element targeting big challenges and game-changing technologies with an emphasis on demonstration. Focus areas include developing advanced materials and manufacturing technologies, establishing a rapid qualification framework, evaluating materials performance in nuclear reactor environments, and technology demonstration and deployment.

- *Capability Development and Transformative Research*

This program element supports the development of experimental and computational capabilities needed for the core program and innovations. It will also support transformative research that may result in significant advances in materials design, discovery, and processing.

- *Collaborative Research and Development*

This program element is intended for collaboration and partnership to support the diverse needs of the nuclear energy community. We will work with other DOE programs, funding agencies, industry, and universities to investigate a broad range of advanced materials and manufacturing techniques, address reactor-specific issues, leverage and collaborate on capability development, and provide near-term material solutions to the nuclear industry through collaborative R&D.

The thematic execution strategy of the AMMT program is ***Integration and Collaboration***. The AMMT program is comprised of three core technical areas, namely, Materials Development, Advanced Manufacturing, and Environmental Effects. The technical areas mesh with the program elements in a matrix structure to facilitate integration and collaboration. An integrated approach, combining a set of tools including advanced characterization, high-throughput and accelerated testing, modeling and simulation, and machine learning and artificial intelligence will be used across all the areas to support the accelerated development, qualification, demonstration and deployment of advanced materials and manufacturing techniques.

The AMMT program will directly impact the nuclear industry by developing high-performance radiation-, corrosion- and high temperature-resistant materials for advanced manufacturing and/or through advanced manufacturing and accelerating the deployment of advanced materials and manufacturing technologies to enable reliable and economical nuclear energy.

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Acronym

AM	Advanced Manufacturing
AMM	Advanced Methods for Manufacturing
AMMT	Advanced Materials and Manufacturing Technologies
AMO	Advanced Manufacturing Office
ANL	Argonne National Laboratory
ART	Advanced Reactor Technologies
ASI	Advanced Sensors and Instrumentation
ASME	American Society of Mechanical Engineers
ATR	Advanced Test Reactor
B&PV	Boiler and Pressure Vessel
BWR	Boiling Water Reactor
DED	Direct Energy Deposition
DOE	Department of Energy
DOE NE	Department of Energy Office of Nuclear Energy
EBM	Electron Beam Melting
EBW	Electron Beam Welding
FGM	Functionally Graded Materials
HEA	High Entropy Alloy
HFIR	High Flux Isotope Reactor
HIP	Hot Isostatic Pressing
HTGR	High-Temperature Gas-cooled Reactor
IASCC	Irradiation-assisted Stress Corrosion Cracking
ICME	Integrated Computational Materials Engineering
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LFR	Lead-cooled Fast Reactor
LPBF	Laser Powder Bed Fusion
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability
MDDC	Multi-Dimensional Data Correlation
MGI	Materials Genome Initiative
ML/AI	Machine Learning and Artificial Intelligence

MSR	Molten Salt Reactor
NDE	Nondestructive Evaluation
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEI	Nuclear Energy Institute
NEUP	Nuclear Energy University Program
NMDQi	Nuclear Materials Discovery and Qualification Initiative
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
NSUF	Nuclear Science User Facilities
NTD	National Technical Director
ODS	Oxide Dispersion Strengthened
ORNL	Oak Ridge National Laboratory
PIE	Post-Irradiation Examination
PM-HIP	Powder Metallurgy Hot Isostatic Pressing
PNNL	Pacific Northwest National Laboratory
PWR	Pressurized Water Reactor
R&D	Research and Development
SCC	Stress Corrosion Cracking
SFR	Sodium-cooled Fast Reactor
SMR	Small Modular Reactor
TAL	Technical Area Lead
TCR	Transformational Challenge Reactor
TEM	Transmission Electron Microscopy
TRL	Technology Readiness Level
US	United States

1 INTRODUCTION

In the FY21 appropriation, Congress provided funding for a "new program to strengthen the pipeline of new materials that can make the current fleet, as well as new advanced reactors, more resilient and economically competitive." To this end, the Advanced Materials and Manufacturing Technologies (AMMT) program was established in FY22. It integrated three programs below within the Department of Energy's Office of Nuclear Energy Reactor Fleet and Advanced Reactor Deployment:

- Advanced Methods for Manufacturing (AMM)
- Nuclear Materials Discovery and Qualification Initiative (NMDQi)
- Transformational Challenge Reactor (TCR)

Through the integration and coordination of these existing programs, the AMMT program aims to provide national and international leadership in developing technology-based solutions for advanced materials and processes for use in the deployment of advanced nuclear reactors and sustainment of the current fleet.

Advanced materials and manufacturing are enabling technologies that could benefit nuclear energy development tremendously. However, the precedents for the transition of new technologies into nuclear systems have been neither fast nor efficient. The AMMT program seeks to change this by focusing on rapid qualification and technology demonstration. The technologies developed by the AMMT program have the potential to transform materials R&D efforts to be more flexible, rapidly responsive, and efficient. Faster incorporation of new materials and manufacturing technologies into complex products and systems holds the possibility of ever-increasing advantages in cost, performance, durability, and new functionalities.

2 BACKGROUND

2.1 Nuclear Energy Technology Overview

Advanced nuclear energy systems hold enormous potential to reduce emissions, create new jobs, and build a strong economy. Many developers in the United States (US) are pursuing advanced technologies that will make nuclear energy more affordable to construct, operate, and maintain. A broad range of advanced reactor technologies are being considered, including Sodium-cooled Fast Reactors (SFRs), Molten Salt Reactors (MSRs), High-Temperature Gas-cooled Reactors (HTGRs), Lead-cooled Fast Reactors (LFRs), and advanced Light Water Reactors (LWRs). There has been increasing interest in building smaller sizes of reactors such as Small Modular Reactors (SMRs) (reactors with an output of 300 MW of electricity or less) and micro-reactors (reactors with an output of 10 MW(e) or less), owning to their various benefits. Table 1 provides a summary of typical operating conditions including coolant, neutron spectrum, operating temperature, pressure, and candidate materials for each type of reactors and their stakeholders at present [[1],[2]].

Molten Salt Reactors (MSRs) use liquid fluoride or chloride salt as a coolant. MSR concepts have been developed with either a thermal or fast neutron spectrum and with uranium, thorium, and plutonium fuels. The fuel can be solid, as in fluoride salt-cooled high-temperature reactors or can be dissolved in the liquid salt that also serves as the coolant material. Terrestrial Energy, FLIBE Energy, TerraPower, Kairos Power, Moltex, Southern, and Elysium are developing this concept. Development needs have been

[1] Nuclear Innovation Alliance (2021), "Advanced Nuclear Reactor Technology: A Primer."

[2] "Future Nuclear Energy Factual Status Document," resource document for the workshop on Basic Research Needs for Future Nuclear Energy, July 2017.

identified to advance MSR concepts to the deployment stage. One of the technological challenges is to develop materials that are compatible with fluoride or chloride salts, actinides, and fission products, and have adequate radiation-resistance and high-temperature performance.

High-Temperature Gas-cooled Reactors (HTGRs) use a gas coolant to enable high operating temperatures for high-efficiency electricity generation or to provide high-temperature heat for industrial processes. Their designs have either a thermal or fast neutron spectrum. TRISO fuel has been considered in the form of either pebbles or compacts in graphite blocks, or UC, PuC in SiC matrix or cladding. Companies who are currently developing this reactor technology are General Atomics, X-energy, and Framatome. Key material development needs are high-temperature, radiation-tolerant structural materials, such as C/C and SiC/SiC composites for core components, and high-temperature alloys for reactor vessel and piping systems. Resolving these material issues provides an opportunity to increase operating temperatures and optimize reactor performance, making the technology more flexible and attractive.

Sodium-cooled Fast Reactors (SFRs) are one of the most developed advanced reactor concepts. They use liquid sodium as coolant, providing systems with low pressure and high-heat removal capability and high-power densities. SFRs are designed to operate with a fast neutron spectrum providing high uranium resource utilization and waste minimization. The outlet temperature is above 500°C, higher than LWR outlet temperatures but not as high as in other advanced reactor concepts. Several SFR designs are being developed by TerraPower, GE Hitachi Nuclear Energy, and ARC. High-performance structural materials are needed to reduce cost and improve safety and reliability of SFRs. Austenitic stainless steels and ferritic/martensitic steels are the two classes of alloys that are of most interest for SFR structural applications. While these materials are generally compatible with liquid sodium, carbon transfer and the resulting effect are of concern for their SFR applications.

Lead-cooled Fast Reactors (LFRs) use lead or lead-bismuth eutectic as a low neutron absorbing, high-temperature coolant. LFRs are designed to operate with a fast neutron spectrum, supporting sustainable fuel cycle objectives. Molten lead, as a coolant, has a very high boiling point (1749°C) and does not react significantly with air or water. It provides potential benefits in terms of safety and design, including the elimination of intermediate loops required in other fast reactor concepts. Lead bismuth eutectic has a lower melting point than lead (124°C vs. 327°C), potentially allowing for simplified designs and operations. Key materials development needs include corrosion-resistant materials or coatings with good compatibility with lead or lead-bismuth in addition to radiation and heat resistance. Westinghouse is the main developer of LFR technologies.

Water-cooled Reactors use water as a coolant and moderator and operate with a thermal neutron spectrum. Light water reactors have two categories: Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). PWRs operate typically at reactor outlet temperatures of about 300°C. The fuel consists of uranium dioxide pellets clad in zirconium alloy tubes and arranged in fuel assemblies, supported by various structural components and systems contained in a pressure vessel. Most of nuclear power generated in the world today uses water-cooled reactor technology. These designs are well established and have a long history of performance. Their limitations are thermal efficiency, limited upper operating range, and generation of used nuclear fuel. The advanced reactor designs being developed aim to overcome these limitations. Advancement in structural components and materials provide benefits for life-extension and new construction.

Table 1. General operating conditions and key material systems of various nuclear reactor technologies.

Reactor Type	**Coolant**	**Neutron spectrum**	**Operating temperature (°C)**	**Operating pressure (MPa)**	**Fuel**	**Moderator**	**Structural Materials**	**Stakeholders**
SFR	Na	Fast	500-550°C	Near atmospheric	Metallic and oxide fuels	None	Steel alloys, e.g., G91, 316H, A709	Terrapower, GE, ARC
MSR	Fluoride/ chloride salt	Thermal or fast	600-750°C	Near atmospheric	Liquid or solid fuels	Graphite or zirconium hydride for thermal systems	Graphite, ceramic composites; vessel and piping generally high-Ni, low-Cr alloys, and low-cost steel alloys	Terrapower, Southern, Terrestrial, Elysium, Karios, Flibe, Moltex
HTGR	He	Thermal or fast	≤850°C	7 MPa	TRISO fuel	Graphite for thermal systems	Graphite, ceramics; A800H, A617, LAS, FM steels, 316H with cladding	General Atomics, X-Energy, Framatome
LFR	Pb, Pb-Bi	Fast	480-550°C	Near atmospheric	UO_2, UO_2-PuO_2 UN, UN-PuN	None	Steel alloys with coatings	Westinghouse
LWR/SMR	H_2O	Thermal	≤320°C	15 MPa	UO_2	H_2O	ASS, F/M, LAS, Ni alloys	NuScale, GE, EPRI, Westinghouse, Framatome, Holtec
Micro-reactor								Westinghouse, BWXT, X-Energy, Radiant, Oklo, USN

Smaller-sized reactors, such as SMRs and micro-reactors, are of great interest due to their flexible power generation options, the wide range of their applications, enhanced safety resulting from inherent passive safety features, reduced upfront capital investment, and possibilities for cogeneration and non-electrical applications. At the same time, they face various technical and economic challenges to their development and wide-scale deployment. It should be mentioned that these smaller reactors can be any of the reactor technologies described above.

Small Modular Reactors (SMRs) refer to reactors with small reactor size (up to 300 MW(e)) and an ability to combine multiple standardized modules. In contrast to conventional large-sized reactors that are built onsite, major components of the nuclear steam supply system of SMRs can be manufactured in factories and shipped to the power plant site. This allows the buildings and the reactors to be constructed simultaneously, reducing the deployment time. While SMRs can be based on a variety of reactor concepts, water-cooled SMR designs are leading the race of deployment. NuScale Power is building a small, modular, factory-built PWR. A plant can contain up to 12 modules with each module producing 77 MW of electricity. GE-Hitachi, Holtec are also working on their SMR designs. Structural materials being considered include austenitic stainless steels, low-alloy steels, ferritic-martensitic steels, and nickel-based alloys. Advanced high-performance materials and advanced manufacturing technologies are of great interest for enhanced safety, reliability, and economics of SMRs.

Micro-reactors refer to reactors with an output of 10 MW(e) or less. The main benefits of micro-reactors include that they are small and portable, or simple in design, and can be installed quickly onsite. Examples of micro-reactors under development are the Aurora Powerhouse (fast, heat pipes, >500°C) by Oklo, a micro modular reactor (thermal, graphite-moderated, helium-cooled, 630°C) by Ultra Safe Nuclear Corporation, a mobile micro-reactor (thermal, gas-cooled, >750°C) by BWXT, the XE-Mobile reactor (thermal, helium-cooled, >500°C) by X-Energy, and the eVinci™ micro-reactor (thermal, heat pipes, >750°C) by Westinghouse, and the helium-cooled Kaleidos micro-reactor by Radiant.

2.2 Industry Benefits

Deployment of advanced reactor technologies is critically dependent on the availability of materials with adequate performance in high-temperature, radiation, and corrosive environments. The diverse, new reactor concepts use various coolants, have different radiation environments and unique temperature and loading requirements, and their operating conditions are much more demanding than current nuclear power plants. Common challenges for reactor materials are radiation damage, coolant compatibility, and long-term effects of high-temperature exposure, and mechanical loads. Materials being considered today can be improved or completely new materials are needed to make advanced reactors safer and more reliable and economical.

As an enabling technology, advanced materials and manufacturing can have a broad impact on the nuclear industry. Materials with improved high-temperature performance enable reactor designs with higher operating temperature and greater thermal efficiency, provide a larger safety margin in component design, and/or reduce the material quantities for better economics. Advanced corrosion-resistant materials are needed to function in demanding environments so that advanced reactor concepts such as molten salt reactors and lead-cooled reactors can move forward and new reactor concepts that use different cooling mechanisms may become a reality. Corrosion-resistant materials can also reduce maintenance cost and increase the lifetime of a reactor. In all reactor concepts, neutron irradiation can cause significant displacement damage, resulting in severe degradation of the material properties of core components and pressure boundary structures. The benefits of advanced materials with radiation resistance includes long lifetime, less inspection and maintenance cost, and fewer component replacements.

The impact of advanced manufacturing technologies on advanced reactors has been demonstrated in several aspects. New manufacturing technologies under development offer the promise to fabricate components with increasingly complex designs and design flexibility. New geometries can be built that cannot be fabricated with conventional methods, opening up design possibilities. Parts can be made as one-off components, and the design-fail-fix cycle can be shortened significantly. All these advantages of advanced manufacturing offer the potential to drastically lower the cost and lead time of product development. Innovative manufacturing technologies such as additive manufacturing also offer new ways to produce materials with tailored properties that were impossible with traditional manufacturing methods. Embedded sensing enabled by advanced manufacturing allows for enhanced system control, health monitoring, and autonomy. These new manufacturing technologies will be responsible for enabling the next generation of nuclear technology in addition to potentially significantly reducing the cost and supply chain dependence of reactor components.

2.3 Challenges

While the benefits and impact of advanced materials and manufacturing technologies are evident, several grand challenges must be addressed to accelerate their commercialization for nuclear energy applications.

Corrosion is a major concern in MSR design. Corrosion negatively impacts the mechanical performance, integrity, and longevity of structural components. Selecting the right corrosion-resistant material is crucial to the safety, durability, and economics of MSRs. To date, only a limited number of materials are resistant to molten salt environments. The passivated oxide layer formed on metallic materials provides minimal protection as it can be readily removed in MSR environments. In lead-cooled reactors, the corrosion and precipitation of corrosion products at colder locations in the reactor system is a major challenge in addition to liquid metal embrittlement. In sodium-cooled fast reactors, austenitic stainless steels and ferritic-martensitic steels are generally compatible with liquid sodium. However, carbon transfer in the sodium-material system can affect their microstructural stability and long-term performance and has been a concern in the structural designs of SFR components. Helium environments in high-temperature gas-cooled reactors can lead to environmental degradation of high-temperature alloys used for internals and heat exchangers in the presence of a low level of impurities in the helium coolant in the primary circuit. A fundamental understanding of corrosion mechanisms in various reactor environments is critical to the development of corrosion-resistant materials, performance predictions, and risk analysis.

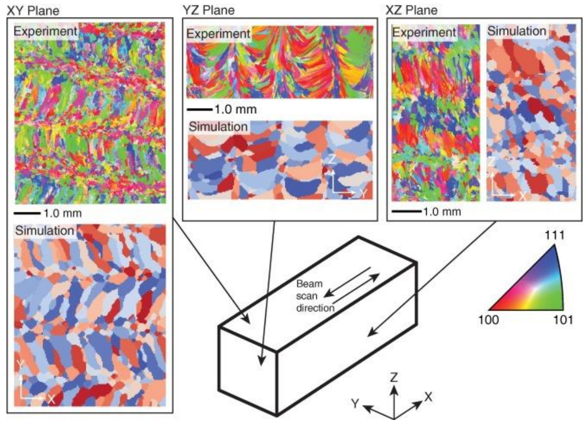
Materials degradation in irradiation environments is a universal issue for all reactor systems. Radiation damage processes are highly dependent on the material system and the irradiation environment of each reactor type. In general, radiation damage is manifested via five damage processes: radiation-induced hardening and embrittlement, irradiation-induced or enhanced segregation and phase stability, irradiation creep, void swelling, and high-temperature helium embrittlement. Radiation-resistant materials may be designed through using matrix phases with inherent radiation tolerance, selecting materials with low vacancy mobility at the operating temperature, or materials engineered with high sink densities such as high-angle grain boundaries, immiscible interfaces of nano-layered composites, twin boundaries, free surfaces, or phase boundaries to achieve enhanced radiation resistance. [[3]] Smaller reactors are also

[3] S. J. Zinkle and L. L. Snead, Annu. Rev. Mater. Res. 44 (2014) 241.

sensitive to neutron economy, which may be addressed by advanced materials and manufacturing to some degree.

Advanced reactors are expected to operate at higher temperatures than current nuclear power plants. The high-temperature requirement is a challenge on its own and even more so when combined with corrosion and irradiation environments. A desire for lifetimes of 60 years or beyond in advanced nuclear energy systems has also placed severe restrictions on structural materials used at high temperatures. Due to a lack of understanding of very long-term microstructural stability and high-temperature properties such as creep and creep-fatigue, it is difficult to predict the performance of structural components in service environments, and very few materials are qualified for the design of the 60-year design life. Currently, only six materials have been approved for nuclear construction at elevated temperatures in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code. Accepting a new structural material into the Code is a lengthy process, which limits the number of qualified materials. The most-recently qualified material, Alloy 617, was added to the Code in 2019, and it is the only high-temperature material approved for Code use since the 1990s. The current qualification approach of high-temperature materials relies on extensive testing and empirical data extrapolation. It requires years of testing to qualify a new material for commercial use. This seriously delays the acceptance of new materials for nuclear construction at elevated temperatures even if they are relatively mature and have wide acceptance in other applications. Slow qualification and regulatory acceptance of new materials and manufacturing technologies has become a bottleneck for their deployment in advanced reactor systems and the existing fleet.

Qualification of materials made by advanced manufacturing (AM) technologies for nuclear use poses an additional challenge. AM materials are unique in many ways relative to materials made by conventional manufacturing methods. Materials designed and made for conventional manufacturing (e.g., casting, forging, rolling, etc.) rely on a well-defined thermal and mechanical processing condition that defines the material properties. The manufacturing process must then be performed in a qualified manner to ensure repeatability in creation of a component. Finally, the component itself must be certified to ensure that it meets the intended design performance. In contrast, advanced manufacturing technologies have thermomechanical conditions that may vary across a broad continuum between near and far from equilibrium conditions within a single component, resulting in local microstructure and mechanical property variations. For example, by building a component flexibly point by point, line by line, and layer by layer, additive manufacturing allows producing heterogeneous alloys with location-specific compositions and microstructures (Fig. 1) to meet functional requirements. This highly localized process gives rise to the advantages of versatility and flexibility, while in the meantime can lead to much greater variability in AM materials than conventionally made materials. The inhomogeneous nature of an AM material can lead to uncertainties in material performance and challenges at the component scale that make the qualification and certification process quite complex and expensive. In addition, these conditions vary as a function of geometry. Components with different geometries made using the same feedstock and the same process can have different defects, properties, and performance. For demanding nuclear applications where materials are exposed to high temperature, stresses, radiation, and corrosive environments, it is time-consuming, costly, and sometimes impossible to develop a large statistical database, particularly when different structures and properties throughout the volume of a part are considered. This severely limits the ability to implement new materials and manufacturing practices. A paradigm shift is needed to qualify materials and components made by advanced manufacturing technologies for use in nuclear energy systems.



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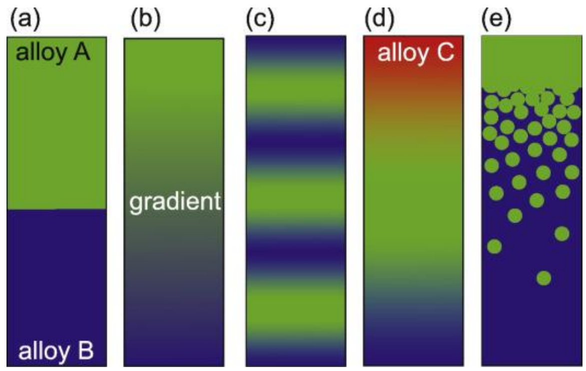

(2)

Figure 1. (1) spatially heterogenous microstructures of an additively manufactured alloy revealed by experiments and modeling [4]; (2) composition of different alloys to form functionally graded parts [5].

2.4 Opportunities

Many opportunities exist to develop high-performance materials to meet the demanding requirements of advanced reactors and to shorten the time from discovery to commercialization of new materials and manufacturing technologies. The Materials Genome Initiative (MGI) launched in 2011 aims to significantly reduce the time and cost for materials discovery and development. The vision of the MGI is to accelerate the discovery, design, development, and deployment of new materials through integrated efforts of experiment, theory, and computation. This new paradigm changes the historically sequential process of materials development to a concurrent process, in a circular way, to shorten the material development cycle. In a similar concept, the Integrated Computational Materials Engineering (ICME) framework uses multiscale computational tools to link the processing-structure-property-performance to predict component performance or to design materials for targeted functions to accelerate materials development and deployment. These methods rely on iterative, predictive approaches that integrate experiments and simulations to elucidate the fundamental mechanisms of materials microstructure development and property degradation at various length- and time-scales. The development under this new framework greatly accelerates the simulation-based design and qualification of new materials and systems, paving the way for rapid commercialization. While these advances have made a broad impact in other industries, their applications in the nuclear industry have not been widely adopted. A great opportunity exists for accelerating the development, qualification, demonstration, and deployment of nuclear materials

[4] T. M. Rodgers, J. D. Madison, V. Tikare, Comput. Mater. Sci. 135 (2017) 78.
[5] N. G. March, D. R. Gunasegaram, A. B. Murphy, Add. Manu. 64 (2023) 103415.

and components using an integrated approach incorporating the use of computational and data-driven methods coupled with advanced characterization and high-throughput testing techniques.

In situ process monitoring and sensing is beginning to see broad adoption in the additive manufacturing community [[6]]. Integration of process sensors and monitoring tools into the manufacturing process allows for detailed characterization and understanding of the build process. A wide range of optical, acoustic, and thermal signals can be recorded with various types of process sensors. When *in situ* monitoring data are linked with location-specific microstructure, properties of the printed component can be predicted (Fig. 2). Real-time process control is made possible by acquiring multiple sensor signals in real time and in a holistic manner and processed by machine learning and artificial intelligence-based tools. *In situ* real-time monitoring of process signals and part properties can provide feedback to modify the process parameters on-the-fly and operate in a closed loop, allowing for rapid optimization of processing conditions and component performance enhancement. Process data from *in situ* sensors can also be used to characterize the as-built component for features of interest for subsequent testing and part qualification and certification. Many opportunities exist in developing novel sensors, improving sensing techniques, developing computer vision-enabled automation of real-time data processing, and understanding how best to relate the *in situ* monitoring data to the quality of the final product. Integration of physics-based and/or data-driven models into the design tools and qualification framework are important steps for eventual use of *in situ* nondestructive evaluation (NDE) records for part inspection and qualification. These developments will ultimately allow greater acceptance of advanced manufacturing in the nuclear industry and unlock their full potential.

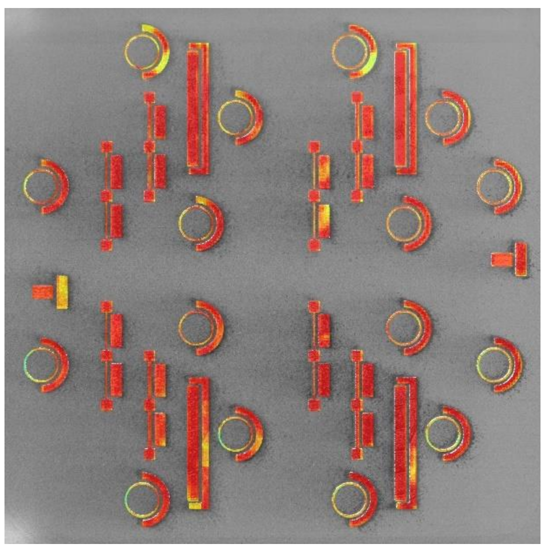

Figure 2. AI-based prediction of mechanical performance based on *in situ* processing data (colors represent mechanical property values; the shapes are parts within the printing layer).

High-throughput testing has the potential to significantly reduce the time of a material's development cycle through scaling up data generation and increasing the rate of sample exploration. These high-throughput approaches enable a rapid iterative down-selection process and have the potential to drastically accelerate nuclear materials discovery. Examples of high-throughput methods include rapid

[6] Q. McCann, et al., "In-situ sensing, process monitoring and machine control in laser powder bed fusion: a review," Add. Manuf. 45 (2021) 102058.

processing of large composition and phase fields guided by thermodynamics and kinetics (e.g., CALPHAD), testing a large array of materials with different composition/structure *in situ* and/or *ex situ* in simulated environments (e.g., ion irradiation or simulated corrosion environments) to generate large datasets for rapid screening; non-destructive, rapid characterization (e.g., synchrotron X-ray techniques) of a large number of samples; and automated hardness measurements and tensile tests to acquire mechanical property data.[7] The large datasets generated by high-throughput methods when coupled with machine-learning/artificial intelligence tools are extremely valuable to the understanding of the processing-structure-property-performance correlations of engineering materials.

Recent advances in electron, X-ray, and neutron characterization techniques have provided us unprecedented time and spatial resolution and *in situ* testing capability in complex sample environments, shedding new light on the mechanisms and pathways of microstructural evolution and its correlation with a material's macroscopic behavior. The advances in transmission electron microscopy (TEM) make it possible to directly observe defect dynamics and study the relationships among structure, chemistry, and behavior of individual nanoscale objects and internal interfaces through a variety of *in situ* experiments. Combining *in situ* ion irradiation, defect imaging, and spectroscopic mapping allows for examinations of the evolution of defects, phases, interfaces, and chemical segregation simultaneously under irradiation. High-energy X-rays and neutron beams provide high penetrating power, allowing for construction of complex, robust sample chambers that provide sample environments involving irradiation, temperature, load/pressure, and corrosive conditions that are significantly difficult or impossible to achieve with other techniques. Studies of lab-scale bulk specimens with these advanced techniques can provide measurements of real materials under real conditions in real time. Dynamic phenomena, e.g., defect formation and evolution, phase transformation, and mechanical deformation and failure, can be revealed with these *in situ* measurements, shedding new light on key processes controlling material macroscale behavior. Three-dimensional characterization techniques provide a more complete understanding of microstructural heterogeneity and localized deformation and corrosion, which are critical to the understanding of materials behavior and predicting a material's performance, aging, and degradation in nuclear environments.

As powerful as it can be, no single technique or single experiment can provide sufficient information to paint a complete picture of material responses to complex reactor environments. Combining a suite of scattering, imaging, and spectroscopy techniques involving electrons, X-ray, and neutrons to analyze the material behavior at multiple length scales is necessary to develop an integrated and accurate view of the structural interactions across the scales. More importantly, advanced characterization and *in situ* experiments must be integrated with computer modeling to maximize their impact.

Multiscale modeling and simulation and data-driven computational methods are important tools to understand and predict the full range of physical phenomena that occur during manufacturing processes and under the service environments in nuclear reactors. For example, a phase field approach can be used to determine the effects of solidification conditions, weld pool geometry, and multiple passes of the heat source on the resulting grain morphology during manufacturing. Precipitation modeling is used for industrial process optimization of new alloys. Crystal plasticity-based micromechanical simulation and machine learning methods such as neural networks can map out the key trends linking processing-structure-property-performance and allow for reliable data extrapolation to predict a material's long-term behavior. Multiscale modeling of radiation damage has significantly advanced our understanding of fundamental processes of displacement damage to materials under irradiation. By incorporating greater use of computational and data-driven methods coupled with advances in characterization and testing, a new

[7] Adrien Couet, "Integrated high-throughput research in extreme environments targeted toward nuclear structural materials discovery," J. Nucl. Mater. 559 (2022) 153425.

framework can be established to accelerate the development and qualification of new materials and manufacturing technologies for nuclear applications.

3 PROGRAM OVERVIEW

3.1 Mission, Vision, and Goals

The mission of the AMMT program is to develop cross-cutting technologies in support of the current fleet and the next generation of advanced nuclear reactor technologies, and to maintain US leadership in materials and manufacturing technologies for nuclear energy. The overarching vision of the AMMT program is to accelerate the development, qualification, demonstration, and deployment of advanced materials and manufacturing technologies to enable reliable and economical nuclear energy. Three major goals were set to realize the mission and vision of the AMMT program: (1) to develop advanced materials and manufacturing technologies that have cross-reactor impacts, (2) to establish a comprehensive framework for rapid qualification, and (3) to demonstrate and deploy technologies with commercial stakeholders to bring new materials and manufacturing technologies to market in a timely manner.

3.2 Program Strategy

The AMMT program strategy includes the following key objectives:

- Target big challenges and game-changing technologies with the focus on demonstration.
- Develop a broad range of materials and manufacturing technologies that have cross-reactor impacts.
- Perform transformative research to develop new materials concepts and design.
- Integrate materials development, advanced manufacturing, and environmental effects to accelerate qualification.
- Combine experimental, computational tools, and digital data for design of materials and systems throughout the product lifecycle.
- Execute R&D in multidisciplinary and cross-organizational teams to leverage collaboration and integration.
- Engage with all stakeholders to understand their foundational needs for industry, standards, Code bodies, and regulators.
- Demonstrate and deploy technologies with commercial stakeholders to enable technology adoption by the nuclear industry.

3.3 Program Elements

The AMMT program will address both near-term and long-term technological challenges facing the nuclear community. While it is important to provide near-term solutions to the nuclear industry to bring their designs to market, it is also imperative to invest in science and technology that could have high impact to provide long-term, game-changing solutions to fulfil the full mission of the Department of Energy (DOE). Given the complexity and breadth of the scientific and technological challenges that must be addressed by the AMMT program, collaboration and partnership with other entities is essential to the success of the AMMT program. In this context, the AMMT program will have the following three program elements:

Development, Qualification, and Demonstration

This is the core program intended to target big challenges and game-changing technologies with the focus on technology demonstration. The objectives of the core program are to:

- Develop advanced materials and manufacturing technologies
- Establish a rapid qualification framework
- Evaluate material performance in nuclear reactor environments
- Accelerate commercialization of new materials and manufacturing technologies through demonstration and deployment projects

Capability Development and Transformative Research

This program element supports the development of capabilities needed for the core program and innovations. It will also support transformative research that may result in significant advances in materials design, discovery, and processing. Efforts will be made to:

- Develop accelerated testing and high-throughput characterization techniques
- Develop modeling capabilities for materials design, development, and qualification
- Perform transformative research to develop new material concepts and design

Collaborative Research and Development

This program element is intended for collaboration and partnership. Working with other DOE programs, funding agencies, industry, and universities will allow us to:

- Investigate a broad range of advanced materials and manufacturing technologies
- Address reactor-specific issues
- Leverage and collaborate on capability development
- Provide near-term material solutions to the nuclear industry

4 RESEARCH FOCUS AREAS

In support of the objectives under the first two program elements, i.e., "Development, Qualification, and Demonstration" and "Capability Development and Transformative Research," we have identified the following seven research focus areas.

4.1 Advanced Materials and Manufacturing

The vision of the AMMT program is to develop materials as an integrated part of advanced manufacturing. The development of advanced manufacturing in recent years has opened up new fields in modern metallurgy. Advanced manufacturing can enable new material designs (compositional and microstructural) that are currently unavailable or with limited possibilities using conventional manufacturing methods. For example, the unique characteristics of additive manufacturing such as rapid, localized heating, exceptionally high cooling rates, and inherent chemical heterogeneities can unlock the potential to create unique microstructures unachievable with conventional manufacturing techniques. We will focus on developing materials that can be optimized or improved for advanced manufacturing technologies or completely new innovative materials enabled by advanced manufacturing. An application-based materials design and development approach will be used, integrating functional requirements, characterization, manufacturing data, AI/ML and modeling and simulation.

Several research topics have been identified in the advanced materials and manufacturing area including:

- Materials optimization/development for AM technologies
- Innovative new materials developed through AM technologies
- AM process understanding and technology development
- Multi-attribute optimization of innovative materials for use in nuclear environments
- Integrated design of material, manufacturing and product for functionality
- AM component design optimization by integrating the processing-structure-property-performance relationships into Design-for-Functions tools
- Multifunctional, multi-material component designs and fabrication
- Design of embedded sensors for reactor in-service monitoring

4.1.1 Materials Development

Through advanced manufacturing techniques, new materials can potentially be created for many applications in nuclear reactors [8]. Advanced manufacturing techniques range from additive manufacturing such as laser powder bed fusion (LPBF) to coating techniques such as cold spray. Additive manufacturing is an innovative technique that can produce components at near net shape with minimal machining. Existing engineering alloys are not always well-suited for fabrication with additive manufacturing, because their compositions have been tuned to optimize fabrication via conventional methods. Thus, research is needed to produce similar alloys with modified compositions that are better-suited for additive manufacturing and for improved performance. There is great potential to develop AM-based steels that can benefit from the thermal cycles associated with AM to improve radiation tolerance and creep resistance while using elements that reduce neutron activation. The high cooling rates together with the re-heating cycle during sequential layer building may result in high densities of precipitation in ferreous alloys, significantly increasing their performance in high-temperature and irradiation environments. The quenching cycles that occur during additive manufacturing may produce novel routes to manufacture innovative alloys for high irradiation dose applications. Optimized microstructures may be achieved through combined alloy composition and process designs. Alloys may be designed less sensitive to AM thermal signatures to reduce variations introduced by geometrical factors and processing effects, or conversely, more sensitive to AM processing to obtain tailored, unique microstructures and properties.

Additive manufacturing can also be a novel approach for developing metal matrix composites such as oxide dispersion strengthened (ODS) alloys. Opportunities exist to obtain more homogenous distributions of dispersed strengthening particles using additive manufacturing, which are difficult to obtain through conventional manufacturing. Liquid state AM processes like LPBF, electron beam melting (EBM), and direct energy deposition (DED) can provide rapid cooling rates that severely reduce the diffusional growth time of strengthening phases to achieve more uniform distribution of second-phase precipitates and to retain fine-grained structures to enhance the mechanical properties and radiation resistance of the alloys.

Components made of high-melting point refractory metals and alloys such as tungsten, molybdenum, tantalum, and niobium have unique properties and applications in high-temperature, corrosive, and irradiation environments. They are, however, difficult to process using conventional metal processing methods. AM technology could help expand the use of these materials in advanced reactors. One example of a radiation-tolerant alloy composed of refractory metals are the refractory metal high

[8] F. Balbaud, C. Cabet, S. Cornet, Y. Dai, J. Gan, M.H. Mayoral, R. Hernandez, A. Jianu, L. Malerba, S.A. Maloy, J. Marrow, S. Ohtsuka, N. Okubo, M.A. Pouchon, A. Puype, E. Stergar, M. Serrano, D. Terentyev, Y.G. Wang, A. Weisenburger, "A NEA review on innovative structural materials solutions, including advanced manufacturing processes for nuclear applications based on technology readiness assessment," Nuclear Materials and Energy 27 (2021).

entropy alloys (HEAs). AM could be used to produce these materials for nuclear applications where high temperature strength and extreme radiation tolerance are required.[9]

There is also a tremendous opportunity in producing functionally graded materials (FGMs) with additive manufacturing. The point-by-point and layer-by-layer building process allows an unprecedented freedom in manufacturing complex, heterogeneous structures with high precision. By locally controlling material composition and process parameters, the desired microstructure and properties can be achieved as a function of position with good spatial resolution. The possibility of designing the microstructure through targeted optimization of composition and process parameters in FGMs could pave the way towards broad applications of AM materials in the nuclear sector.

Solid-based AM techniques can overcome some of the challenges in liquid-based AM processes and should therefore be considered in material design and manufacturing as well. Solid-state additive manufacturing techniques are generally divided into two broad categories, plastic deformation-based and sinter-based, depending on the metallurgical bonding mechanisms, range of processible alloys, and resulting microstructures [10]. Binder jetting uses a binder to hold powder together followed by sintering that consolidates the powder into a dense part without melting. This technology may be well-suited for producing complex parts of ODS alloys. Other advanced manufacturing techniques use severe deformation to impart high densities of dislocations in the material while forming it into a tube or plate form [11]. This does not allow one to produce complex shapes but can be used to produce tube, plate, or rod materials with a high density of sinks for extreme radiation tolerance.

Advanced manufacturing techniques such as cold spray, thermal spray deposition, atomic layer deposition, vapor plasma spray, chemical vapor deposition, and physical vapor deposition can also lead to improved and/or new materials for nuclear applications. During a loss of coolant accident scenario, the core of the LWR can reach temperatures over 1000℃ in steam. Advanced reactors such as molten salt reactors require materials with improved corrosion resistance. In both scenarios, providing a coating (e.g., chromium for LWR or nickel for MSR) using advanced coating technologies can significantly improve the corrosion or oxidation resistance, leading to improved performance in these harsh service conditions.

To enable the design and development activities planned for this research area, the methodology for designing alloys best-suited for AM must be thoroughly evaluated. One such methodology study addresses these challenges by designing new alloys that are less sensitive to variation in AM processing conditions effectively and economically. This led to the focus on "printability," a global quantifiable indicator for the resistance of an alloy-process combination to the formation of defects that compromise the integrity of the print [12]. A new AM material design and optimization framework consisting of modeling and experimental aspects enables the determination of processing windows for newly developed AM alloys

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[9] O. El-Atwani, N. Li, M. Li, A. Devaraj, J.K.S. Baldwin, M.M. Schneider, D. Sobieraj, J.S. Wrobel, D. Nguyen-Manh, S.A. Maloy, E. Martinez, "Outstanding radiation resistance of tungsten-based high-entropy alloys," Science Advances 5(3) (2019).
[10] Nihan Tuncer and Animesh Bose, "Solid State Manufacturing: A Review," JOM, Vol. 72, No. 9, 2020, https://doi.org/10.1007/s11837-020-04260-y.
[11] A. Azushima, R. Kopp, A. Korhonen, D.Y. Yang, F. Micari, G.D. Lahoti, P. Groche, J. Yanagimoto, N. Tsuji, A. Rosochowski, A. Yanagida, "Severe plastic deformation (SPD) processes for metals," CIRP Annals 57(2) (2008) 716-735.
[12] L. Johnson, M. Mahmoudi, B. Zhang, R. Seede, X. Huang, J.T. Maier, H.J. Maier, I. Karaman, A. Elwany, R. Arróyave, "Assessing printability maps in additive manufacturing of metal alloys," Acta Materialia, 176 (2019) 199-210

in an efficient and accelerated fashion using readily available resources for AM practitioners without relying on proprietary models and codes [13]. A similar framework can be adapted for other AM processes.

The AMMT program will also evaluate the critical minerals applicable to the nuclear industry and determine activities to increase the effective use of such minerals through advanced manufacturing processes to minimize the wasteful use of critical minerals and therefore positively contribute toward the saving of scarce raw materials. The 2022 final list of critical minerals, which revises the final list published in 2018, includes the following 50 minerals: aluminum, antimony, arsenic, barite, beryllium, bismuth, cerium, cesium, chromium, cobalt, dysprosium, erbium, europium, fluorspar, gadolinium, gallium, germanium, graphite, hafnium, holmium, indium, iridium, lanthanum, lithium, lutetium, magnesium, manganese, neodymium, nickel, niobium, palladium, platinum, praseodymium, rhodium, rubidium, ruthenium, samarium, scandium, tantalum, tellurium, terbium, thulium, tin, titanium, tungsten, vanadium, ytterbium, yttrium, zinc, and zirconium. The Energy Act excludes "fuel minerals" from the definition of critical minerals, and uranium is used as a fuel [14]. The methodology identifying and defining a "critical mineral" includes three evaluation criteria, namely: (1) a quantitative evaluation of supply risk wherever sufficient data is available, (2) a semi-quantitative evaluation of whether the supply chain has a single point of failure, and (3) a qualitative evaluation when other evaluations are not possible. Although the full lifecycle of critical minerals may have an impact on potential optimization of processes to minimize the waste of critical minerals, two specific areas has been identified for focused research and development, namely: (1) waste minimization in current manufacturing processes by optimization or applying advanced manufacturing techniques, and (2) to design new alternative materials or alloys to replace the need for the critical minerals or to minimize the dependance on these materials. Advanced manufacturing processes may provide opportunities for manufacturing new materials with chemical compositions that are not previously possible.

4.1.2 Advanced Manufacturing

The Nuclear Energy Institute (NEI) identified 16 advanced manufacturing methods that are of the most interest to the nuclear industry. [15] The Nuclear Regulatory Commission (NRC) is currently evaluating five AM technologies, including LPBF, DED, powder metallurgy hot isostatic pressing (PM-HIP), electron beam welding (EBW), and cold spray [16]. Though additive manufacturing is the most well-known advanced manufacturing method, other manufacturing technologies also have great potential for nuclear applications. For example, the PM-HIP technique has potential applications in Class 1, 2, and 3 nuclear components and reactor internals. Cold spray may be used for mitigation or repair of stress corrosion cracking and has shown promise for in-plant repair applications. While these technologies are "mature" technologies in non-nuclear fields, they are considered as advanced manufacturing methods by the NRC. The advanced manufacturing technologies defined by the NRC are those techniques and material processing methods that have not been traditionally used or formally standardized/codified by the nuclear industry. These "mature" manufacturing technologies are being developed and demonstrated by the nuclear industry with the support of the Department of Energy Office of Nuclear Energy (DOE NE). For example,

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13 B. Zhang, R. Seede, L. Xue, K.C. Atli, C. Zhang, A. Whitt, I. Karaman, R. Arroyave, A. Elwany, "An efficient framework for printability assessment in Laser Powder Bed Fusion metal additive manufacturing," Additive Manufacturing, 46 (2021) 102018.
14 Federal Register/Vol. 87, No. 37/Thursday, February 24, 2022/Notices, page 1038.
15 "Roadmap for regulatory acceptance of advanced manufacturing methods in the nuclear energy industry," Nuclear Energy Institute, May 13, 2019.
16 NRC ML21074A037, "Draft advanced manufacturing technologies review guidelines."

EPRI together with several other industry partners are developing and demonstrating electron beam welding and PM-HIP to produce a 2/3-scale rector pressure vessel. A modular in-chamber EBW capability is being established in the US with funding support from the DOE NE and cost-shared with EPRI and NuScale Power. This project will significantly advance EBW technology for large-component applications and establish large-scale EBW capabilities for pressure-retaining components in the US. Various advanced manufacturing technologies are also being investigated in several Nuclear Energy University Program (NEUP) projects, e.g., friction stir welding optimized for joining ODS alloys, hot isostatic pressing (HIP) cladding and joining to manufacture large dissimilar metal structures, and cold spray for manufacturing ODS steel cladding tubes. The AMMT program will continue collaborations with industry, universities, and other programs/funding agencies to support the near-term applications of these technologies in nuclear sector.

We will initially focus on "new" technology, additive manufacturing. Despite that additive manufacturing has undergone significant development, an increased understanding of both manufacturing science and technology-related issues is needed for its wide adoption by the nuclear industry. Figure 3 summarizes key scientific and technological challenges in metal additive manufacturing. For powder-based manufacturing technologies, a better understanding of powder characteristics is required, e.g., the effects of variations in powder composition and characteristics on the microstructure to determine the powder chemistry and quality and their acceptable ranges to ensure adequate component performance. Understanding of the process-structure relationships in AM materials and prediction of spatial variations of microstructure, phases, and defects with respect to component geometry and location-specific process variations is critically important. The thermal history experienced by a material during additive manufacturing is very different from that of conventional manufacturing. Microstructures are produced through rapid solidification and high thermal gradients under far from the equilibrium conditions. The evolution of key microstructural features, e.g., solidification morphology, grain structure (size and shape), crystallographic texture, cell structures, secondary phases, chemical segregation, defects, and inclusions, are all affected by the processing parameters, and these microstructural features have a profound effect on the mechanical performance of AM components. The columnar grain structure and strong crystallographic texture along the building direction can contribute to anisotropy in mechanical properties of printed parts. The sharp thermal gradients associated with AM generate large residual stresses that can cause distortion and mechanical property degradation of AM components. Formation of defects during AM, such as porosities, delamination, and balling remains a challenge. Post-processing treatment, e.g., stress relief heat treatment, and HIP are commonly used to remove these defects. It is essential to understand the influence of both processing and post-processing conditions on residual stress, porosity, and microstructure of AM materials and determine the key processing and postprocessing conditions that have the most influence on component performance in nuclear environments. It is also important to perform sensitivity analysis for uncertainty quantification and determine the phenomena that most significantly contribute to these uncertainties.

Challenges pertaining to AM products also include surface finish, part size, part dimension accuracy, and product quality variations between machines and between batches of productions. There is a lack of a comprehensive understanding of the effects of component geometry on part quality and print consistency including geometric accuracy, defects, surface finish, residual stress, location- and orientation-dependence of microstructure and properties, and machine-to-machine variability and repeatability of printed components, all of which call for extensive R&D to accelerate commercialization of this new manufacturing technology. Efforts are also needed to develop a technical basis by intentionally generating defects in mechanical testing specimens and determining what types/sizes/distributions of defects should be concerned for mechanical performance in reactor environments and to establish defect acceptance criteria of printed components to meet performance requirements.

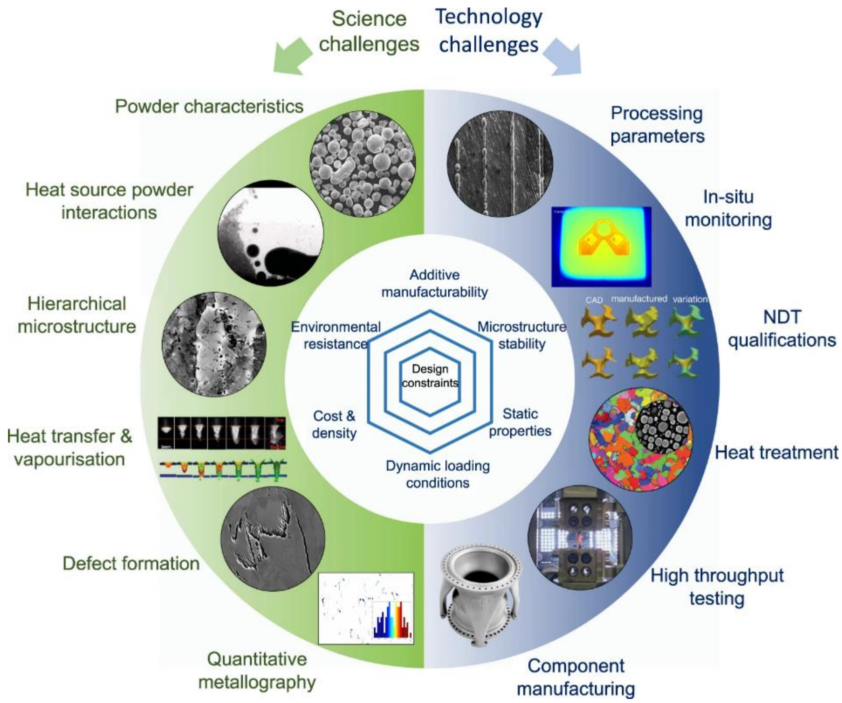

Figure 3. Key scientific and technological challenges in metal additive manufacturing [17].

Process sensing can record a wide range of optical, acoustic, and thermal signals during the advanced manufacturing process. These signals when acquired in a holistic manner and coupled with artificial intelligence-based machine control allow for rapid optimization of processing conditions and various properties of final products. Several issues remain to be elucidated, e.g., what needs to be measured, which *in situ* monitoring systems are best for a given purpose, how these measurements are related to the defects and microstructure of AM parts, and how best to use *in situ* process monitoring to recognize performance-limiting features. Integrated in-process sensing, monitoring, and control technologies need to be developed with the considerations of cost, machine compatibility, and workflow (e.g., optical and thermal imaging, spectroscopy, and other *in situ* NDE techniques). The *in situ* process data must be linked with residual stress, defects, and microstructure of parts printed in various geometries and dimensions, and their measured mechanical strength and ductility. How *in situ* monitoring (layer and sublayer measurements) during the build process will ensure the quality of a printed part must be demonstrated. The resolution, accuracy, and reliability of the sensors used must be understood especially when the final products are to be used in safety critical applications. What in-process monitoring data is needed for verification and validation of the part for nuclear applications remains to be determined. Other areas needing further development include computer vision and machine learning-enabled automated image analysis tools for *in situ* monitoring, physics-based and/or data-driven models that can be integrated into the design tools and qualification framework, and pathways that allow use of *in situ* NDE records for component inspection and qualification.

[17] C. Panwisawas, Y. T. Tang, R. C. Reed, Nature Communications 11 (2020) 2327.

Post-process NDE has been identified as a universal need for the qualification and verification of components made by advanced manufacturing [18]. One of the key barriers is that existing NDE techniques are not optimized for AM processes, materials, or components. Advanced reliable and high-resolution NDE techniques are needed for non-destructive evaluation of parts with complex geometry. Developing accurate, sensitive, and rapid NDE techniques for AM is a key technology development need.

4.2 Rapid Qualification

Advanced manufacturing poses a unique challenge to the qualification. Because of local variations and spatial dependence of AM components, we must consider different microstructures and properties throughout the volume of a component that cannot be easily handled by traditional qualification methods. We will take this opportunity 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 (ML/AI) tools, in concert with accelerated testing and high-throughput characterization techniques. We select LPBF 316 SS as a test case based on the results of the material scorecards described below. 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.

4.2.1 Material Scorecards

The selection of additively manufactured 316 SS as a case study was based on the recent material scorecard work funded by the DOE NE. Research was conducted to develop material scorecards to prioritize for advanced manufacturing [19]. Effort was guided by the evaluation criteria established by the program, including (1) Code availability for the material and manufacturing process; (2) gaps in data availability for performance values and measurements; (3) technical maturity for the end use/development stage (technology readiness level (TRL) and manufacturing readiness level); (4) deployment readiness requirements (from the near term to long term); (5) supply chain availability; and (6) programmatic factors i.e., applicability across reactor types. Nine materials were considered, namely, 316 SS, 304 SS, Alloy 800H, Alloy N, HT9, Alloy 617, Alloy 718, Graphite C/C, and SiC composites. The material selection was based on a survey and the number of times the material type was referenced for all reactor types including LWR, SFR, LFR, MSR, VHTR, and micro-reactor. The assessment showed that additively manufactured austenitic steel grades 316L SS and 304 SS were most promising for nuclear deployment and had the highest level of overall maturity and readiness level (Fig. 4).

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[18] J.M. Waller, B.H. Parker, K.L. Hodges, E.R. Burke, J.L. Walker, and E.R. Generazio, Nondestructive Evaluation of Additive Manufacturing State-of-the-Discipline Report, (2014).
[19] T. Hartmann, S. Maloy, M. Komarasamy, "Materials scorecards, Phase 2," PNNL-32744, PNNL, March 2022.

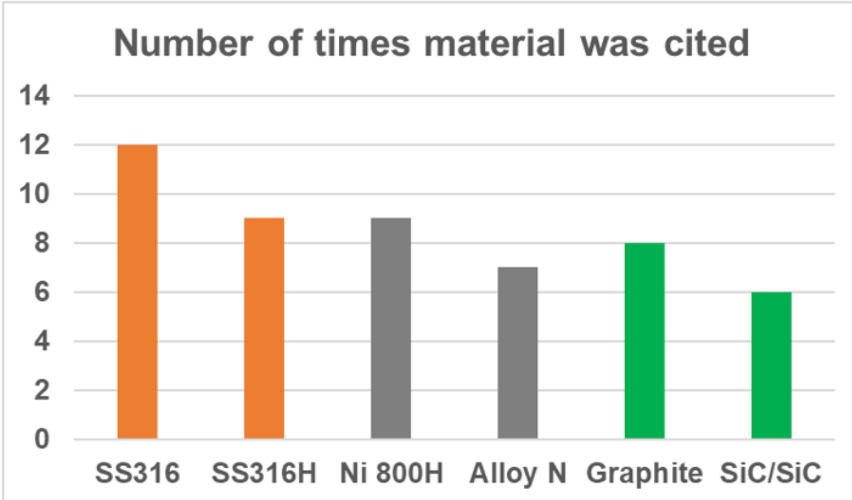

Figure 4. The number of times a material was referenced by survey participants as a candidate for advanced manufacturing for nuclear application. [[20]]

4.2.2 Qualification Approaches

A number of qualification pathways have been proposed for AM materials, processes, and components [[21],[22]] e.g.:

(1) 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.

(2) 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.

(3) *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, e.g. *in situ* Infrared (IR) 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.

(4) 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

[20] T. Hartmann, R. Devanathan, "Materials scorecards, Phase 1," PNNL-32373, PNNL, November 2021.

[21] https://www.nist.gov/programs-projects/qualification-additive-manufacturing-materials-processes-and-parts.

[22] C. Hensley, K. Sisco, et al., J. Nucl. Mater. 548 (2021) 152846.

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.

A quantitative understanding of processing-structure-property-performance correlations is essential for laying scientific foundations for accelerated qualification of new materials and manufacturing technologies. An AM qualification approach must consider a large number of variables involved in the AM processing and post-processing, e.g., machine settings (beam power, beam size, scan speed, scan pattern, layer thickness), powder characteristics (particle size and size distribution, flowability, spreadability), and various post-build thermal-mechanical treatment conditions. All these variables affect microstructure (e.g., phases, grain size and shape, texture, dislocations), residual stress, internal defects (e.g., porosity, lack-of-fusion voids), and external defects (e.g., surface roughness and distortion). Mechanical properties of interest for nuclear structural applications, including tensile properties, creep, fatigue, creep-fatigue, impact property, fracture toughness, crack growth rates, etc., are all affected by microstructure and part defects, as well as the long-term behavior of materials in service environments of irradiation, high temperature, and corrosion. Some properties are very sensitive to defects while others are dominated by microstructural features at a range of size and length scales depending on the property of interest. Furthermore, location-specific microstructural heterogeneity is expected/desired in parts with complex geometries. This highlights the strong need for a comprehensive examination of various factors controlling the mechanical behavior of AM materials and a solid understanding of the processing-structure-property-performance relationships.

In situ process monitoring and control is an essential part of an accelerated qualification framework. Integrating various process monitoring and measurement tools can produce multiple parts consistently across machines, operators, and manufacturing facilities, and can have a significant impact on part qualification and certification. Given the wealth of *in situ* data collected as part of the digital manufacturing process (e.g., manufacturing data, process parameters, sensor measurements, etc.), the new qualification scheme can take full advantage of the digital information and use machine learning to discover correlations from data produced through additive manufacturing and microstructural data critical to the performance of the component. Due to the complicated nature of the AM process, a coherent integration between various stages and scales of modeling the material behavior and the corresponding measurements is critically needed to enable an efficient qualification process using a physics-based, data-driven approach.

The concept of “qualify as you go” uses pre-process, in-process, and post-process measurements to demonstrate that a part will function as expected. This paradigm can be realized using a holistic, ICME-based qualification framework that encompass pre-process, in-process, and post-process data. The ICME-based qualification uses predictive and measurement tools to model heat transfer conditions, evaluate defect formation and microstructural evolution based on heat transfer, and predict the effects of defects and microstructure on properties and performance in nuclear environments. Extending an ICME approach to AM qualification is a paradigm shift. However, extensive effort is needed to develop model tools for complex AM process and for demanding nuclear applications where materials are exposed to high temperature, stresses, high radiation fields, and corrosive environments, limiting the ability to implement new materials and manufacturing practices in the near term. We will take a phased approach, transitioning from a more traditional approach such as a statistical-based qualification or an equivalence-based qualification to an eventual model-based qualification, to allow for near-term deployment of AM technologies while developing a long-term, game-changing solution.

It should be mentioned that while additive manufacturing is the focused manufacturing technology to drive the new materials development and qualification, we will ensure that the overall qualification framework to be developed is applicable to other material systmes and manufacturing technologies including qualification of conventionally made materials.

4.3 Material Performance Evaluation

Material evolution and lifetime in the harsh environments of advanced reactors must be considered as part of a reactor material development and qualification program. For materials and components used in nuclear reactors, environmental effects must be addressed to evaluate how the material and component will perform under irradiation, corrosion, and high-temperature loading conditions. Irradiation damage and high-temperature and corrosion degradation in nuclear reactor environments are complex and often coupled phenomena. Evaluation of nuclear environmental effects can be a long, expensive process. The goal of the AMMT program is to develop and use accelerated evaluation tools to perform rapid evaluation of environmental effects and understand time-dependent responses through modeling and simulation and data-driven tools to extrapolate short-term experimental data to long-term behavior in operating environments to accelerate materials development and qualification.

While advanced materials and manufacturing technologies can offer major advances in advanced reactor designs and sustainable operations of the existing fleet, evaluation of irradiation performance of new materials has become one of the most critical technical hurdles for their rapid adoption in nuclear energy systems. Studies of radiation damage and evaluation of materials performance under irradiation require multiple tools. Neutron irradiations in reactor environments are costly and take a long time to accumulate the damage of interest and require handling of radioactive materials. Ion irradiation as an accelerated irradiation tool can be used for rapid screening and evaluations of new materials to accelerate the development process. However, acceptance of data generated by ion irradiation to qualify new materials is a significant challenge yet to be addressed.

To address irradiation data needs, we will develop and demonstrate a new methodology that allows rapid, cost-effective, and reliable evaluation of the irradiation performance of new materials by an integrated approach combining high-throughput, accelerated ion irradiation and neutron irradiation testing, advanced characterization, multi-scale/multi-physics modeling and simulation, and machine learning and artificial intelligence. Considered by some to be the “holy grail” of radiation materials science, accurate quantitative predictions of materials evolution under irradiation must account for irradiation temperature, flux, fluence, energy, irradiating particle type, and sample geometry as well as materials composition and metallurgical conditions. Physics-based models are necessary to bridge the gap between ion and neutron irradiation as well as predict environmental effects under various reactor conditions. Machine learning models are useful for quantifying microstructural features and developing engineering-scale behavior models. Irradiation experiments and characterization are needed to provide the experimental input and validation data for the modeling approaches. Low-dpa irradiation data can provide information about the initial stages of irradiation damage in materials for input to physics-based and machine learning models, while high-dpa irradiations will provide validation data to the developed models. Research will focus on addressing the dose rate effect, effect of the primary damage spectrum, injected interstitials, sample geometrical effects, recoil energy spectra, cascade morphologies, effects of transmutation products, etc., observed in typical radiation behavior.

Regulatory acceptance of combined neutron and ion irradiation data in concert with modeling and simulation for qualifying new materials will be pursued as part of the new qualification framework. It is well recognized that both neutron and ion irradiation tools have their advantages and limitations. Significant efforts have been made in the past to establish the intercorrelations of neutron and ion irradiation data. While this attempt is important, it may be valuable to focus on the unique and complementary information each irradiation tool can provide and use the collective information to establish a technical basis needed for a material's qualification. For example, ion irradiation can be conducted in highly controlled environments and can generate high-fidelity experimental data useful for the microstructural-level understanding of a material's radiation behavior and for refinement and validation of computer models. The results can aid in the design of neutron irradiation experiments and analysis of neutron irradiation data and the predictions of material properties under design-base conditions. Both neutron and ion irradiation data need to be coupled with physics-based modeling to maximize their values. Future modeling effort needs to move beyond the current state of mean-field theories and isolated length scale modeling (atomistic, mesoscale, and macroscale) and integrate physics-based and machine learning models across length and time scales that allow the data extrapolation to the operating conditions to be achieved in a reliable fashion. By incorporating physics-based modeling results, design rules for radiation effects, which are still largely of empirical form, can be also improved. Initial effort will focus on additively manufactured 316 SS, but the methodology will be generalizable to other materials systems. The potential impact is to drastically shorten the development, qualification, and deployment cycle of new materials and manufacturing technologies for the nuclear industry.

Time-dependent deformation and fracture of materials at elevated temperatures remains one of the most challenging engineering problems. To develop an improved design methodology for structural components operating at high temperatures, several key high-temperature deformation and fracture mechanisms and their synergism must be understood. Long-term exposure at operating temperatures in advanced reactor systems can result in microstructural changes and associated mechanical property degradation. Correlation between microstructure and mechanical properties is important for extrapolating materials short-term behavior to the long design lifetime. There are also significant issues in the current ASME Code approach to extrapolate high stress and short-term creep data to determine design limits for low-stress and long-term conditions. However, extrapolation of test data is unavoidable because it takes too long to generate data that are prototypical. Fatigue at high temperature is a complex phenomenon due to a number of time-dependent processes involved. Time-dependent creep deformation can significantly reduce fatigue life, and, in turn, fatigue deformation can seriously reduce creep life. The interaction of fatigue and creep, the so-called "creep-fatigue interaction," is a significant structural failure mode that must be considered in the design of elevated-temperature components. Other processes such as oxidation, microstructural evolution, dynamic strain aging, etc., further complicate the creep-fatigue interaction process. Despite significant progress in this area, understanding of the complex creep-fatigue mechanisms is far from complete. To shorten the development and qualification cycle of new materials and manufacturing technologies, it is essential to be able to predict long-term high-temperature performance including creep and creep-fatigue behavior by performing short-term creep and creep-fatigue tests and modeling and simulation.

Materials in nuclear reactors can experience many forms of corrosion, e.g., stress corrosion cracking, irradiation-assisted stress corrosion cracking, general corrosion, oxidation, dissolution, liquid metal embrittlement, etc. Much knowledge has been developed over the years to understand the corrosion behavior of materials in various coolants at high temperatures. There is a lack of understanding to predict the effect of the corrosion process on microstructure and properties and associated degradation mechanisms, particularly in irradiation environments. Few studies have been done to understand the corrosion behavior of AM materials in reactor-relevant environments. The unique characteristics of AM materials, e.g., surface roughness, porosity, microstructural and microchemical heterogeneities, can make AM materials more susceptible to localized corrosion and galvanic coupling in different scales. Thin-wall structures made by

AM may have shorter lifetimes due to corrosion or stress corrosion cracking [23]. Systematic research is needed to understand the microstructure and the associated corrosion mechanisms of AM materials in environments of various reactor types. Corrosion behavior may be predicted under thermal and/or irradiation conditions, but an assessment of the state of corrosion modeling and identification of the needed type of prediction are first required.

4.4 Technology Demonstration and Deployment

Demonstration and deployment follow the research, development, and preliminary qualification of materials and manufacturing technologies based on processing-structure-property-performance relationships, as planned by the AMMT program. This represents the final step of the vision to accelerate development, qualification, *demonstration, and deployment* of advanced materials and manufacturing technologies, and would *secure access to and application of the technologies* by commercial stakeholders in the nuclear industry or their subcontractors. For new materials and reactor components, this stage aims to provide a test of technical performance under representative operating environments and further investigate economical and regulatory feasibility, which will require collating information/data, developing new documentation supporting the demonstration, evaluating and helping refine the manufacturing supply chain, and, finally, post-demonstration analysis. Achieving these goals will also command close interaction with the ASME Code Committees and the NRC. For experimental and computational tools and frameworks assisting materials development and qualification and for manufacturing technologies, the demonstration and deployment stage implies working with partners to enable application of these capabilities to problems of importance to them, which involves documentation, validation, verification, quality control, and collecting example problems.

Figure 5. The fuel assembly channel fasters printed at ORNL using the additive manufacturing technique and installed on ATRIUM 10XM fuel assemblies at Framatome's nuclear fuel manufacturing facility in Richland, Washington.

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[23] Cem Örnek, "Additive manufacturing – a general corrosion perspective," Corr. Eng. Sci. & Tech. 53 (2018) 531.

The actual demonstration and deployment of materials and components would be performed, first, in close collaboration with relevant DOE research programs, e.g., advanced reactor campaigns and the National Reactor Innovation Center (NRIC), and second, with commercial reactor developers and vendors or other non-nuclear commercial partners. This ensures engagement with stakeholders as well as prudent use of resources and facilities. The first step is intended to offer a low-barrier opportunity for initial demonstration, the results of which would be used to convince commercial stakeholders to pursue demonstration and deployment in collaboration with the AMMT program, which aims to build a case for full regulatory acceptance. The deployment targeted by the AMMT program refers to the pre-commercial stage, which could be followed by reactor developers, vendors, or their subcontractors adopting the technologies for commercial use. The format of the collaboration with stakeholders on demonstration and deployment is flexible and is expected to be formalized in close collaboration with partners and the DOE. We will learn from the past success of technology demonstrations under the TCR program (an example shown in Fig. 5) and continue to work closely with industry.

Success of the demonstration and deployment is defined in two parts. First, completing documentation, example problems, validation, verification, quality control, and supply chain management to perform demonstration of new materials and/or components that enable improved performance, cost reduction, or other benefits in representative operating environments, while maintaining an accelerated schedule compared to current practice. Second, for manufacturing technologies and for experimental and computational tools and frameworks, completing documentation, validation, verification, quality control, and examples are to have the capabilities be adopted and used in a productive manner by partners.

4.5 Advanced Experimental Tools

The successful execution of the AMMT vision requires a holistic research infrastructure for material development, rapid qualification, and understanding of processing-structure-property-performance relationships in reactor environments. A suite of experimental, computational, and data-driven methods has been identified to support the acceleration of materials development and qualification at all stages. Advanced experimental tools being considered are:

- *Non-destructive, 3D materials characterization*. Non-destructive, 3D characterization of defects and microstructures via X-ray, neutron, and/or other non-destructive imaging mechanisms can provide structural information and visualization of external and internal defects in materials and components. 3D characterization is particularly important for investigating materials with microstructural heterogeneities like AM materials. For example, 3D X-ray diffraction provides information of phases, residual stress, dislocations, grain/subgrain size distributions, and texture, which are particularly useful for understanding the spatial heterogeneity of AM materials. X-ray tomography can be used to inspect specimen geometry, dimensions, and porosity. Ultrasonic testing is an important NDE method for AM components.
- *High-throughput subsize specimen testing and validation*. Advanced manufacturing provides the possibility of functionally graded materials as well as novel geometries, and therefore a much higher level of characterization and testing is needed than in conventional manufacturing. Advanced manufacturing techniques, in particular additive ones, are expected to exhibit spatially dependent properties. This drives a need for high-throughput, subsize specimen mechanical testing and validation. Extraction of useful physical information from sub-sized specimen testing for AM materials is needed to screen and validate the proposed materials and for benchmarking and validations of physics-based or data-driven models. It is also necessary to demonstrate extrapolation of small-scale sample testing data to ASTM standard testing data and data validation assisted by computer models.

- *Automated microstructural analysis and quantification*. New material candidates and fabrication techniques are emerging rapidly for nuclear energy systems. In addition, advanced nuclear reactors operate at much wider conditions (e.g., temperatures, irradiation damage, corrosion environments) as compared with LWRs. The combination of the large number of new materials and the wide testing conditions makes material evaluation a great challenge. Particularly, the characterization of material microstructures is time-consuming and is often the bottleneck of material investigation. A machine-learning based microstructure feature extraction tool (2D and 3D) from non-destructive and destructive imaging using computer vision is of great importance. Accurate quantification of microstructure is essential to determining the properties and performance of the material. While good progress is being made in computer vision for microstructural analysis, a focused effort within the program will help unify individual approaches. Of particular importance is computer vision-enabled automated analysis of dynamic data from either *in situ* process monitoring or *in situ* observations of defect dynamics under irradiation. Key microstructural features with associated chemical information need to be identified for each targeted processing-structure-property-performance relationship.
- *Accelerated creep and creep-fatigue testing*. Conventional creep and creep-fatigue testing probe time-dependent material properties at elevated temperatures and involve long-term testing of many specimens. The long service-life requirements of nuclear structural components and the limited time available for development and qualification of materials require accelerated creep and creep-fatigue testing techniques to reduce the time required for testing material responses. An integrated modeling capability is also required to understand the time-dependent deformation and damage accumulation and predict the long-term behavior of materials. A multi-pronged approach of increasing the throughput of creep and creep-fatigue testing, use of advanced instrumentation and measurements techniques, in combination with modeling and simulation and AI/ML is necessary to decrease time requirements for material qualification.
- *Accelerated evaluation of material irradiation performance*. The response of materials to irradiation in reactor service environments is crucial to the lifetime and safety of nuclear reactor components. Each new material proposed for insertion into reactor environments must be assessed for its irradiation response, and irradiation response is strongly sensitive to composition changes as well as the as-fabricated microstructure, which varies depending on the specific processing details. Ion irradiation allows for much more rapid evaluation of radiation damage than neutron irradiation, speeding the timeline to understand radiation behavior. Advanced neutron irradiation platforms are also needed for the different environmental conditions of advanced reactor technologies. A feasible path forward is to use combined ion irradiation and neutron irradiation data supported by modeling and simulation for accelerated qualification of materials for use in nuclear reactors.
- *Accelerated characterization of combined irradiation and corrosion effects*. Evaluation of corrosion behavior to predict service life of structures in corrosive environments is a challenging task. Irradiation can accelerate corrosion of reactor core materials, and the combined irradiation and corrosion environments place the most severe demands on materials. A fundamental understanding of their combined effect is largely lacking. A new accelerated corrosion test method that can shorten the time needed to evaluate the corrosion performance of materials in nuclear reactor environments and predict the long-term performance of components is needed. Ion irradiation in highly controlled environmental cells (temperature, chemical environment, stress) can be used for rapid screening of materials and to understand coupled irradiation and corrosion effects. New tests may be needed for evaluating the corrosion effects of advance manufactured materials. Another key issue is the acceptance of data generated by surrogate tools, providing irradiated sample data and model predictions such that reactor designers, operators and regulators have confidence that materials are suitable for use in advanced reactor systems.

4.6 Advanced Computational Tools

- *Thermodynamics and kinetics*. CALPHAD methods have been widely used in alloy and process design. They allow for evaluation of multi-component, multi-phase systems in a wide range of composition, and processing conditions. The capability of computational materials design and accelerated qualification has been demonstrated for new alloy compositions on an industrial scale in other industries. The same approach can be applied to materials for nuclear applications to shorten the development and qualification cycle.
- *Microstructure models.* The design, development, and qualification of nuclear reactor materials relies on the processing-structure, structure-property, and structure-performance relationships. Understanding microstructure and its evolution under far-from-equilibrium conditions such as additive manufacturing and irradiation is fundamental to explaining a material's properties and performance. A multiscale tool is needed to quantitatively predict the evolution of microstructural features, e.g., grains, crystallographic texture, dislocations, dislocation substructures, stable and metastable phases, and various types of radiation defects during the manufacturing process and in-service environments involving irradiation, high-temperature, and corrosion.
- *Property prediction*. The mechanical properties of a material strongly depend on chemical composition and processing parameters. Understanding how each variable affects such properties is critical to materials design, development, and qualification. Physics-based predictive modeling combined with data-driven tools make it possible to identify the most relevant parameters that determine the properties of reactor components.
- *Radiation damage*. Radiation damage is an inherently multi-scale, multi-physics phenomenon, spanning time scales from picosecond to decades and length scales from atomistic to meters. A detailed understanding of the mechanisms of defect production, accumulation, and microstructural evolution and their effects on physical and mechanical properties is required to predict the performance limits in service environments. Multiscale computation tools together with advanced characterization techniques are essential to further the understanding of materials behavior under irradiation.
- *Computer vision and ML/AI tools*. Microstructural characterization, analysis, and quantification are essential steps in establishing the processing-structure-property-performance relationships. Recent advances in computer vision and machine learning offer great opportunities for microstructural quantification by extracting information from microstructural images. The computer vision and machine learning methods provide a promising direction to address the microstructural analysis and quantification challenge to advance the understanding of processing-structure-property-performance correlations. Data-driven ML/AI tools can also bridge the atomistic, microscale, and mesoscale for materials modeling, offering new insights into the design, development and qualification of new materials. More importantly, ML/AI tools can play a unique role in tackling complex engineering materials and manufacturing technology issues that involve a large number of variables.

4.7 Transformative Research

Material innovations call for transformative research that may result in significant advances in materials and manufacturing technologies, with the emphasis on the fundamental understanding of material behavior and exploratory materials development. These R&D efforts could have high impact but requires long-term, sustained investment. These long-term science and technology investments will pave the way for future breakthroughs in materials and manufacturing technologies to meet the needs of next-generation advanced reactors.

New materials have been historically developed through a trial-and-error experimental approach and a discrete and repetitive process. This development cycle is inevitably long and incurs high cost. Recent advancements in computational and experimental tools make mode-based design of new materials possible. Materials can be developed from a standpoint of fundamental properties (e.g., defect formation energy, phase stability, interfacial energy) to be resistant to advanced reactor conditions. Ideally, new materials will be designed with target properties for their service conditions to maximize their lifetime and avoid catastrophic failure mechanisms. The effect of irradiation on materials can be predicted via quantitative microstructure modeling under irradiation. Further, material compositions and as-fabricated microstructures can be selected to optimize material behavior (e.g., phase stability, swelling resistance, ductility) in reactor conditions depending on the performance metrics of interest. Material design capabilities developed within the AMMT program and by other research for non-nuclear materials (such as the MGI and the ICME approaches) can be leveraged with a new focus on advanced reactor considerations, especially combined irradiation, corrosion, and high-temperature effects.

The demanding, and often competing functional requirements of nuclear reactor materials require balance/trade-offs between many different properties, e.g., high-temperature strength, radiation resistance, corrosion resistance, economics, fabricability, scale-up, and weldability. A high-dimensional, nonlinear design strategy is needed to achieve multi-attribute optimization. The goal is to predict a composition and processing variables that are most likely to fulfil the multi-criteria target specification using a combination of physics-based and ML/AI models. Although it may take long time for this goal to be fully realized, interim, significant milestones can be impactful and beneficial to the industry.

Additive manufacturing provides a tremendous opportunity for integrated design and development of components, materials and manufacturing processes. An agnostic data-driven, physics-based material design and development framework will not only enable optimization of existing materials classes to improve radiation, corrosion, and high-temperature resistance, but also offers opportunities for designing and manufacturing innovative new materials incorporating understanding of new processes.

5 A FIVE-YEAR ROADMAP

Figure 6 shows our five-year plan that outlines major research topics and milestones of the AMMT program. Research activities in each topical area are elaborated in the following sections.

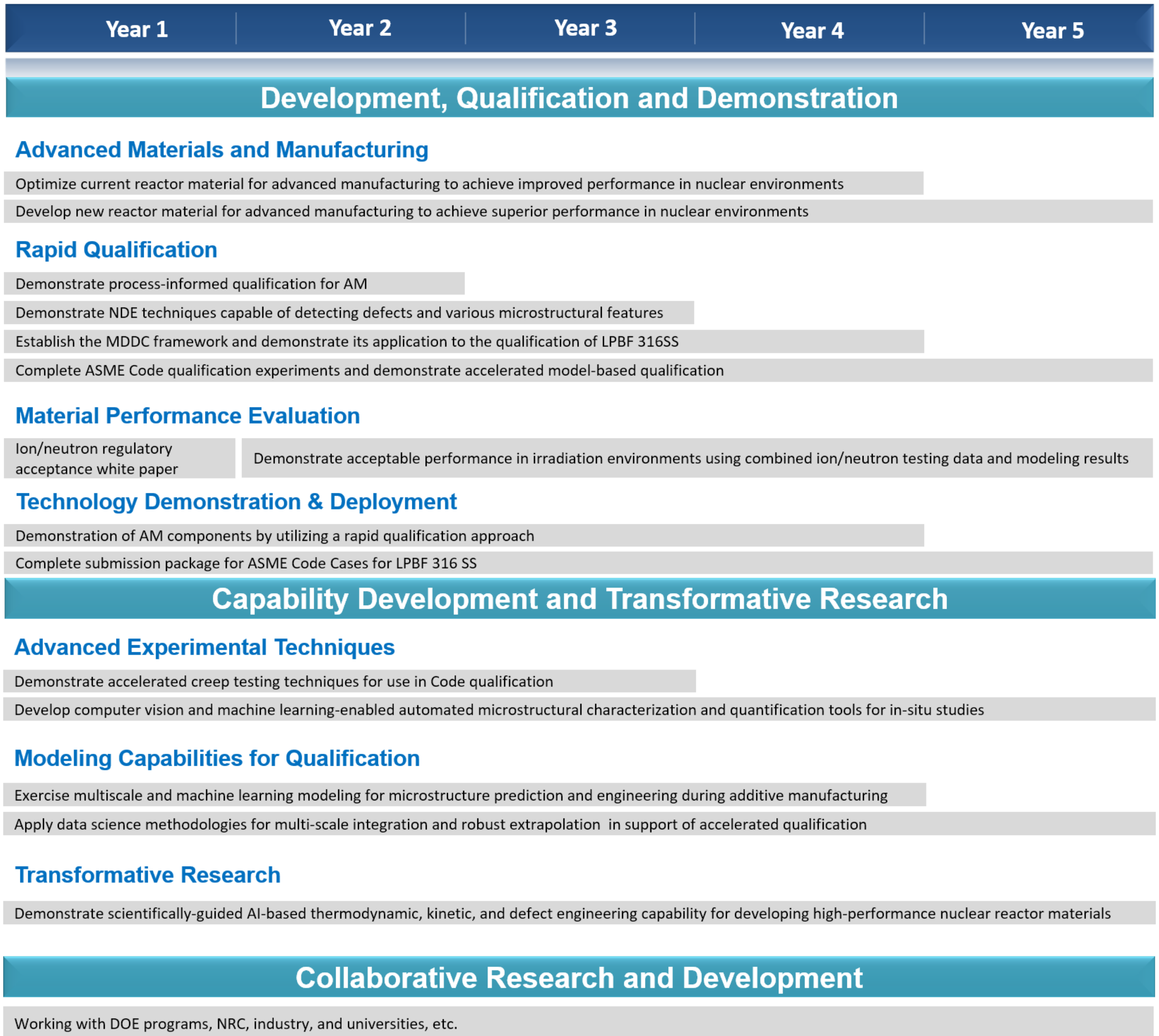

Figure 6. AMMT 2022 five-year roadmap.

5.1 Development, Qualification, and Demonstration

The Development, Qualification, and Demonstration program element integrates the materials lifecycle for materials enabled by advanced manufacturing. Integration is key to this program element as materials development, manufacturing, and qualification stages are envisioned to be performed in-parallel with close inter-linkages. It aims at achieving an optimal outcome for materials performance as well as reaching the demonstration stage, to be followed by deployment, in a timeframe that is reduced by a significant amount (half or less) compared to the current standard in the nuclear industry. The main target of this effort is reactor in-core and out-of-core structural materials, though a broader scope may be considered.

5.1.1 Advanced Materials and Manufacturing

Materials development focuses on products enabled by advanced manufacturing technologies that can achieve enhanced high-temperature properties and corrosion and radiation resistance. It considers both the improvement and optimization of existing materials for advanced manufacturing and the development of innovative new materials through advanced manufacturing. Material optimization will focus on austenitic stainless steels, ferritic-martensitic steels, and Ni-based alloys. Solutions to specific nuclear materials problems will be sought by various advanced manufacturing techniques, e.g. claddings/coatings to prevent corrosion in molten salt environments, unfavorable interactions between structural materials and coolant mediums or moderators in other reactor concepts. Novel manufacturing processes for fabrication of large-scale components will be explored for nuclear energy applications. Development of new materials enabled by advanced manufacturing technologies will consider material classes such as AM-based metal composites (e.g., ODS alloys), refractory alloys, high entropy alloys, ceramic composites, and functionally graded materials. In addition, the critical minerals task aims to develop resilient and secure supply chains for non-uranium significant materials critical to the success of nuclear energy technologies. Two major milestones to be achieved are (1) optimizing a current reactor material for advanced manufacturing to achieve improved performance in nuclear environments, and (2) developing a new reactor material through advanced manufacturing to achieve superior performance for nuclear applications.

- *Optimize and manufacture existing reactor materials*

The number of alloys currently commercially available for metal additive manufacturing is significantly smaller than ones available for conventional manufacturing processes. This limitation is regarded as a crucial barrier for the widespread adoption of new manufacturing technologies. Efforts will be made to optimize the existing reactor materials for advanced manufacturing to increase the number of alloys that can benefit from the new manufacturing technologies for nuclear construction.

Based on current use and advanced manufacturing readiness for materials, additively manufactured 316 SS is chosen as the first target material for design improvements. Specifically, optimized AM 316 SS will be developed to minimize microstructure heterogeneity through combined composition modification and manufacturing process optimization. The optimized AM 316 SS grade is expected to be less sensitive to AM thermal signatures and less dependent on geometrical and processing effects. A second objective is to modify 316 SS with tailored microstructures (e.g., controlled porosity, internal stress, grain and dislocation structures, and solute distribution) for improved radiation, corrosion, and heat resistance.

Although the highest priority material for nuclear applications was identified to be 316 SS, other types of austenitic stainless steels, ferritic-martensitic steels, and Ni-based alloys are also of high interest and will be addressed. Initial effort will focus on understanding potential candidate alloys, material prioritization, and down-selection. The selection process will be based on the significance to the nuclear industry, material processability via AM technologies, and improved performance. Materials for AM will be selected by considering their relative importance among the candidate nuclear materials as well as technological readiness levels of the base alloys for possible nuclear applications. The selected materials will be further developed for advanced manufacturing to achieve improved performance in advanced nuclear energy systems.

- *Develop and manufacture new materials*

Advanced manufacturing enables new material designs in both compositional and microstructural space that are currently unavailable or with limited possibilities using conventional manufacturing methods. We will exploit additive manufacturing to introduce new high-performance materials into nuclear energy systems. A select number of new materials will specifically be designed and developed for advanced manufacturing, which include AM-based metal composites (e.g., ODS alloys), ceramic composites, and refractory metals and alloys that can benefit from advanced manufacturing to expand their use in high-temperature, corrosive, and irradiation environments. Functionally graded materials enabled by advanced manufacturing that show promise for nuclear reactor applications are also of high interest, and coatings/cladding may be considered a sub-category of FGMs.

The most effective approach to designing radiation-resistant alloys involves the selection of intrinsically irradiation resistant crystal structures as well as the design of nanoscale features that can attract and annihilate radiation-induced defects. ODS ferritic alloys are currently the gold standard for high irradiation resistance and high-temperature dimensional stability, but they suffer from challenges of expensive conventional manufacturing costs and fabrication of complex component shapes. Conventional austenitic stainless steels suffer from poor void swelling resistance, which is a major concern for most reactor concepts. Swelling resistance of austenitic stainless steels can be improved by dispersion strengthening as well. Development of additive manufacturing and post-build processing routes for ODS alloys will be pursued for future nuclear applications. The process development will focus on optimizing the size and spatial distributions of oxide particles. Successful development in AM of ODS alloys will avoid the time-consuming ball milling process and can be a truly impactful technology for future nuclear applications.

High entropy alloys (HEAs) are a promising option for advanced nuclear applications, although knowledge of the radiation behavior and manufacturing capabilities of this material class is generally at a low TRL. Effort will be made to explore the recent advances in this material group due to the possibility that their composition can be optimized for a variety of parameters for enhanced high-temperature performance and corrosion and irradiation tolerance. Specifically, the need for manufacturing techniques for the upscaling of bulk HEAs is still one of the biggest hurdles in advancing the TRL of this alloy group and will be addressed.

New composite materials that benefit from various types of advanced manufacturing technologies for nuclear energy applications will also be explored, including ceramic composites in conjunction with a metallic (Mo, Zr, W) liner deposited using advanced manufacturing techniques. If successful, composites would be revolutionary when applied as claddings or casings for heat pipes and fuel and even structural core components. Refractories have similar applications and are also of interest to molten salt reactors as coating/cladding materials. In addition, bulk refractory alloys will also be assessed for their feasibility for advanced manufacturing processes.

- *Large-scale additive manufacturing for nuclear applications*

Large-scale metal additive manufacturing technologies like DED can fabricate components on the size scale of meters such as valves, pumps, impellers, etc., that are challenging or difficult to source, especially when developing new systems or replacing obsolete components. We will examine the possibility of using large-scale DED to fabricate nuclear components directly as well as the fabrication of HIP can technology for powder metallurgy applications. We will demonstrate the ability to fabricate large components for pressure boundary applications. *In situ* process monitoring will be employed to understand how to verify process quality and ultimately certify components for applications. Initial effort will focus on understanding the current state of large-scale DED technology for the deposition of 316 SS for final components and mild steel for use in nuclear manufacturing processes such as HIP can fabrication.

- *Critical minerals*

Advanced manufacturing may have a positive effect on the estimated demand and production capacity of critical minerals for nuclear energy. Critical minerals are defined as elements that are critical for materials' functionality and at the same time subject to supply chain constraints. We will address the supply of critical minerals, decrease the risk of supply while increasing cost effectiveness by applying more effective manufacturing processes. Experiments will be developed and performed for critical minerals for waste minimization of non-uranium significant materials for reactor deployment. These experiments will show the feasibility of how advanced manufacturing techniques can decrease the supply and economic risk including estimated demand and production capacity. The next step will be to develop a supply solution through application of replacement material design and development enabled by advanced manufacturing.

5.1.2 Rapid Qualification

Development of new and improved materials by advanced manufacturing must be combined with a rapid qualification framework to ensure timely deployment to reactor applications. A rapid qualification framework will be developed and prototyped using LPBF 316 SS as a test case and with combined experimental and computational efforts. It will be further supported by developing the MDDC platform to handle multi-length scale data needed for informed qualification and certification of nuclear components. Major milestones for the rapid qualification effort include (1) demonstrating process-informed qualification for AM, (2) demonstrating NDE techniques capable of detecting defects and various microstructural features, (3) establishing the MDDC framework and demonstrating its application to the qualification of LPBF 316 SS, and (4) completing the ASME Code qualification experiments and initial demonstration of accelerated model-based qualification.

- *Process understanding for qualifying LPBF 316 SS*

The first step in qualifying LPBF 316 SS is to understand the manufacturing process and how it correlates with microstructure and properties, both between components as well as spatially for a single component. Unlike traditional manufacturing, a part made by additive techniques is expected to exhibit variations in properties as a function of build geometry. The relationships governing this variation must be understood to achieve qualification. This will result in an ability to understand, predict, and control the effects of component geometry on part quality and print consistency including geometric accuracy, defects, surface finish, residual stress, and the location- and orientation-dependence of microstructure and properties. Several studies, such as fabricating square blocks of various sizes to introduce variations in thermal history and fabricating specimens for microstructure and mechanical property testing will be explored to accomplish this goal. Modeling and simulation will be utilized to understand the variations in thermal history and explain the testing results (an example shown in Fig. 7). The additive manufacturing process is sensitive to the specifics of each machine. Consequently, understanding machine-to-machine variability and repeatability is required for qualification across manufacturing platforms and sites and will also be investigated.

For qualifying LPBF 316H SS for high-temperature nuclear applications, research efforts are needed to develop processing conditions and proper post-processing treatments of the material to yield optimal material properties. Material properties must be evaluated across multiple AM platforms and locations. Effort will be made to understand the effects of processing and post-processing conditions on residual stress, porosity, and microstructure of LPBF 316H SS; identify the key process parameters and post-processing conditions that have the most influence on component performance; and determine the essential processing and post-processing variables and their ranges to ensure acceptable component performance. A round robin-style testing campaign is planned across multi-lab teams to understand the effects of processing conditions from different AM systems (i.e., Renishaw, EOS, and/or Concept Laser, etc.) and understand the variability of a specific equipment supplier (i.e., Renishaw) at each national laboratory. This will help to access the variability that is expected within the nuclear supply chain and help transfer the understanding gained within the AMMT program to industrial partners.

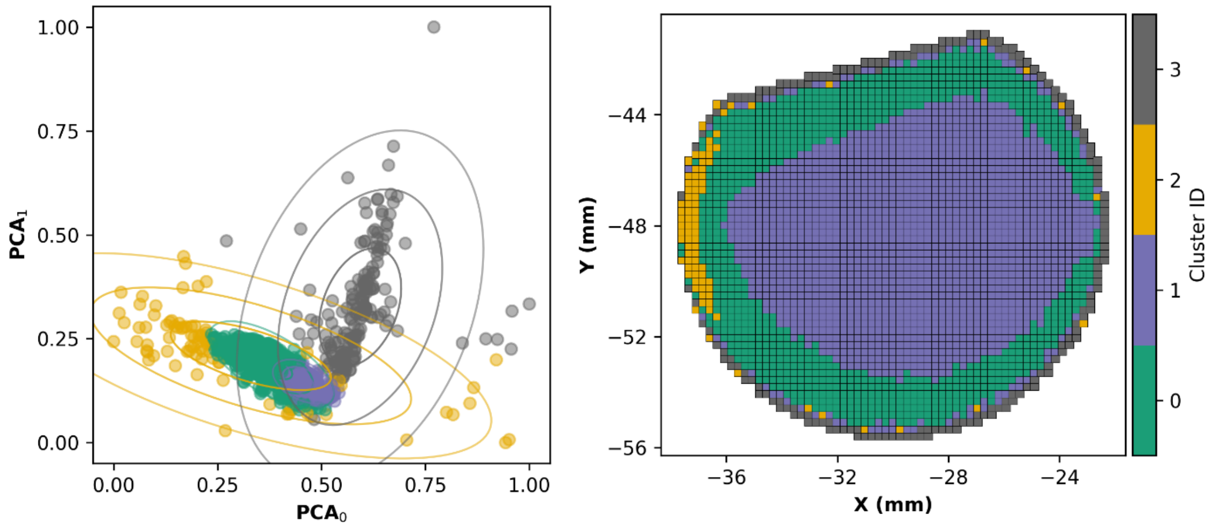

Figure 7. Cluster analysis of simulated melt pool characteristics in a 3D printed stainless steel.

ASME Code Cases for LPBF 316H SS must be supported by a comprehensive high-quality dataset on as-built materials and any post-treated materials. The dataset would include relatively short-term tensile properties, creep, fatigue, and creep-fatigue properties, and thermal aging data and extrapolation to long-term performance supported by modeling and simulation and ML/AI methods. Understanding the relationship between defects and properties, including the ability to model them, can be enhanced by intentionally generating defects by advanced manufacturing techniques and characterizing the resulting properties for use in development and validation of modeling capabilities. The goal is to determine what types/sizes/distributions of defects should be concerned for mechanical performance in reactor environments.

- *In-process Monitoring*

Licensing and qualification of AM materials for nuclear applications will likely rely on the successful integration of *in situ* process monitoring data with exhaustive characterization and testing to ultimately link specific processing conditions to microstructures to corresponding thermomechanical properties and irradiation performance. To translate the process understanding to qualification, it must be coupled to in-process monitoring techniques. Methods will be developed for identifying bounding process parameters, identifying the range of microstructures that could result for a given material system and fabrication process, and examination of additional sensor packages and techniques for rapidly identifying and quantifying how these extremes could impact functionality and performance under expected operating conditions. This includes the integration of novel instrumentation that could be used to characterize the evolution of residual strains resulting from the fabrication process or during qualification testing. These are all necessary to ease the burden of qualification by providing valuable *in situ* information regarding component health during nuclear operation and reduce the reliance on exhaustive testing.

- *Post-process NDE*

NDE is of critical importance to the certification and qualification of AM components. Although many NDE methods may provide accurate information for various types of components, it is not clear how advanced manufacturing may alter the results and accuracy of these methods. Specifically, advanced reliable and high-resolution NDE techniques for non-destructive evaluation of parts with complex geometries need to be identified or developed based on specific qualification requirements. We will explore the application of advanced ultrasonic testing and resonant ultrasound spectroscopy methods to LPBF components, evaluate their capabilities to verify materials properties, e.g., elastic modulus, hardness, and part defect detection capabilities, and their potential to be adapted from laboratory to industrial applications. Effort will also be made to develop a computed tomography technique combining X-ray computed tomography and neutron computed tomography, and the use of novel, laser-based measurements for examining thermal diffusivity to detect subsurface defects. We will also demonstrate how *in situ* process data can be used to complement/guide post-process NDE and to determine what *in situ* monitoring data is needed for verification and validation of the part for nuclear applications.

- *Mechanistic modeling for time extrapolation for accelerated qualification*

Prediction of high-temperature mechanical performance is important for understanding material property, performance, and component lifetime. Increased time extrapolation is one promising approach for accelerating the material qualification process for materials subject to high-temperature, long-duration service. Current empirical extrapolation techniques allow extrapolating the test data by about a factor of three to five (so a service life of 300,000 hours would require 60,000 to 100,000 hours of test data). Mechanistic, physics-based models are one way to increase this time extrapolation factor and therefore reduce the duration and amount of time-dependent testing required for material qualification. The modeling and simulations would encompass as-built and annealed materials, starting from material point predictions as a function of the local microstructure with extensions to full-component simulations. The ultimate goal is to be able to model the correlation of mechanical properties to microstructural and material processing parameters with uncertainty quantification. The grand challenge nature of this problem implies that a graded approach must be applied to ascertain timely progress and delivery. A mechanistic model for LPBF 316H SS targeting key material properties for applications in high-temperature nuclear reactors will be developed first. Irradiation creep behavior of LPBF 316H SS will also be modeled via mesoscale crystal plasticity models and macroscale reduced-order models.

Given the wide spectrum of microstructures produced by AM, tools to predict the potential variability in the tensile, creep, and creep/fatigue response caused by microstructure are needed. As the material is subjected to temperature and stresses, its microstructure will evolve notably by forming precipitates. To date, precipitate nucleation and coarsening is modeled using software such as PrecipiCalc and TC-Prisma. These are, however, weakly sensitive to internal stresses and to defects resulting from processing. A fundamental modeling framework is necessary to quantify how aging kinetics and precipitate distributions may be different in a metal processed by additive manufacturing vs. a conventional material. Modeling and simulation will be closely linked with experimental work for model development, calibration, and validation. A goal is to demonstrate a rapid qualification methodology supported by physics-based modeling and machine learning methods.

- *Multi-Dimensional Data Correlation (MDDC) platform*

For advanced manufacturing technologies to be integrated into mainstream production processes, we must be able to determine how materials will react to the manufacturing process, the resulting material performance over the lifetime of the component, and how we can guarantee repeatable quality. Although these processes are typically complicated, they can be interrogated during the manufacturing process using advanced sensors and produce significant quantities of data (upwards of terabytes of data and beyond). Utilization of artificial intelligence, machine learning, data analytics, and computer vision on this data has shown the ability to control the material performance at length scales well beyond traditional processes. The AMMT program intends to build an MDDC platform to seamlessly integrate data from designers, manufacturers, and the certification process flows, as illustrated in Fig. 8. This platform will be capable of correlating the geometry, process, material inputs, and modeling information with outcomes of the process including advanced characterization, mechanical properties, radiation and corrosion behavior, and models of predicted performance. The creation and utilization of the MDDC platform enables the ability to understand and improve advanced manufacturing processes while rapidly defining the key processing parameters governing material performance, rapidly develop new materials with superior performance and lower cost than conventionally fabricated materials, and aid in the certification and qualification for AM technologies.

The MDDC platform is envisioned as the container of manufacturing and characterization data as well as modeling and will have a central role in the qualification framework. As such, the first step is to establish an understanding of qualification processes and strategies used in the nuclear industry and other industries with lessons-learned and current acceleration activities underway in industry, national labs, standards organizations, regulatory organizations, etc., that will shape the digital platform to be developed. Regardless of the details of the architecture, the development will take an incremental approach to the problem. The first step is to incorporate five pedigree datasets and incorporate five data modalities, followed by a second step in which an additional five data modalities will be incorporated with the added goal of demonstrating linkage between data modalities. Predictive modeling will be tied to the digital platform with the goal of demonstrating the ability to link the experimental data to the predictive models. The developments of the MDDC platform will be put to test by demonstrating the framework for qualification of LPBF 316SS components. Following this demonstration, application of the MDDC framework to other manufacturing technologies will be pursued.

The MDDC framework is intended to be applied to multiple manufacturing processes in a systematic way based on industry inputs. Specific components of the platform, including materials modeling, advanced characterization methods, mechanical testing, and predictive performance models, are mostly independent of the manufacturing process and can be applied to a range of different processes. The initial framework development will be based on LPBF although many aspects of the framework can be similarly applied to DED or other advanced manufacturing technologies. Initial material of focus is 316 SS. As more tools are developed and the framework is refined, additional materials relevant to the nuclear industry will be incorporated from the materials task. The framework development will be focused on data creation and utilization of the framework for demonstration activities with the intent of transferring the knowledge gained from this platform to the nuclear industry and to ultimately have the framework utilized across industry.

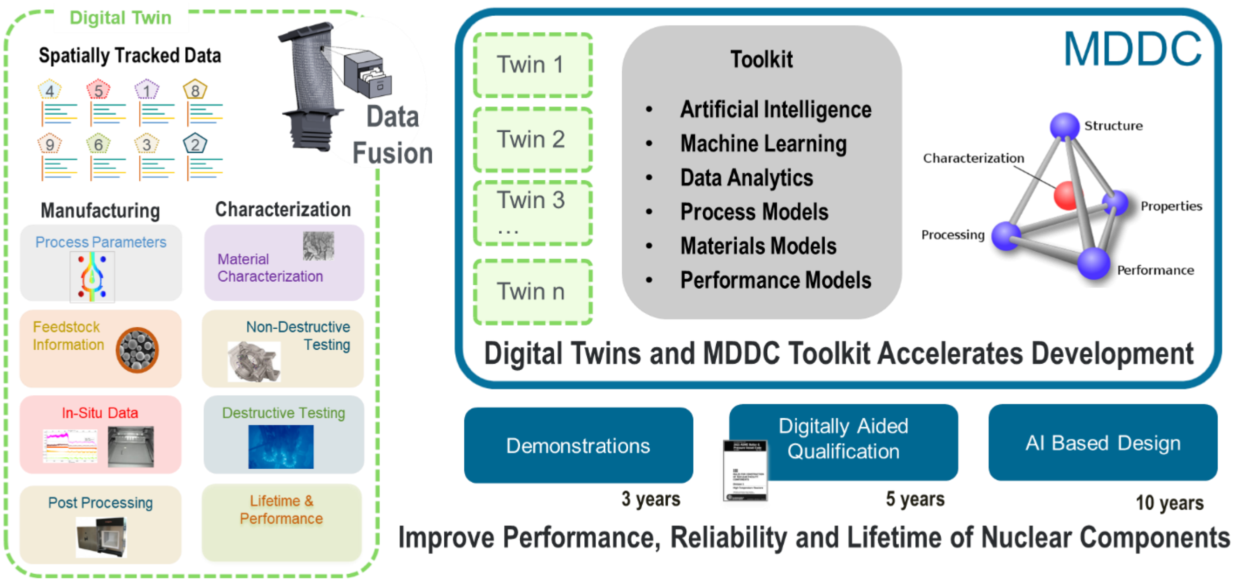

Figure 8. Concept of the multi-dimensional data correlation (MDDC) platform.

5.1.3 Material Performance Evaluation

The evolution of materials properties in reactor environments, i.e., the influence of environmental effects as a function of time, is critically important to the integrity and lifetime of reactor components. Irradiation and corrosion effects and their impact on properties are at the heart of the unique challenges experienced by the nuclear industry. These challenges will be addressed by developing an understanding of the effects of composition, processing, and microstructure on irradiation behavior, e.g., irradiation creep, swelling, high-temperature He embrittlement, and microstructural stability of AM 316 SS and other materials, and the combined effects of irradiation and corrosion under a range of temperature and chemistry conditions depending on the reactor type. This effort will encompass assembling a database of microstructure and mechanical properties of irradiated materials, to be leveraged and supported by models of the irradiation response based on the microstructure of the material. The microstructure-based understanding will enable addressing the performance of AM components by linking to local microstructural variations under different processing and post-processing conditions. Specific tasks described below are planned to achieve the milestones: (1) developing a white paper to address material qualification using combined neutron and ion irradiation data and gaining the support of the NRC, and (2) demonstrating the acceptable performance of materials in irradiation environments using combine ion-neutron data and modeling results.

- *Neutron irradiation and post-irradiation examination*

Neutron irradiation and post-irradiation examination (PIE) activities will be conducted in support of the establishment of a technical basis for regulatory acceptance of AM 316 SS. Irradiations of additional materials under development within the AMMT program will also be performed to evaluate their performance in reactor environments. Neutron irradiation experiments at the Advanced Test Reactor (ATR) and the High Flux Isotope Reactor (HFIR) are planned. The materials selected for irradiation will be linked to AM builds with high-pedigree digital signatures and well-characterized local microstructures. Microstructure and mechanical properties data will be collected to understand how the as-fabricated composition and microstructure perform following irradiation. Neutron irradiation and post-irradiation experiments will provide data to establish the Materials Property Handbook for engineering designs and qualification of reactor components that will be integrated into the MDDC Platform. The Material Property Handbook will be updated on an annual basis comprehensively covering all the collected pre- and post-irradiation data on the physical, thermal, mechanical properties, and microstructure of the subject material.

- *Accelerated material qualification using combined neutron and ion irradiation data*

Ion irradiation as an accelerated irradiation tool allows for much more rapid irradiation damage evaluation than neutron irradiation, speeding the timeline to understand the radiation damage behavior of the material. However, fundamental differences in ion and neutron irradiation mean that there is not a one-to-one correspondence between ion and neutron radiation response behavior for a material. Thus, modeling and simulation is needed to provide a means of interpreting accelerated ion irradiation testing results in the context of neutron radiation. In addition, neutron radiation behavior is also dependent upon neutron flux, spectrum, irradiation condition, etc., and modeling can be used to predict the neutron irradiation response of a material in different conditions.

Irradiation testing is planned to involve both neutrons and ions. Ion irradiation experiments will be performed on material developed by the AMMT program for fast screening to support new materials development and to provide high-fidelity data for model refinement and validation. Modeling and simulation will be performed to interpret the ion and neutron irradiation damage behavior and predict the behavior for different irradiation conditions. A white paper will be developed to discuss a path forward for promoting the regulatory acceptance of using combined ion and neutron irradiation data for material qualification in concert with physics-based modeling and machine learning focusing on 316 SS for demonstration. Previous and ongoing research efforts, such as the SNAP project, will be leveraged. Rather than focusing on the direct correlation between ion and neutron irradiation data as done in the previous work, we will address how to take advantage of the unique aspects of ion and neutron irradiation tools to provide complementary data of a material's radiation behavior. The unique complementary information provided by neutron and ion irradiations together with modeling and simulation can lead to a more comprehensive understanding that facilitates the accelerated qualification of a material at a fraction of the cost.

- *Corrosion testing of AM materials*

In addition to irradiation, corrosion has an important impact on materials performance in nuclear environments. There is limited information of the corrosion performance of materials made by advanced manufacturing in nuclear reactor environments. The goal is to leverage existing knowledge on corrosion and adapt it for AM materials and to understand how corrosion impacts materials performance, including Stress Corrosion Cracking (SCC)/Irradiation-assisted Stress Corrosion Cracking (IASCC) for LWR applications and other corrosion failure mechanisms in advanced reactor systems.

A comprehensive review will be performed to understand the state-of-the-art of the field and to identify the research needs and strategies of AM materials for nuclear applications. The objective is to develop a knowledge base of research activities and testing capabilities to characterize the environmental effects (specifically, corrosion effects) of AM materials and to determine the basic needs and concerns specific to corrosion of AM materials for structural applications in reactors conditions. This initial study will guide future efforts for determining the corrosion responses of new AM materials in reactor environments, including different types of corrosion tests in relevant reactor environments, characterizations at different length scales for general and localized corrosion, the effect of microstructure and manufacturing method on corrosion performance, and the development of any new testing methods required for evaluating the corrosion behavior of AM materials.

5.1.4 Technology Demonstration

In order to connect the development and qualification efforts to applications, the AMMT program incorporates technology demonstration as a core component. The goal is to enable technology transfer to stakeholders and, by extension, use of materials and techniques developed by the program in existing and to-be-built nuclear reactors. An important corollary is to ensure that the research and development performed to accomplish the programmatic vision and goals are aligned with the interests of stakeholders. The best way of putting the work to test is by pursuing demonstrations and documenting the corresponding lessons-learned. Technology demonstration involves coordinated efforts with industry, and some of the activities will occur through R&D performed directly by industry or in collaboration with national laboratories and universities.

The work to be performed relies heavily on input from other research focus areas within the AMMT program. The demonstration and deployment area on its own will only have limited research and development activities. Rather, the focus is on providing the necessary documentation, validation, verification, quality control, example problems, supporting the manufacturing supply chain, and integration with stakeholders to enable the demonstration, followed by post-demonstration analysis. The materials targeted for demonstration and deployment would be inherited from the stakeholder-informed and opportunity-based choices made in the AMMT research areas. New materials demonstration would first focus on additively manufactured 316 SS, followed by Ni-based alloys and ferritic martensitic steels. This scope is big, the priority list will evolve as we continuously evaluate progress and stakeholder interest, and the plan would be adjusted accordingly. Demonstration and deployment of more novel advanced materials (gradient materials, composites, cladding, ODS alloys and refractory metals) would follow in the third step, which is presently slated for the out-years of the roadmap due to the amount of supporting R&D still required. A range of operating environments will be considered for the demonstration, but the focus is on realistic high-temperature irradiation environments of critical importance to advanced reactors. Deployment of manufacturing techniques would follow the research and development identified as high priorities in the corresponding technical area, i.e. LPBF and DED, with other techniques following in the out years.

Technology demonstration effort will also include close interaction with the ASME B&PV Code Committees and pursue materials qualification through ASME nuclear Code Cases. The nuclear industry has specific requirements in terms of quality control and assurance, which makes qualification of nuclear products extremely challenging and significantly delays the transfer from R&D to commercialization. Codes and standards can facilitate the technology transfer, particularly for deployment of new materials and manufacturing technologies in advanced reactors. For US-based reactors, including a material in Section III, Division 5 of the ASME B&PV Code is currently the primary means for qualifying materials for structural applications for high-temperature nuclear reactors. A nuclear Code Case is one approach for qualifying a material via inclusions in the ASME Code. We plan to establish a Code case for LPBF 316H SS for initial demonstration of the accelerated qualification framework. Major milestones to be achieved include (1) demonstration of AM components by utilizing a rapid qualification approach, (2) developing an ASME Code qualification plan for LPBF 316H SS, and (3) completing submission package for an ASME Code case for LPBF 316H SS.

- *Component manufacturing and demonstrations of AM 316 SS*

We will engage with industry partners to identify different components for potential demonstration projects using AM technologies. Industrial partner projects will be discussed within the AMMT program to determine the appropriate industrial partner and specific application in which the AMMT-funded work scope can be leveraged to be successful. These selected components will be manufactured using AM technologies, and both modeling and *in situ* data will be included to complete the MDDC platform.

In collaboration with partners, the design of the material will be completed based on specific reactor applications, ideally targeting AM 316 SS grades based on the programmatic investment in this area. Industry partners will develop supply chains and establish vendor qualification, perform equipment calibration, and achieve certification supported by knowledge and capabilities developed by the program. This is followed by component manufacturing, including wrought benchmark samples and integration of sensor technology as appropriate and documenting quality assurance and property characterization. These steps would support obtaining the approvals and establishing partnership agreements needed to initiate the demonstrations. The completion of the first phase of the demonstrations will also be marked by completing simulations of the demonstrations. Analyses of the demonstrations will be performed and benchmarked against modeling and simulation results, which will form a basis for the deployment stage depending on the outcome of the demonstration. The lessons-learned from AM 316 SS demonstrations will be applied to complete a roadmap for demonstration of other advanced materials and manufacturing techniques.

- *ASME engagement for material qualification*

We aim to establish a Code case for LPBF 316H SS for 100,000 h to demonstrate the successful adoption of the new, rapid qualification framework by the ASME, NRC, and the nuclear industry. We will develop a Code qualification plan in the first year for qualifying LPBF 316H SS for use with the ASME Section III, Division 5 rules covering the design and construction of high-temperature nuclear reactors. The plan will include the types and number of experimental tests required for qualification, a general description of how the data will be processed into the design material information required by the ASME, a plan to ensure the material test data is representative of future LBPF parts, and addressing key differences between past experiences qualifying conventionally manufactured material and the unique characteristics of LPBF materials. The plan will also include a strategy for engaging with the cognizant ASME Code Committees, both during data collection and when the complete Code Case is ready for balloting. A description of opportunities for accelerating the current ASME qualification process will also be addressed. This plan will guide the test campaign and shape the program's engagement with the ASME as the Code Case is developed. Frequent and early engagement with the cognizant ASME Code Committees will be critical in developing and eventually securing approval for a Code Case.

5.2 Capability Development and Transformative Research

The Development, Qualification, and Demonstration program element supports the need to deploy new materials and manufacturing technologies in the nuclear industry. These efforts rely on a range of capabilities that in some cases exist for immediate use and in some cases require further development. The need for additional capability development is addressed in the Capability Development and Transformative Research program element. Several important topics to be addressed in the first five years are given below. Additional topics will be addressed as the program evolves and the priority may change. Transformative research to be performed is also described below to build a pipeline of future high-impact capabilities and discoveries.

5.2.1 Advanced Experimental Techniques

The rapid qualification approach relies on being able to rapidly evaluate material properties, accelerate investigations of the responses to environmental conditions, connect the microstructure state of the material to properties and performance, and model all of the above in such a way that performance may be predicted for long-service conditions with quantified uncertainties. These problems span a substantial research space that this program cannot address alone, which implies that leveraging capabilities across DOE and other research organizations is key to success. However, a number of capabilities and research areas are identified as critical and sufficiently unique to the AMMT program to be incorporated in the roadmap. Significant achievements envisioned in this area including demonstration of accelerated creep/creep-fatigue testing techniques for use in Code qualification, and computer vision-based automated microstructural characterization and quantification tools for *in situ* studies.

- *Computer vision-enabled automated microstructural quantification*

Qualification of the AM process will require a significant amount of characterization including non-destructive techniques such as X-ray and neutron computed tomography as well as microstructural characterization using optical and scanning and transmission electron microscopy, X-ray diffraction, scattering, spectroscopy and imaging, and atom probe tomography, etc. Characterization of material microstructures is time-consuming and is often the bottleneck of material investigation. Microstructural information has traditionally been obtained by repetitive generation of microstructural images and manual identification and measurement of microstructural features to obtain statistically significant data. This manual workflow is time-consuming, error-prone, lacks reproducibility, and is difficult to scale up. The issue is even more serious when it comes to dynamic video data of manufacturing, and defect and microstructural evolution captured by high-speed camera. Hundreds to thousands of images per dataset prohibit detailed quantitative measurement by hand, which often leaves the valuable dynamic information underutilized. Recent development of computer vision applications on microscopy data can mitigate the above issues by providing fast and consistent data analysis and, more importantly, enable frame-by-frame analysis of video data to capture the dynamic information.

Computer vision-enabled automated microstructural analysis and quantification will be applied to a suite of microstructural characterization techniques that spans from atomistic scales (e.g., TEM) to meso scales (e.g., optical microscopy). The initial focus will be on applications of computed tomography for detecting large defects formed during manufacturing, which is important in determining the processing window (power, velocity, composition, etc.) for printed materials to minimize defect formation in components. Computer vision analysis of TEM data focuses on accelerated material characterization of radiation defects at the atomic scale (an example shown in Fig. 9). Multi-modal characterization capabilities are envisioned to improve the ability to understand material properties across the length scales and how they interrelate with the microstructure state of the material. Being able to characterize and link the microstructure and composition of a material to processing conditions and properties is important for both material development and qualification, and automated microstructural analysis and quantification by computer vision is viewed as an enabling technology for this field.

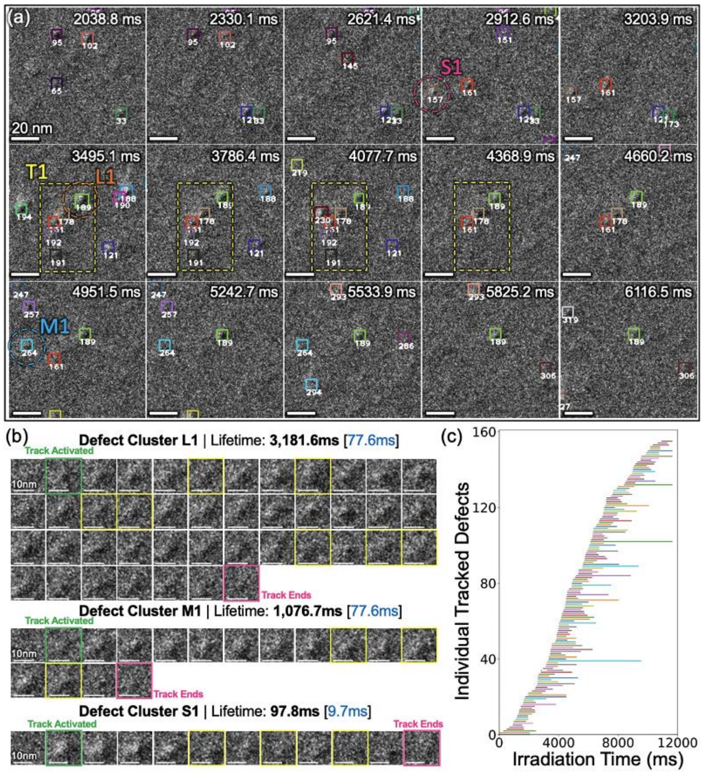

Figure 9. Visualization of the *DefectTrack's* multi-object tracking performance on a representative test set of TEM video data showing formation and annihilation of defect clusters during *in situ* ion irradiation. [24]

- *Accelerated creep and creep-fatigue testing techniques for Code use*

Creep and creep-fatigue testing probes time-dependent material properties at elevated temperatures, and creep and creep-fatigue damage are the key damage modes experienced by structural alloys in nuclear reactor environments. The long service life requirements of nuclear structural components and the limited time available for developing and qualifying materials require accelerated creep and creep-fatigue testing techniques to reduce the time required for testing material responses. The overall objective is to decrease the time required for Code qualification through the development of accelerated creep and creep-fatigue testing techniques including in-pipe creep testing and data extrapolation methods to long service lives. This objective will be accomplished through a multi-pronged approach to examine the feasibility of increasing the throughput of creep and creep-fatigue testing, as well as exploring the use of advanced instrumentation and measurement techniques to increase the relevant data generated from mechanical loading. A concurrent effort includes computational approaches for creep and creep-fatigue modeling, which also aims to reduce the time requirements for Code qualification of AM materials and components. An important task during the development stage is interaction with relevant ASME Code Committees (such as the Allowable Stress Criteria Working Group) on the proposed testing techniques and preliminary results to receive feedback and to brief committee members on the findings and proposed approaches.

[24] Rajat Sainju, Wei-Ying Chen, Samuel Schaefer, Qiang Yang, Caiwen Ding, Meimei Li, Yuanyuan Zhu, "*DefectTrack*: a deep learning-based multi-object tracking algorithm for quantitative defect analysis of in-situ TEM videos in real-time" *Sci Rep* **12**, 15705 (2022).

5.2.2 Computational Capabilities for Qualification

The AMMT program has identified a suite of computational and data-driven tools required to support the acceleration of materials development and qualification at all stages. While tool development will heavily leverage what is being developed under the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program, the AMMT program will emphasize the applications of these computational capabilities to the understanding and predictions of the processing-structure-property-performance relationships. A particular area of interest is the integration of machine learning/artificial intelligence and physics-based modeling and simulation in understanding the complex behavior of engineering materials in nuclear reactor-relevant environments, especially targeting advanced materials and those made by advanced manufacturing techniques.

Physics-based modeling and simulation have proven essential to the development of structure-property-performance relationships. High-throughput physics-based modeling can be combined with data analytics to achieve data-driven predictions of materials performance under irradiation at short and longer timescales, bridge results across length scales, combine single-physics effects via transfer learning, and perform advanced image analyses. Several needs to advance the current state-of-the-art must be met, including development of accurate atomistic methods for predicting the effects of irradiation, temperature, stress, and chemistry. An example is shown in Fig. 10 where the energetics of atomic-scale composition variation using integrated physics-based modeling and machine learning tools is predicted, which enables the calculation of multicomponent phase diagrams of an Fe-Cr-Al ternary alloy.

Data analytics efforts will focus on the implementation, integration, and application of standard databases and machine learning techniques. Deep learning methods will manage the challenge of data scarcity in the process of aiding in the discovery and development of new materials. They will also be tightly integrated with physics-based modeling to drive the understanding and prediction with a physical meaning.

We aim to achieve two major milestones in this area, including exercising multiscale and machine learning modeling for microstructure prediction and engineering during additive manufacturing; and applying data science methodologies for multi-scale integration and robust data extrapolation in support of accelerated qualification.

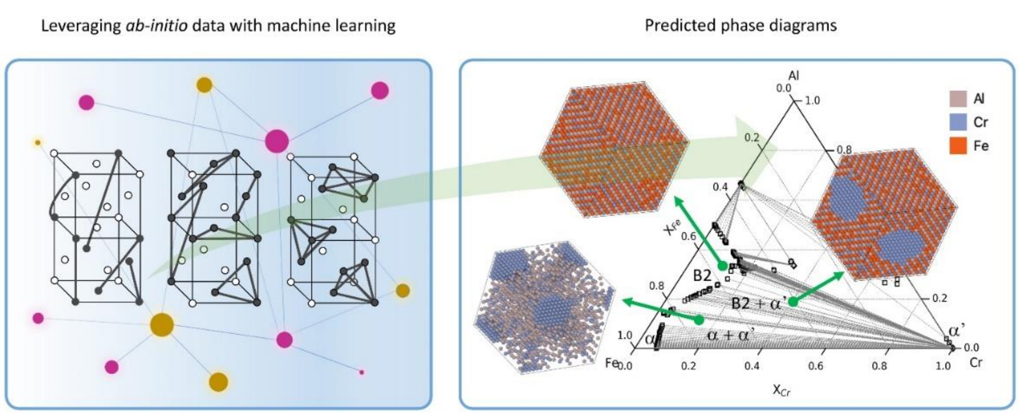

Figure 10. Integrating physics-based modeling with machine learning to predict the energetics of atomic-scale composition variation enables calculation of multicomponent phase diagrams without experimental data. [25]

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[25] Jia-Hong Ke, Andrea M. Jokisaari, "Machine learning pipeline to predict defect behavior in metallic alloy systems," INL-RPT-22-68286.

5.2.3 Developing Materials from Fundamental Properties

Understanding of materials microstructure, its link to properties, and the evolution of microstructure and properties during service influenced by various environments gives the opportunity to develop materials based on their fundamental microstructure and properties with specific applications in mind. In some sense, this is nothing new to the field of materials science and engineering; however, the tools currently available for this grand challenge make it possible to achieve real progress. In the AMMT program, this challenge will be approached by exercising state-of-the-art computational and experimental tools, including some tool development in cases where that is deemed necessary, to develop one or several new alloys for specific applications. The first two steps envisioned are to (1) define performance metrics and environments of interest for materials design and assess existing tools and potential partner institutions and (2) select alloy composition for performance metrics of interest and assess fundamental properties and predict ordered phases that can form under irradiation for alloy composition range. The second phase would involve microstructure optimization with respect to irradiation performance and mechanical properties. The final step would be to fabricate the new materials design and characterize its properties, including irradiation response. These results would be compared to the design targets, and lessons-learned would be summarized. The objectives of the materials design effort referenced above focus on materials performance and do not directly include requirements such as economics, scale-up, weldability, etc. Multi-attribute optimization will be explored in a later stage to develop a high-dimensional, nonlinear design strategy with multiple objectives to enable balance/trade-offs between different properties and requirements. Scientifically-guided AL-based capability for developing high-performance reactor materials will be demonstrated.

5.3 Collaborative Research and Development

Collaborations and partnerships will be required for the AMMT program to be successful, as many of the problems to be addressed by the AMMT program are incredibly challenging, the scope of the AMMT program is necessarily broad, and many scientific and technological challenges in materials and manufacturing in nuclear energy systems are not unique. Even though only a few cases were explicitly described in the overview of AMMT research focus areas and the five-year plan, collaborations and partnerships are integral to the roadmap and program implementation.

The DOE NE sponsors several research programs that provide collaboration opportunities. The AMMT program intends to leverage and collaborate with the capability development performed by the NEAMS program on the constitutive modeling of alloys for structural applications, where the AMMT program will use and expand on technology developed by the NEAMS program for materials manufactured by traditional techniques to simulate properties of additively manufactured materials and their performance in nuclear reactor applications, including methodologies for extrapolation in data-poor regimes in support of rapid qualification. The experimental data collected by the AMMT program is expected to provide value to NEAMS-specific applications of these material models. The DOE Advanced Reactor Technologies (ART) program has a history of alloy development and Code qualification. The research and development performed by the AMMT program will add new materials and advanced manufacturing and rapid qualification techniques to the portfolio currently under the ART program. This scope aims to be complementary to current efforts under the ART program, thus providing new options for reactor designers and developers that would otherwise not have been pursued. The AMMT program will actively work to coordinate efforts and exchange information with the ART program and collaborate and partner with the ART program on demonstration and deployment. The Light Water Reactor Sustainability (LWRS) program is engaged in materials aging problems related to life extension for the current fleet of LWRs. The AMMT program seeks to engage in collaborative research that supports this mission by leveraging advanced manufacturing to, for example, replace critical parts, do repairs of components, or predict performance related to qualification. Advanced manufacturing effort will involve fabrication of embedded sensors for continuous monitoring of material performance in operating environments, which will use new sensor technology that is envisioned to be developed in collaboration with the Advanced Sensors and Instrumentation (ASI) program. Ion and neutron irradiations and materials characterization and modeling will utilize some resources provided by the Nuclear Science User Facilities (NSUF), and the AMMT program will also consider making to-be-developed capabilities available through the NSUF mechanism. Demonstration and deployment are key goals for the AMMT program, and as one of several pathways to accomplish this, we hope to leverage opportunities provided by the National Reactor Innovation Center (NRIC) in synergy with their stakeholders and industry connections. Although the AMMT program does not consider nuclear fuels, the vision of rapid qualification of structural materials shares many characteristics with accelerated fuel and cladding qualification pursued by the Fuel Cycle R&D and NEAMS programs. Knowledge and lessons-learned would be exchanged between these programs in order to accomplish the desired acceleration of the qualification timeline compared to the current norm. Research on advanced materials and manufacturing performed under the Nuclear Energy University Program (NEUP) will make significant contributions to the AMMT portfolio, and active engagement is sought to bring in knowledge and capabilities made possible by the NEUP program. This list of DOE NE programs is not mean to be exhaustive.

In addition to the DOE NE programs covered above, the AMMT program will engage with other funding agencies and communities, e.g., Advanced Materials and Manufacturing Technologies Office (AMMTO), Office of Science, NASA, DoD, NIST, etc., and seek to harvest advances made by others that would facilitate our mission. As examples, the AMMTO has significant investments in some of the manufacturing infrastructure to be utilized by the AMMT program, the Office of Science will provide capabilities for advanced characterization, and NASA, DoD, and NIST are each pushing AM initiatives that target improved properties and qualification as major thrusts. Nuclear industry organizations such as EPRI and NEI have a significant stake in advanced manufacturing, and we will engage with these organizations on the development of new technology as well as demonstration and deployment through their industrial stakeholders. The NRC is the body that ultimately makes decisions on licensing reactor designs and components utilizing advanced manufacturing. It has an active program preparing for license applications based on advanced manufacturing and has outlined requirements for regulatory acceptance, which the AMMT program has used as guidance in the development of the research and development roadmap. Regular interactions and exchanges of information are planned to receive critical feedback on AMMT activities related to rapid qualification of AM materials and regulatory use of ion-neutron irradiations. Efforts on Code qualification of AM materials are formulated to directly engage with the ASME Codes and standards body. Finally, impact on and knowledge transfer to the nuclear industry greatly benefits from collaborations and partnerships. These will be pursued under demonstrations and deployment.

The goal of the collaborative R&D program element is to accelerate progress on our objectives through collaborations and partnerships to investigate a broad range of advanced materials and manufacturing technologies, address reactor-specific issues, leverage and collaborate on capability development, and provide near-term material solutions to the nuclear industry.

6 PROGRAM ORGANIZATIONAL STRUCTURE AND CORE TECHNICAL AREAS

6.1 Organizational Structure

The AMMT leadership team has five members, which include national technical director (NTD), deputy NTD, and three technical area lead (TALs) (Fig. 11). They are from five different national labs and have diverse technical expertise. The team includes:

- Meimei Li, NTD, Argonne National Laboratory (ANL)
- David Andersson, Deputy NTD, Los Alamos National Laboratory (LANL)
- Isabella van Rooyen, TAL for Materials Development, Pacific Northwest National Laboratory (PNNL)
- Ryan Dehoff, TAL for Advanced Manufacturing, Oak Ridge National Laboratory (ORNL)
- Andrea Jokisaari, TAL for Environmental Effects, Idaho National Laboratory (INL)

The AMMT program has a steering committee, representing five different national laboratories. An industry council is to be established.

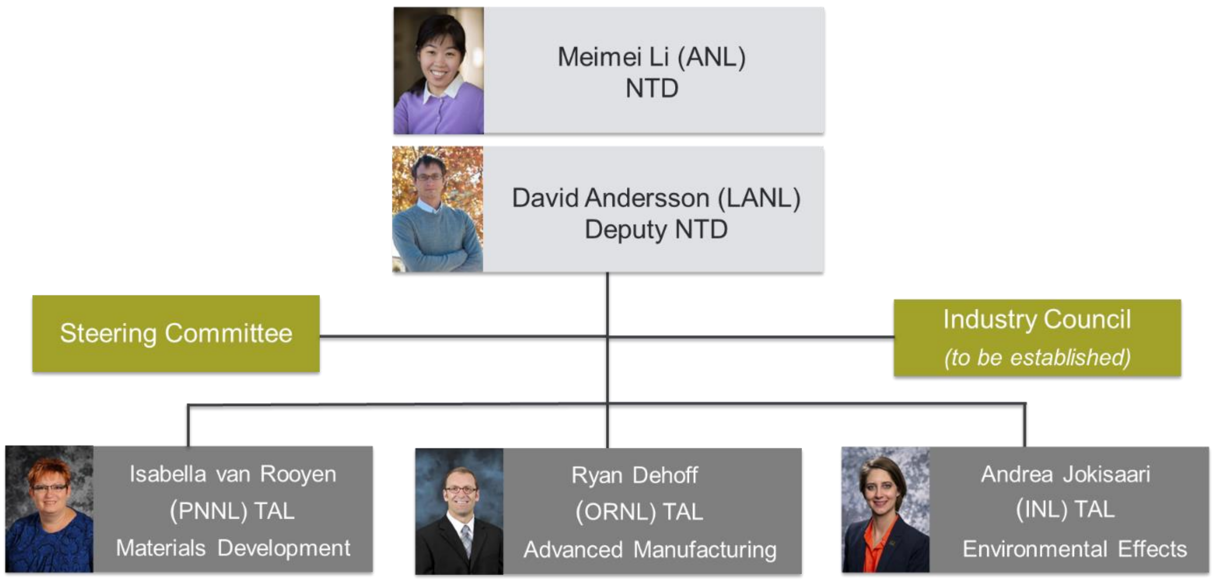

Figure 11. AMMT organizational structure.

6.2 Program Integration

The thematic execution strategy of the AMMT program is ***Integration and Collaboration***, as illustrated in Fig. 12. The AMMT program is comprised of three core technical areas, namely, Materials Development, Advanced Manufacturing, and Environmental Effects. The technical areas mesh with the program elements in a matrix structure to facilitate integration and collaboration to achieve the overall goal of the AMMT program.

Besides integrating three core technical areas, we will employ an integrated approach, combining a set of tools including advanced characterization tools, high-throughput and accelerated testing techniques, modeling and simulation, and machine learning and artificial intelligence across three technical areas to support the accelerated development, qualification, and demonstration of advanced materials and manufacturing technologies.

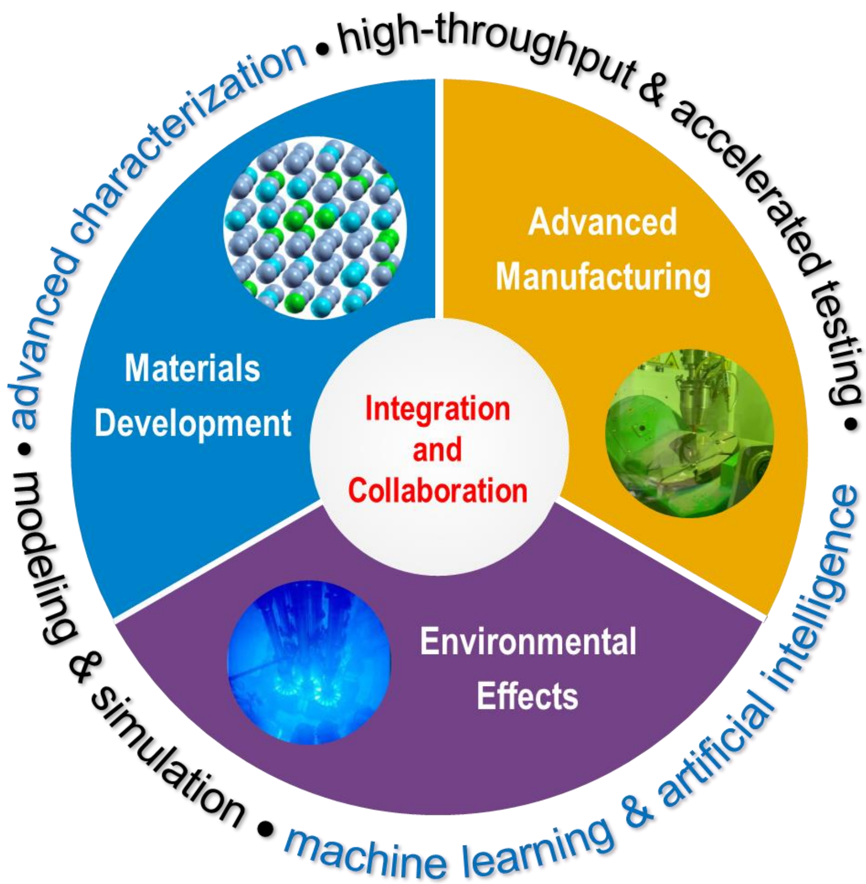

Figure 12. Integration of core technical areas and experimental and computational tools under the AMMT.

7 SUMMARY

The AMMT program within the DOE NE is to develop cross-cutting technologies in support of current fleet and next-generation advanced nuclear reactor technologies and to maintain US leadership in materials and manufacturing technologies for nuclear energy applications. The overarching vision of the AMMT program is to accelerate the development, qualification, demonstration, and deployment of advanced materials and manufacturing technologies to enable reliable and economical nuclear energy. The major goals to achieve the mission and vision of the AMMT program are: (1) to develop advanced materials and manufacturing technologies that have cross-reactor impacts, (2) to establish a comprehensive framework for rapid qualification, and (3) to demonstrate and deploy technologies with commercial stakeholders to bring new materials and manufacturing technologies to market in a timely manner.

The AMMT program will address both near-term and long-term technological challenges facing the nuclear community. While it is important to provide near-term solutions to industry to bring their designs to market, it is also imperative to invest in science and technology that could have high impact to provide long-term, game-changing solutions to fulfil the full mission of the Department of Energy. In this context, the AMMT program consists of three program elements: *(1) Development, Qualification and Demonstration, (2) Capability Development and Transformative Research, and (3) Collaborative Research and Development*.

The AMMT program integrates three core technical areas, namely *Materials Development, Advanced Manufacturing, and Environmental Effects*, and uses an integrated approach combining a set of tools including advanced characterization tools, high-throughput and accelerated testing techniques, modeling and simulation, and machine learning and artificial intelligence. This integrated effort will enable us to build a novel framework for accelerated development, qualification, and demonstration of advanced materials and manufacturing technologies.

The AMMT program will directly impact the nuclear industry by developing high-performance radiation-, corrosion- and high temperature-resistant materials for advanced manufacturing and/or through advanced manufacturing and accelerating the deployment of advanced materials and manufacturing technologies to enable reliable and economical nuclear energy.

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