

Technologies to Reactors:

Enabling Accelerated Deployment of Nuclear Energy Systems

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**TECHNOLOGIES TO REACTORS:
ENABLING ACCELERATED DEPLOYMENT OF NUCLEAR ENERGY SYSTEMS:
REPORT OF THE OFFICE OF NUCLEAR ENERGY WORKSHOP**

**Report of the US Department of Energy Office of Nuclear Energy Workshop
held July 25–26, 2018**

Cover image:

*UO₂ Oak Leaf Encapsulated in Iron-
Chromium-Aluminum Alloy using Advanced
Manufacturing Techniques*

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Technologies to Reactors: Enabling Accelerated Deployment of Nuclear Energy Systems

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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

AI	artificial intelligence
ALARA	as low as reasonably achievable
ANL	Argonne National Laboratory
APT	atom probe tomography
ATR	Advanced Test Reactor
BIM	building information management
BRN	basic research needs
CAD	computer assisted design
CASL	Consortium for Advanced Simulation of Light Water Reactors
CEDS	Cybersecurity for Energy Delivery Systems
CESER	Office of Cybersecurity, Energy Security, and Emergency Response
CFD	computational fluid dynamics
CILC	crud-induced localized corrosion
CIPS	crud-induced power shift
CRP	Coordinated Research Project
DOE	US Department of Energy
DOE-EERE	DOE Office of Energy Efficiency and Renewable Energy
DOE-NE	DOE Office of Nuclear Energy
DSS	Dynamic System Scaling
EI	embedded intelligence
EMMC	European Materials Modelling Council
ENIAC	Electronic Numerical Integrator and Computer
EPC	engineering, procurement, and construction
EPRI	Electric Power Research Institute
EPZ	emergency planning zone
FB	frequency banding
FEA	finite element analysis
FIB	focused ion beam
FMEA	failure modes and effects analysis
GE	General Electric
GFLOPS	giga floating-point operations per second
GTRF	grid-to-rod fretting
HFIR	High Flux Isotope Reactor
HIP	hot isostatic pressing
HT-UPS	high-temperature ultrafine-precipitation-strengthened steel
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
IAPWS	International Association for the Properties of Water and Steam
IEEE	Institute of Electrical and Electronics Engineers

IM2B	International Materials Modelling Board
INL	Idaho National Laboratory
ISA	International Society of Automation
KL	Kullback–Leibler
LWR	light water reactor
M&C	monitoring and control
M&S	modeling and simulation
MIT	Massachusetts Institute of Technology
MITR	MIT Reactor
NAMAC	Nearly Autonomous Management and Control
NASA	National Aeronautics and Space Administration
NAVAIR	US Naval Air Systems Command
NDE	nondestructive evaluation
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NPIC & HMIT	Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies
NRC	US Nuclear Regulatory Commission
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
OSU	The Ohio State University
PCI	pellet-clad interaction
PFLOPS	peta floating-point operations per second
PHM	prognostics and health management
PLM	product life management
PNNL	Pacific Northwest National Laboratory
POWID	Power Industry Division
PTD	priority technology direction
R&D	research and development
RF	radio frequency
S&T	science and technology
SAFT	synthetic aperture focusing technique
SME	subject matter expert
SMR	small modular reactor
SNS	Spallation Neutron Source
SS	stainless steel
SSC	structures, systems, and components
STEM	scanning transmission electron microscopy
TEM	transmission electron microscope
TRL	technology readiness level
TVA	Tennessee Valley Authority
UAM	ultrasonic additive manufacturing

UNCC	University of North Carolina, Charlotte
UQ	uncertainty quantification
UTK	University of Tennessee, Knoxville
VERA	Virtual Environment for Reactor Applications
VVUQ	verification and validation and uncertainty quantification

EXECUTIVE SUMMARY

Nuclear energy provides almost 20% of the electric power in the United States, producing power with high availability while accounting for 63% of our carbon-free energy production. While we have the capacity to expand this clean power source within the United States, we have not built any advanced reactor plant designs in our rapidly evolving electricity generation market, where cost is a major driver. With construction cost and plant safety being major elements of cost for new nuclear, advanced reactor technologies could provide lower cost, safer, carbon-free, grid-resilient energy sources for the US electricity grid.

When the current fleet of nuclear reactors was originally designed, many of today's science and technology (S&T) advances were not available. Today these advances show great promise for transforming our national approach to nuclear reactor design. Other industries are capitalizing on rapid innovations in materials, manufacturing, sensors and control systems, and high-fidelity modeling and simulation (M&S), along with data analytics to provide lower costs in manufacturing and extended ranges of operations. In the nuclear industry, these innovations can translate into similar benefits as well as rapid design and qualification of advanced nuclear fuels. Effectively implementing these types of innovations could position American expert leadership to compete more fully in the international nuclear energy market.

In July of 2018, the US Department of Energy (DOE) Office of Nuclear Energy sponsored a workshop to address these possibilities: "Technologies to Reactors: Enabling Accelerated Deployment of Nuclear Energy Systems." Workshop participants explored how modern and emerging S&T can be used to transform the approach to nuclear reactor design, licensing, and operation to accelerate deployment of advanced nuclear energy systems.

More than 80 experts from federal agencies, academia, and industry participated in the workshop to develop consensus on priority technology directions (PTDs) and recommend technology and deployment initiatives to explore and demonstrate key benefits for the nuclear community.

These panel-led discussions addressed the following topics within each technology area:

- State-of-the-art concepts in each technology and their use today
- Applications that might provide a basis to accelerate deployment of modern nuclear plants
- Economic, safety, and regulatory implications of applying new approaches enabled by these technologies
- Further advances needed, including
 - Recommended technology initiatives
 - Recommended deployment initiatives, where feasible

Four panels developed the PTDs and recommendations outlined below.

Panel A: Accelerated Development and Qualification of Materials and Fuels

1. Explore and adopt high performance materials
2. Implement real-time in-situ surveillance (e.g., advanced sensors or surveillance articles) as part of the design and manufacturing processes
3. Educate and employ the art of what is possible in advanced materials

Panel B: Advanced Manufacturing Technologies to Enable New Designs

1. Manufacture and deploy replacement parts
2. Design and fabricate new components using advanced manufacturing (clean sheet design)
3. Develop a methodology to rapidly bridge the gap between new designs/materials

Panel C: Sensors and Control Systems for Autonomous Operations

1. Develop autonomous control with inherent digital security
2. Develop sensors for control, autonomous operation, and M&S
3. Develop applications for prognostics and health management

Panel D: High Fidelity M&S and Data Analytics for Design, Manufacturing, Licensing, and Operations

1. Expand optimization beyond the core
2. Enable robust, automated optimization of reactor designs
3. Optimize design through verification, validation, and uncertainty quantification (VVUQ) and margin characterization

We also established a fifth panel, Panel E, that sent representatives to observe panels A-D during the workshop to identify key areas of technology overlap that should be highlighted in the report to emphasize the connections that exist between the panel topical areas. While Panel E did not generate PTDs, they did make a series of recommendations as described below.

Panel E led a discussion around crosscutting technologies, resulting in recommendations to:

1. Reduce material development time by implementing a combination of high performance computing, improved sensing, and additive manufacturing
2. Ensure that a given advanced manufacturing component can be *born qualified*, or manufactured to a standard performance confidence, through a combination of data analytics, instrumentation methodology, and rigorous quality control practices
3. Design innovative, optimized nuclear systems using a combination of advanced M&S tools and methodologies to take advantage of advanced manufacturing and qualification techniques

Throughout the workshop, participants considered the inherent connectivity between advances and opportunities in each area. The implications of leveraging these applications for more rapidly advancing nuclear energy affordability and performance were discussed. For example, M&S and sensor technologies can substantially impact materials and fuels performance. Participants agreed that early demonstrations of combined technologies should be used to help characterize the benefits, highlight gaps in application, and inform the appropriate regulatory bodies. Participants also agreed on the need to demonstrate rapid design and construction of prototype reactors and/or reactor plant components.

1. INTRODUCTION

The basis for our current approach to nuclear reactor development and deployment was established in the 1950s and 1960s. Many changes in nuclear energy technologies have been incremental, resulting in important improvements in safety and operations. However, this approach is time consuming and uneconomical.

Science and technology (S&T) advances in areas such as materials and fuels, manufacturing, sensors and control systems, high-fidelity modeling and simulation (M&S), and data analytics can be used to transform the approach to nuclear reactor design, deployment, licensing, and operation. For reactor concepts that take advantage of these innovations:

- Design constraints can be modified appropriately based on improved insights into materials properties and manufacturing control, and increased complexity can be achieved because ***advances in materials and manufacturing technologies*** will allow us to build the new concepts.
- More efficient regulatory approaches can be used as a result of the ***depth of understanding and the confidence*** gained while building the new concepts.
- Operational envelopes can be widened because we have gained ***comprehensive insights into real-time and predictive performance***.
- A rapid innovation cycle can be achieved because ***rapid iteration and demonstration of concepts*** are possible.
- Flexible, scalable solutions can be deployed because the technology approaches can be ***rapidly adapted to new designs***.
- A movement toward autonomy is reasonable because ***approaches already being used in other industry sectors*** can be adapted.

On July 25 and 26, 2018, the US Department of Energy Office of Nuclear Energy (DOE-NE) sponsored a workshop at Oak Ridge National Laboratory (ORNL) which served as a forum to explore the S&T advances that may enable the accelerated deployment of economical nuclear energy systems. Panels of experts were assembled to evaluate specific S&T areas. Questions addressed in each area included:

- What is the state of the art across diverse fields?
- How can advances in each area be applied to design, manufacture, licensing, and operation of reactors?
- What are the economic, safety, and regulatory implications of taking new approaches enabled by this S&T area?
- What further advances are needed?

Rather than proposing new research programs, the primary goal of this workshop was to understand how existing, modern technologies can be applied to nuclear energy deployment.

1.1 PLENARY SESSIONS AND STAGE-SETTING TALKS

Plenary sessions were organized to provide the participants with a high-level view of a number of topical areas encompassing advanced technologies and regulatory directions that would set the stage for detailed discussions regarding the advanced technology focus areas of the panel groups. These topics included:

DOE-NE perspective. Shane Johnson, DOE-NE's Deputy Assistant Secretary for Nuclear Technology Demonstration and Deployment, stated that (1) the federal regulatory structure is open to changes in reactor types and their use of emerging advanced technologies, (2) there is strong Congressional support for advanced reactors because industry continues to invest its own time and money based on the projected benefits of these reactors, and (3) DOE continues to encourage and make financial investments in the development of advanced nuclear power concepts and advanced technologies for nuclear power.

DOE Office of Energy Efficiency and Renewable Energy (EERE) Advanced Manufacturing Office perspective. Rob Ivester, Director of DOE's Advanced Manufacturing Office, described how his office is analyzing 14 technology areas for applications of advanced manufacturing. He encouraged workshop members to focus on early-stage applied research and development (R&D).

Industry perspectives on drivers and barriers for deployment of advanced technologies and reactor concepts. Industry perspectives were presented by Dan Stout, Senior Manager, Small Modular Reactors, Tennessee Valley Authority (TVA), Jonathan Cirtain, BWXT's Vice President of Advanced Technology Programs, and Andrew Sowder, Technical Executive, Advanced Nuclear Technology Program, Electric Power Research Institute (EPRI). These presentations covered factors that influence new-build decisions, cost drivers, how uncertainty can be a significant barrier to deployment, and how proposed new approaches must promise solutions that would be dominant in the marketplace.

Policy and regulatory approaches. Mike Case, Director of the Division of Safety Analysis, Office of Nuclear Regulatory Research, US Nuclear Regulatory Commission (NRC), discussed how the NRC is preparing for emerging, transformative technologies and concepts. He encouraged workshop participants to create opportunities for discussions among all parts of the enterprise, with a goal of discussing the issues and advantages of using emerging technologies and concepts before they appear on the desks of regulators.

Stage-setting talks. In addition to the plenary sessions, the workshop included stage-setting talks to bring attention to emerging technologies and concepts in *materials* (Kevin Field, R&D Associate and Weinberg Fellow, ORNL), *advanced manufacturing* (Suresh Babu, UT/ORNL Governor's Chair of Advanced Manufacturing, University of Tennessee, Knoxville [UTK]), *sensors and controls* (Richard Vilim, Manager, Plant Analysis & Control and Nondestructive Evaluation [NDE] Sensors, Argonne National Laboratory [ANL]), and *modeling and simulation* (Jess Gehin, Chief Scientist, Nuclear Science and Technology Directorate, Idaho National Laboratory [INL]).

1.2 PARALLEL PANEL SESSIONS

The plenaries and the stage-setting talks helped the audience a common understanding of federal, industrial, and research perspectives. After these initial sessions, audience members divided into five panels which worked in parallel to address the charge of the workshop. At the end of the first day, each panel presented preliminary, high-level results from the day's discussions, and at the end of the workshop, the updated results were presented to all participants.

The following sections present the panel results:

- 2.1 Panel A: Accelerated Development and Qualification of Materials and Fuels
- 2.2 Panel B: Advanced Manufacturing Technologies to Enable New Designs
- 2.3 Panel C: Sensors and Control Systems for Autonomous Operations
- 2.4 Panel D: High Fidelity Modeling and Simulation and Data Analytics for Design, Manufacturing, Licensing, and Operations
- 2.5 Panel E: Crosscutting Issues for Technology Integration

2. PANEL REPORTS

2.1 PANEL A. ACCELERATED DEVELOPMENT AND QUALIFICATION OF MATERIALS AND FUELS

Nuclear power represents a significant portion of the world's non-carbon-emitting power generation. While most of this generating capacity is based on water reactor designs, there are more advanced systems under consideration and in the stages of initial deployment. Reactors using higher temperature coolants such as supercritical water, sodium, lead, gas, and molten salts have been researched and demonstrated to varying degrees. These advanced nuclear energy system concepts have been developed to provide improved efficiency, greater fissile fuel utilization, reduced high-level waste generation, and increased margins of safety over today's water-cooled systems. Furthermore, these concepts may enable missions beyond electrical generation, including process heat, desalination, and other objectives.

Nuclear reactor materials must survive extreme conditions in a unique setting that includes highly corrosive media, a radioactive environment, and high temperatures. Technical challenges must be addressed with water and alternative coolant systems. To promote broader, accelerated deployment of these systems, additional R&D work is required, particularly in the areas of fuels and materials. This research will provide an opportunity to develop new methods and approaches that can easily surpass current capabilities. Improvements in fuels and materials have the potential to provide opportunities for simplified design and reduced capital cost. Advanced materials may also allow for improved safety and longer component lifetimes.

The development and deployment of advanced reactors requires R&D of materials and further understanding of the chemistry of coolants, fuels, and interactions. As noted in a recent DOE assessment of basic research needs (BRN) for advanced nuclear systems, several common areas for key materials must be overcome to enable advanced nuclear energy systems.¹ This report specifically notes:

Coolant compatibility is a key limitation for many advanced concepts, although the specifics vary by coolant and material choices. The impacts of high temperature, mechanical stress, and irradiation environments also pose a key challenge to deployment. The mechanistic understanding of these individual extreme elements and combined environment is needed. The mechanisms for interfacial processes are essential for prediction of degradation and design of tolerant materials.

Similar limitations for nuclear fuels exist. There are key degradation issues that must be resolved for both thermal and fast spectrum reactor fuels. Fuel forms for gas and molten salt cooled reactors have unique issues due to the very high operating temperatures and coolant interactions that must be resolved. Interfacial understanding is essential to predict and mitigate key interactions (e.g., clad and coolant; fuel and coolant; and/or fuel and clad).

Fortunately, in the last decade, there have been substantial advances in the tools and techniques available to resolve these key limitations. Fuels and materials characterization is being enabled by new developments in techniques such as atom-probe tomography, electron microscopy, and neutron scattering. Unraveling the combined effects of irradiation, coolant interaction, and/or temperature has been a challenge for decades, but new understanding and testing approaches are providing new paths to develop and qualify new materials. Non-destructive testing techniques are proving to be very valuable in translating operational and laboratory experience into fundamental understanding. Finally, computational techniques and tools provide new opportunities to couple experimental and theoretical understanding and to predict performance in service. All of these tools will be required to enable advanced nuclear energy systems.

Recent years have brought substantial gains in the state of the art and the art of what is possible for material and fuel science in general. The evolution of both materials science and nuclear reactor technology is shown as a timeline in APT = atom probe tomography

HFIR =

High Flux Isotope Reactor

CASL = Consortium for Advanced Simulation of Light Water Reactors

PFLOPS = peta floating-point operations per second

ENIAC = Electronic Numerical Integrator and Computer

SNS = Spallation Neutron Source

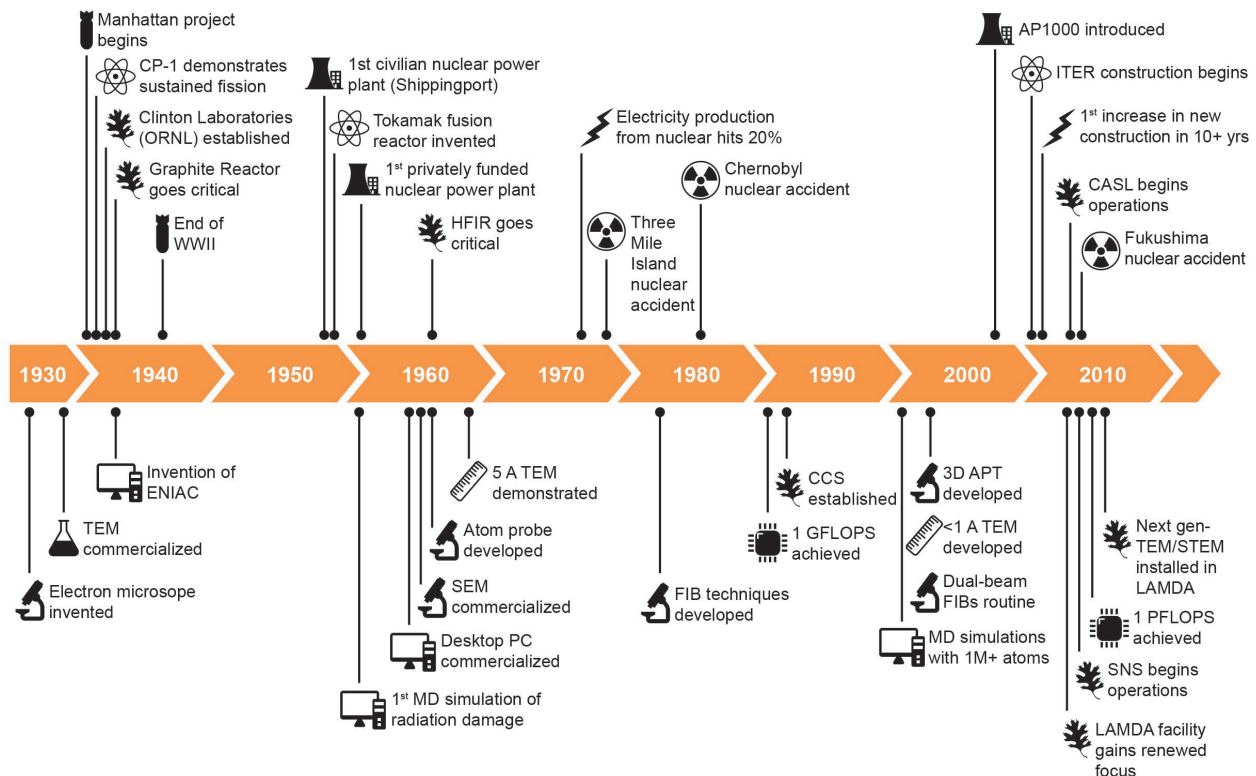
FIB = focused ion beam

STEM = scanning transmission electron microscopy

GFLOPS = giga floating-point operations per second

TEM = transmission electron microscope

Figure 1 below.² There is a great disparity in the pace of innovation of materials science vs. the pace of nuclear technology advancements. An opportunity exists to embed materials science advances within nuclear power technology for increased safety and reliability, as well as improved economics.



APT = atom probe tomography

HFIR = High Flux Isotope Reactor

CASL = Consortium for Advanced Simulation of Light Water Reactors

PFLOPS = peta floating-point operations per second

ENIAC = Electronic Numerical Integrator and Computer

SNS = Spallation Neutron Source

FIB = focused ion beam

STEM = scanning transmission electron microscopy

GFLOPS = giga floating-point operations per second

TEM = transmission electron microscope

Figure 1. Juxtaposed nuclear industry events (above timeline) and materials science events (below timeline) show disparity in the pace of innovation.

Substantial benefits will arise from exploring these advances and *the art of what is possible* in advanced materials (structural, fuel, moderator and/or coolant), modern characterization and testing, and performance monitoring. Specifically, we must inform designers, stakeholders, and decision makers on these advances to end traditional reliance on antique alloys and approaches. R&D should proceed with a tolerance for early failures, which are an integral part of the development and innovation cycle.

As shown above in the excerpt from the BRN document, the art of what is possible is changing rapidly in advanced materials (structural fuel, moderator, and/or coolant), modern characterization and testing, performance monitoring, high performance computing, machine learning, and advanced manufacturing as

enabling technologies. Using these techniques, high performance materials are being developed for many energy, transportation, and defense applications. These advanced materials could show promise for enabling new reactor designs, mission safety/operating margins, and processes to improve performance and economics through construction, operations, and/or major plant upgrades if adapted. Furthermore, the use of existing materials along with modern manufacturing techniques may improve performance for current and future deployment candidates. Incorporating advanced sensors or surveillance articles as part of the design and manufacturing processes may enable new levels of confidence in construction and performance.

In a more detailed example, recent advances in computational thermodynamics and kinetics modeling tools have enabled accelerated design and development of advanced alloys and fuels for nuclear applications. Furthermore, improved high performance computing capabilities and approaches also allow for a greater ability to model and predict material performance over long lifetimes or for off-normal (accident) scenarios. For example, irradiation effects are a unique aspect of nuclear fuel and material performance. Irradiation effects may change local chemistry and diffusivity, resulting in the change of local thermodynamic stability and kinetics. A computational framework that addresses both thermal and irradiation effects is illustrated in Figure 2 below, resulting in combined alloy development and irradiation effects. In this framework, the data structure is divided into three levels. The first level at the top of the schematic is the database, which stores the Gibbs energy of phases, the elemental diffusivity in phases, and the defect-solute interaction energy. The second level is the calculation engine, which integrates modular modeling of different phenomena, including thermodynamics and kinetic modeling of the phase under thermal conditions, radiation-induced defect evolution, radiation-enhanced diffusion, radiation-induced segregation, and radiation-induced phase transformation (e.g., precipitation or dissolution). The third level includes the output results on essential information about irradiated materials microstructure, such as microchemistry at defect and in bulk, as well as phase type, amount, size, distribution and composition. These outputs can be used for future environmental and mechanical property simulation. Results from recent work show early, promising application of such an integrated framework to simulate microchemistry evolution at a grain boundary. The challenge in future work will be to implement the in-situ integration of modular modeling to handle phenomena such as defect evolution, solute/defect diffusion, radiation-induced segregation, and phase transformation (e.g., precipitation and dissolution). This approach shows great promise over traditional approaches and may allow for revolutionary gains. High performance modeling and computing is covered in considerably more detail in Priority Technology Direction (PTD) 3 below.

The challenge to future work will be the in-situ integration of modular modeling to handle phenomena such as defect evolution, solute/defect diffusion, radiation induced segregation, and phase transformation (e.g., precipitation and dissolution).

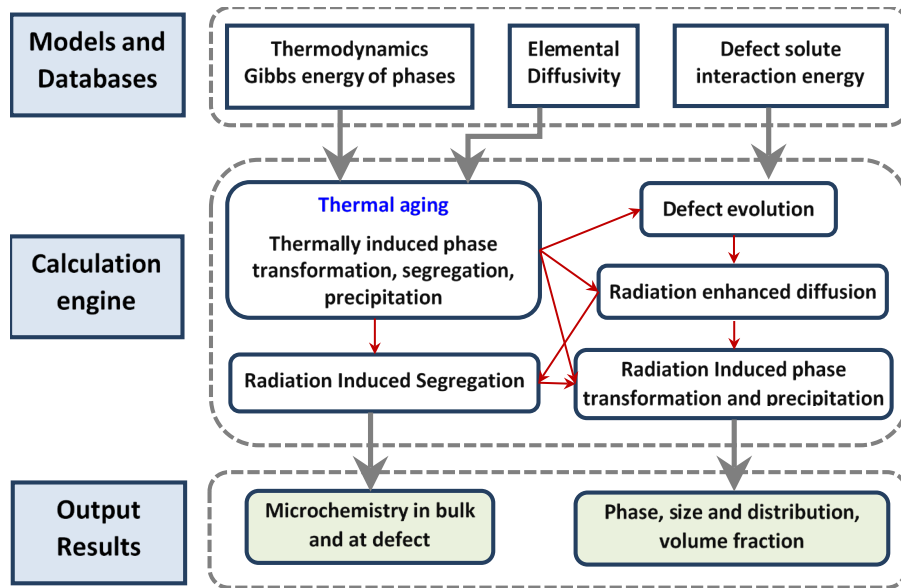


Figure 2. Integrated modeling framework on precipitate evolution in irradiated materials [courtesy of Y. Yang].³

While the recent BRN report cited above thoroughly explores fundamental and mechanistic phenomena requiring additional research, many engineering, component-, and system-level issues remain to be explored through coordinated R&D efforts. This section reviews the expert panel’s input into key areas for advanced fuels and materials to accelerate the development and deployment of advanced nuclear systems. The panel identified three major PTDs:

1. Explore and adopt high performance materials
2. Implement real-time in-situ surveillance (e.g., advanced sensors or surveillance articles) as part of the design and manufacturing processes
3. Educate and employ the art of what is possible in advanced materials

The following sections explore each PTD, analyze the art of what is possible using modern materials techniques, examine how these advances could impact the development and deployment of advanced nuclear energy, and describe what will be required to deploy these technologies. Opportunities for collaboration with other industries are also identified.

2.1.1 Priority Technology Direction A1: Explore and Adopt High Performance Materials

As future advanced fast reactors are designed, several key requirements will drive commercial development and deployment of advanced reactor systems: cost, safety, flexibility, and nonproliferation. Overall, cost is a major factor in commercial nuclear applications, and evaluation of that cost is complex. The costs of virgin or reprocessed fuel and waste disposal must be considered, in addition to reactor costs. Advanced reactor technology must be economically competitive with existing light water reactor (LWR) systems. If an advanced reactor system represents a significant increase in capital investment over that of a more traditional technology for the same use, it will not likely be adopted or commercially deployed. In addition, this advanced reactor technology should be flexible. Finally, and obviously, the reactor technology must ensure safety. Inherent safety features and defense-in-depth will be required for any new system to receive regulatory approval.

The use of advanced fuels and materials can positively impact all of these requirements. Improved materials can allow for higher temperature performance, longer lifetimes, and more efficient power generation, all of which can increase economic performance. Improved materials may also lead to

reduced capital costs via reduced material volumes or raw material commodities, as well as design simplifications. Better material performance can lead to improved flexibility and can provide designers with increased options in mission, component, and system design. Finally, improved material performance enables greater safety margins and more stable performance over a longer lifetime, enhancing reliability and power generation. These trade-offs are illustrated schematically in Figure 3 below.

The figure illustrates that for a temperature of 500°C, design stresses for more modern, higher strength materials are possible. Transitioning from 316 SS material to an alloy such as D9 (Fe-15Cr-15Ni) results in a significant improvement, and further transitioning to a high-temperature, ultrafine, precipitation-strengthened steel (HT-UPS, which is D9 plus precipitate microstructure) results in an improvement of about 150 Mpa when compared to 316 SS. As a result, thinner walled components can be used to meet the same design stress, as shown in Figure 3, or for the same design stress and material thickness, higher temperatures can be accommodated. In the figure, allowable temperatures for 316 stainless steel (SS) are 500°C, while D9 can be used at higher temperatures, and HT-UPS can be used at 650°C, a 150°C increase over that of 316 SS. These results illustrate that adopting a higher performance alloy such as HT-UPS instead of an antique material like 316 SS may improve safety, performance, and economics. The impact for specific applications in terms of economic cost and value should be assessed.

As noted above, advanced reactor concepts can offer several advantages over water reactor technologies, including greater thermal efficiency and passive safety systems. Furthermore, advanced reactor concepts can better enable new missions such as process heat or waste transmutation. However, each design also has barriers to development and ultimate deployment. Common barriers for materials that must be overcome to enable advanced nuclear energy systems include coolant compatibility—a key limitation for many advanced concepts, although the specifics vary by coolant and material choice. The impacts of high temperature, mechanical stress, and irradiation environments also pose challenges to deployment.

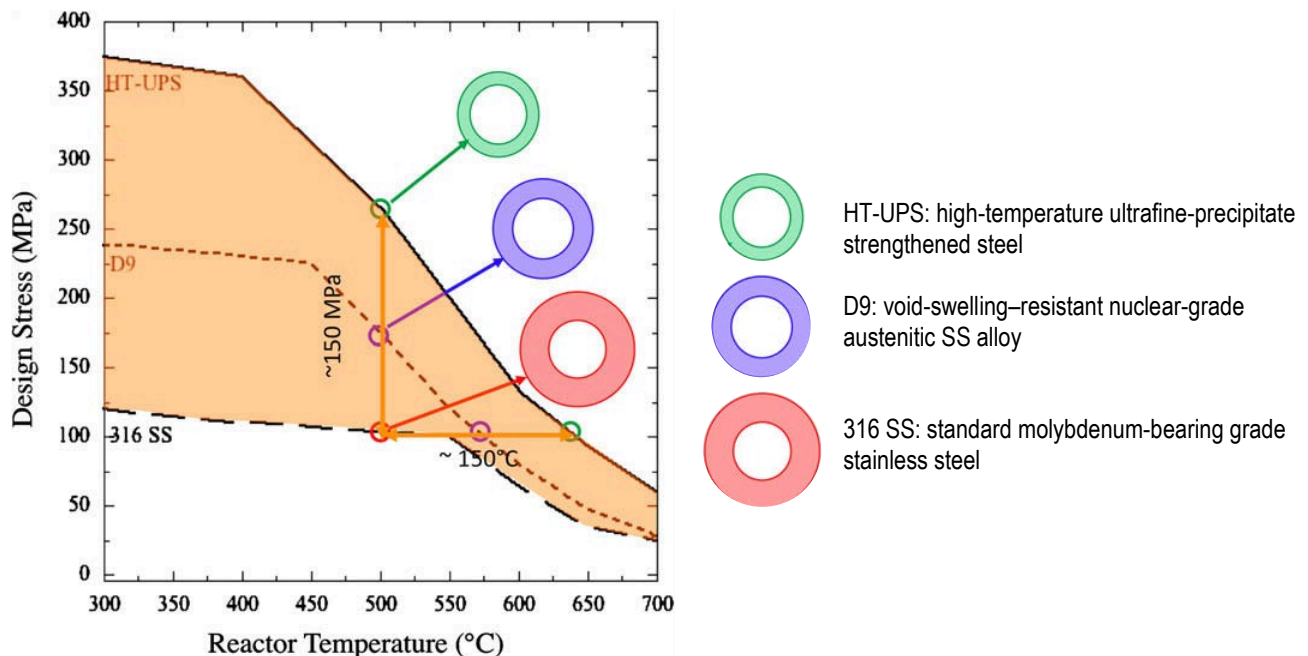


Figure 3. Temperature-design stress curves for 316 SS, D9, and HT-UPS steels. Higher strength can reduce commodities for components and can promote higher operating limits and/or increased safety margins [courtesy of J. Busby].⁴

Material selection for large energy-generating systems is typically governed by a predominant environmental effect such as an oxidizing environment. In advanced nuclear systems, other important

aspects must be considered, including neutronics, the presence of dissimilar materials, and variable environmental interactions that occur in different parts of the plant. For example, in a gas reactor, the pressure vessel is made of low alloy steel, the core internals are graphite, and the power generation modules use nickel-based alloys. In a molten salt reactor, the power conversion system may have molten salt at ambient pressure on one side, which requires a low chromium alloy, and steam at high pressure on the other side, which is highly oxidizing and typically calls for a high-chromium material. Under these circumstances, it is difficult to specify a single coolant condition that is benign to all of the constituents.

In a nuclear reactor, a coolant is a necessity for heat transfer and is therefore essential for power generation and for maintaining a consistent, safe operating temperature. However, a coolant can also fulfill several other key roles, and other properties must be considered, including the desired neutronics properties. However, in some reactor designs, such as water systems, the coolant also serves as the moderator. Frequently, the coolant will remain in either a liquid or gaseous state during operation, although in systems like boiling water reactors, steam is generated in the reactor's core. Therefore, properties such as heat capacity, thermal conductivity, and viscosity are very important. Other factors such as transparency may be important for practical applications in a reactor concept. For instance, a key challenge for sodium-cooled reactors is the inability to see through the coolant and observe components in the reactor's core. This greatly complicates the challenges and opportunities described above. Perhaps one of the most important factors is the potential interaction between the coolant and other structural materials in the reactor. Corrosion (uniform or local), embrittlement, and integrity must all be considered and managed.

As a result of these factors, material and coolant choices in a reactor often involve trade-offs in properties to achieve the right balance for the reactor's mission and lifetime, which can be just as important as its irradiation effects. Reactor design and performance must consider the reactor and its coolant as an integrated system rather than as a series of interconnected components.

Similar limitations for nuclear fuels include degradation issues that must be resolved for thermal and fast spectrum reactor fuels. Fuel forms for gas and molten salt-cooled reactors have unique issues due to their very high operating temperatures and the coolant interactions that must be resolved. Interfacial understanding is essential to predict and mitigate interactions between clad and coolant, fuel and coolant, and/or fuel and clad, for example. Nuclear fuels for fission reactors experience profound changes in their chemistries and physical properties during their lifetimes as a direct result of fission. A system that originally included one or two elements may evolve into a system that includes roughly one third of all elements in the periodic table. The chemistry evolution is often spatially nonuniform, and as a result, chemical potential gradients in the material are complemented with steep temperature and stress gradients. As if the level of complexity were not already overwhelming, extreme radiation damage is another factor that must be considered to understand the phenomena governing fuel behavior. The level of radiation damage for fuels far exceeds that experienced in the most demanding cases for structural materials in fission and fusion reactors and is on the order of thousands of displacements per atom.

While there is great promise in these areas, research is needed to investigate innovative new materials and fuels for advanced reactor designs. In some cases, machine learning may be used to investigate new alloys for extreme environments such as that of the molten salt reactor. Specific needs and next steps should include the following:

- Identify case studies or examples where advanced materials and processes will influence current and future design, operation, and deployment, such as to eliminate the need for complex weld processes, thus reducing cost, increasing safety/operation margins, and enabling new designs. Building on examples and best practices from other industries, case studies demonstrating the power of using modern fuel and material approaches may greatly accelerate adoption of these tools.
- Demonstrate optimization and iterate on existing materials made with modern manufacturing techniques to improve performance for current plants and future deployment. Establish and build

comparative case studies for common materials and conditions to provide input and data to stakeholders and regulators, easing accelerated adoption of these techniques.

- Building on earlier discussions, move beyond the design of materials or components for a given set of conditions. Instead, pilot integration of system, component, or material composition and manufacturing processes for advanced materials during the design process. Demonstrate the ability and capacity for advanced computational and machine learning techniques as a tool for material design in extreme environments. This could allow for expanded exploration of advanced manufacturing beyond alloy families and metal systems.

Ultimately, to be successful, these materials and components must demonstrate performance in harsh, relevant environments. A careful, coordinated qualification protocol must be established. This can be accomplished in conjunction with advanced sensors and control techniques. A summary of the merits of the first PTD, “Explore and adopt high performance materials,” is detailed in Table 1.

Table 1. Explore and adopt high-performance materials.

Advanced Materials and Fuels Panel <i>PTD A1: Explore and adopt high-performance materials</i>	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - High performance materials show promise to enable new reactor designs, expanded mission, improved safety/operating margins, and processes to improve performance and economics through construction, operations, and/or major plant upgrades - Existing materials with modern manufacturing techniques may also improve performance for current and future deployment candidates - High performance computing and machine learning, in combination with advanced characterization/testing as an integral part of the material discovery and design cycle, show promise 	<ul style="list-style-type: none"> - Development and deployment of high performance materials in reactors can overcome obstacles for advanced reactor designs, thus enabling earlier deployment
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Development of improved materials can improve the lifetimes of components in reactors, which can in turn reduce cost - Using advanced materials could enable some advanced reactors to overcome corrosion issues or high dose radiation issues - Improved materials could reduce regulatory issues by increasing the lifetimes of components and avoiding failures 	<ul style="list-style-type: none"> - Identify case studies or examples demonstrating the benefits of using modern fuel and material approaches - Demonstrate optimization and iterate on existing materials made with modern manufacturing techniques to improve performance for current plants and future deployment - Demonstrate the ability to use advanced computational and machine learning techniques as a tool for material design in extreme environments and their applicability to non-metal systems - Demonstrate performance in appropriate nuclear environments (thermal, mechanical, radiation), which likely will be harsh. This may drive the need for an experimental capability that may not exist in the complex

2.1.2 Priority Technology Direction A2: Implement Real-Time In-Situ Surveillance as Part of the Design and Manufacturing Processes

Nuclear reactor research must meet unique demands to deal with highly corrosive media, radioactive samples, and high temperatures. Developments in testing and approaches to this work are enabling new scientific advancements. Materials in reactors are subjected to an extreme environment with multiple components that must be accounted for to understand and predict their behavior. In all reactor designs and concepts, core components are subjected to irradiation, mechanical stress, and a corrosive environment, all at an elevated temperature. Thus, understanding the effects of irradiation alone is insufficient to predict the behavior of materials in such a multidimensional environment. Therefore, the challenge is to devise strategies and techniques to address this multifaceted environment. All of these

objectives must be met in an environment that is safe for researchers, which mandates the use of hot cells and remote handling capabilities. This adds complexity to testing and analysis that is unique to nuclear energy.

The rapid development of computational capabilities has provided new opportunities to explore mechanisms of performance over a wide range of scales in time and space.

The rapid development of computational capabilities has provided new opportunities to explore mechanisms of performance over a wide range of scales in time and space. Significant advances in characterization techniques and tools could enable new modes of material and fuel performance monitoring, which could be a breakthrough for the accelerated deployment of advanced reactor concepts. Development of a tool that estimates or monitors the remaining useful life of a component or subsystem will accelerate materials and system approval, as well as regulatory approval, by reducing or eliminating the need to acquire a lifetime's worth of data before submitting for approval. This could result in one of the most powerful, achievable methods to accelerate advanced reactor technology deployment.

Implementation of real-time surveillance during fabrication using advanced sensors or surveillance articles could build confidence in manufactured components, as the actual processes will be qualified instead of the resulting materials or components. This is the so-called *born-qualified* approach that can be applied to advanced manufacturing, including welding or additive manufacturing. Gathering information from embedded sensors during the build, as well as during operation, may reduce the time required for licensing by showing that the build parameters were substantially similar (e.g., within defined statistical bounds) to those of previously qualified parts. Furthermore, this approach can improve reactor operation by providing data in situ during operation, and it may also improve safety by directly informing lifetime decisions specifically rather than generically.

Nondestructive evaluation (NDE) is the science of materials characterization for detecting and quantifying the performance, quality, or level of defectivity in a material without altering the material under test. Broadly speaking, most NDE techniques apply energy in one form or another (electromagnetic, acoustic, etc.) to the material under test, and then analyze the resulting response to determine the material's condition.

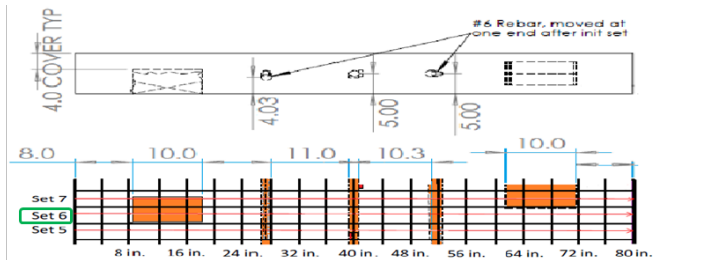
NDE techniques such as ultrasonic, eddy current, or visual examination are currently used to inspect materials and components in nuclear power systems and provide an assessment of material reliability. These techniques are generally applicable for detecting macroscopic cracks and flaws (inhomogeneities in the material), with the smallest reliably detectable flaw sizes on the order of ~1 mm. Recent advances in this area include

- The availability of simulation tools for understanding inspection physics, as in interaction of the applied energy with the crack,

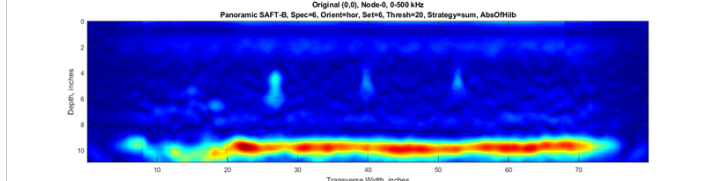
- New sensor designs such as ultrasonic phased array sensors, laser ultrasonic systems, high frequency eddy current arrays, and high-sensitivity thermal imagers,
- New measurement parameters such as the nonlinear ultrasonic parameter,
- the application of machine learning and deep learning technologies for NDE data processing to improve detection capability or sensitivity, and
- Model-based inversion techniques for flaw characterization (size and shape estimation).

For example, consider the case shown in Figure 4. Advanced mathematical processing of very traditional testing techniques for nuclear concrete has enabled new understanding and has dramatically improved confidence in the safety and reliability of this key structural component. As illustrated in the figure, NDE with advanced signal processing can greatly facilitate the identification of flaws, as shown in the concrete specimen schematic (with flaws), which is aligned with the Synthetic Aperture Focusing Technique (SAFT) and Frequency-Banding (FB)-SAFT reconstructions.

A: schematic of concrete defects and internal structure (orange) overlaid with 4-inch black grid and scan path of ultrasonic test instrument (red horizontal lines)



B: SAFT reconstruction of scan line Set-6 (green box in A above)



C: FB-SAFT reconstruction of Z scan line Set-6 (green box in A above) using Wavelet node 16 (31.25–62.5 kHz)

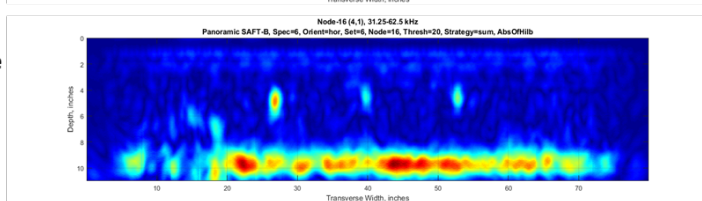


Figure 4. Frequency banding improves the visibility of defects and internal structural elements. FB-SAFT (C) more clearly identifies that the left-hand rebar that was moved vertically to simulate poor bonding [courtesy of A. Albright].⁵

In-situ sensors may be used to monitor processes or materials/components. An in-situ sensor measures the parameter of interest without interrupting the process or removing the material/component to the lab. Some condition measurements are taken of structural materials and fuel while they are being irradiated. Consequently, sensors are needed that can be placed in or near the core to determine process and materials condition (generally in real time) during a test campaign. It is a significant challenge to obtain the necessary information on the dynamics of system performance change (i.e., change in process parameters over time) in a test reactor due to the irradiation/temperature/coolant exposure over longer test durations. These types of measurements require fast response times so that sensors can capture changes, especially during the early portion of irradiation testing. These measurements also require sensor performance over extended lifetimes. Long-lived sensors are necessary to obtain data during longer test durations.

Currently, process monitoring uses many readily available sensors: thermocouples, resistance temperature detectors, pressure transmitters, ultrasonic and magnetic flow meters, flux wires, etc. These sensors are generally able to meet measurement needs in specialized facilities such as test reactors. However, an

important need is to improve reliability of these sensors to meet increasingly challenging measurement needs such as longer durations of analysis, higher temperatures, and higher flux/fluence tests.

NDE techniques and future in-situ monitoring for new materials and fabrication methods are also important.

As current nuclear plants age and advanced reactors are developed, there is increased attention on the aging behavior of new materials. Not only do these materials include newer alloys such as 9Cr-1Mo steel, but they also include materials such as concrete and electrical cable insulation, as well as fuel and cladding. NDE techniques may be required to ensure the integrity of fuel and cladding in intermediate and final storage facilities. The behavior of these materials in relation to temperature, dose, and in some cases coolant chemistry (alone or in combination) is unlike the behavior of classically studied nuclear structural materials. Existing techniques may require adaptation, while new techniques may need to be developed for in-situ assessment.

Recent gains in sensor technology, improved understanding of materials, advances in computational power, and refined manufacturing approaches could be revolutionary if they are harnessed for nuclear energy.

New fabrication methods such as advanced manufacturing are also being investigated. Given the current state of technology and anticipated near-term (5–10 years) developments, it is likely that inhomogeneities in the manufactured component will remain and will thus drive materials performance. Therefore, quality assurance is needed for nuclear materials and components fabricated using these methods. In addition to the challenges identified above, underlying challenges remain, including techniques for post-fabrication examination of advanced manufacturing materials. Reliable methods for in-situ materials monitoring during fabrication would be ideal and would provide a mechanism for real-time control of the fabrication process.

Recent gains in sensor technology, improved understanding of materials, advances in computational power, and refined manufacturing approaches could be revolutionary if they are harnessed for nuclear energy. In addition to the development of the sensor, several key limitations must be addressed:

- Sensors must be selected based on their intended use. The sensor's compatibility and survivability must be established, and it must be tested to ensure (1) that it does not affect the properties of the component and (2) to determine its survivability during reactor operation.
- In-situ monitoring techniques during fabrication have great potential, but they also require specialized development. Specifically, new in-situ sensors must be developed to obtain relevant information, and new methods for processing large data sets are required, as well as improvements in automated processing. Finally, a thorough understanding and control of process parameters is required to ensure reproducibility and process qualification.
- In-situ performance monitoring will require development of new and/or improved monitoring techniques. Processes for transmitting, curating, processing, and analyzing new levels of information must be examined. Surrogate material surveillance and accelerated stressing must also be analyzed and adopted to accelerate development and implementation of monitoring techniques and acceptance criteria.
- The development of any new sensor or monitoring technique comes with a steep requirement to understand the limitations and fidelity of the data being obtained. Is the new technique measuring real effects or artifacts? Do new observations indicate changes in real performance, or do they reflect the inadequacies of older techniques? Careful comparison to known and benchmarked samples/conditions must be performed to ensure smooth, reliable transition to new methods.

A summary of the merits of this PTD is shown in Table 2.

Table 2. Implement real-time in-situ surveillance (e.g., advanced sensors or surveillance articles) as part of the design and manufacturing process.

Advanced Materials and Fuels Panel	
PTD A2: Implement real-time in-situ surveillance (e.g., advanced sensors or surveillance articles) as part of the design and manufacturing process.	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - Advanced sensors or surveillance articles as part of the design and manufacturing processes - Promising work on qualifying fabrication processes (instead of materials or components) to build confidence in advanced manufacturing, including welding or additive manufacturing processes - Use of embedded (passive or active) sensors to actively inform lifetime performance 	<ul style="list-style-type: none"> - Design, manufacture, and licensing of reactors could be accelerated by providing materials produced while monitoring the process with sensors in situ
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Implementation of advanced sensors can improve reactor operation by providing data in situ during operation, and it may also improve safety by directly informing lifetime decisions specifically rather than generically - Manufacturing could be accelerated by making it possible to produce near net shape parts, and licensing could be accelerated by including sensors to monitor the health of the reactor in situ 	<ul style="list-style-type: none"> - Develop new in-situ sensors to extract relevant information, along with new ways of processing large data sets - Examine and demonstrate ways of transmitting, curating, processing, and understanding new levels of information - Explore and adopt surrogate material surveillance and accelerated stressing to facilitate development and adoption of monitoring techniques and acceptance criteria - Understand the limitations and fidelity of the data being obtained

2.1.3 Priority Technology Direction A3: Educate and Employ the Art of What Is Possible in Advanced Materials and Fuels Science

Substantial gains in our understanding of fuels and materials science have been spurred by advances in characterization tools (mechanical, microstructural, and environmental), high performance computing, and synthesis of materials. If these tools are utilized to their fullest, when combined, they could greatly accelerate the development of advanced reactor technologies.

Given the advances in computational capacity, fundamental knowledge, and advances in modern manufacturing, it is equally important that we employ modern materials tools and approaches to enable co-design of reactor configurations, fuels, materials, coolants, and geometries. This approach will allow us to explore combinations that lie outside the traditional approaches. For example, this approach would allow us to enable machine learning and smart designs, new functionalities or geometries, and gradient compositions. This approach is a distinct departure from today’s common approach to developing a reactor concept in which we explore material and fuel choices, adjust the reactor concept and performance to match available materials, and then repeat these steps.

Instead of using this iterative approach, reactor configurations, as well as material and fuel choices, can be optimized in parallel. Instead of using a material that was chosen as the least objectionable option, a material can be designed to match operational needs. Instead of following separate, distinct steps to design a component, components can be designed to take advantage of advanced manufacturing capabilities. Figure 5 illustrates how a radical change can be made by employing these techniques: traditional limitations may no longer apply.

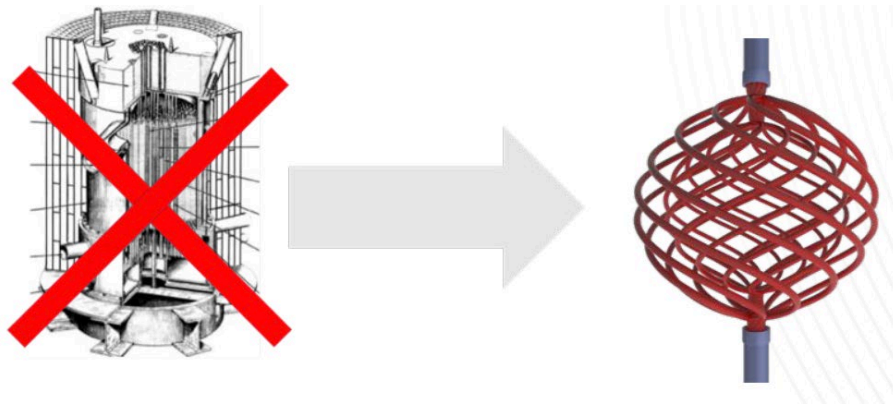


Figure 5. Modern materials science and advanced manufacturing methods can provide for more complexity and better optimization and efficiency while decreasing costs [courtesy of K. Terrani, ORNL].

Furthermore, using advanced fuels and materials produced by advanced manufacturing and characterizing them with modern characterization tools could improve safety and reduce regulatory issues by increasing component lifetimes and avoiding failures. Consider the opportunities afforded by optimizing reactor design in parallel with selecting alloys and coolants. New core configurations and geometries, along with optimized alloys, could reduce irradiation impact to structures, thereby enabling longer lifetimes and greater safety margins.

In addition, new materials and manufacturing approaches may have other positive effects on design and construction. For example, if large-scale components can be fabricated on or near the reactor building/site (or even in-situ), construction time may be reduced by eliminating complex transportation issues for components and streamlining supply chains. This may also enable new reactor siting options if, for example, barge-access for components is no longer required. Advanced materials and fabrication may also mitigate other siting challenges. Improved heat exchanger materials may provide more energy generation efficiency, as discussed above. However, they may also help reduce water usage and return temperature, allowing new areas for deployment. At further extremes, dry cooling may be possible and could enable deployment to large portions of the western United States, where water availability is more limited. While these advantages require testing and verification, their potential impact is significant and worthy of investigation.

Finally, the design, manufacture, and licensing of reactors could be accelerated if materials can be monitored with sensors in situ during their production. Being able to produce near net shape parts could accelerate manufacturing, and licensing could be accelerated by including sensors that monitor the health of the reactor in situ.

Deployment of these ideas and concepts in the nuclear industry is not trivial. Nuclear power development and deployment is conservative, and with good reason given the potential consequences of power plant failures. However, as noted above, deploying modern material and fuel science can also enhance safety and improve new designs.

Several key steps should be enacted to accelerate acceptance of these concepts, including:

- Initiate a broad engagement effort to inform different programs and communities on the art of what is possible through agencies, professional societies, or other reliable networks. This effort should include reactor designers, utilities, advocacy groups, and other communities of material researchers.
- Communicate best practices between different industries and organizations. Are there lessons from aerospace, defense, or fossil energy's development and deployment of materials that can

be extended and shared with nuclear? Are there opportunities to adopt these best practices within the current regulatory framework for greater confidence and an accelerated process?

- Develop a catalogue of examples from other industries to prepare nuclear stakeholders, including past examples of changes in nuclear technology. For example, nuclear energy has adopted and changed water chemistry and cladding materials numerous times to improve reliability and efficiency, as shown in Figure 6.
- Demonstrate advanced technologies on a limited scale to build confidence through rapid, numerous iterative successes and failures. This includes advanced manufacturing and process-based qualification, machine learning, as well as adoption and development of advanced and innovative materials.

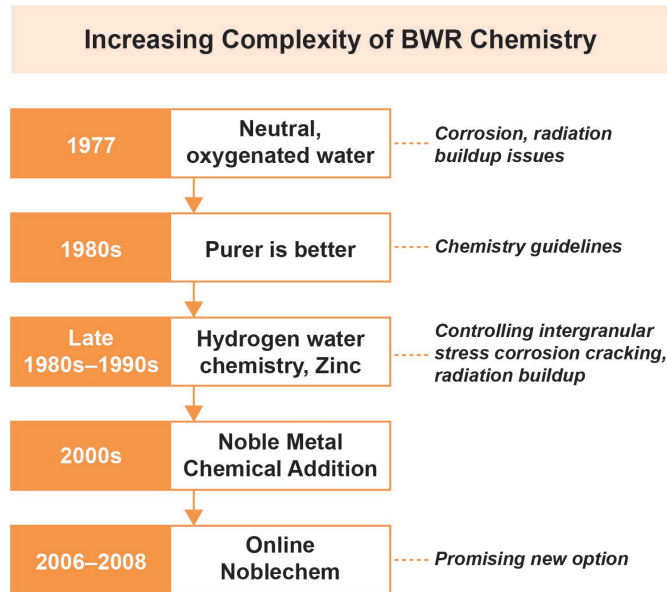


Figure 6. In the last 30 years, boiling water reactor chemistry has become more complex.⁶

Modern material and fuels science have advanced considerably in recent decades. There are significant opportunities to accelerate and broaden deployment of nuclear technology if these advances can be captured and accepted. New designs and missions may be enabled. Improved safety, reliability, and performance are possible. Improved economics and viability are likely. However, a dedicated, sustained effort to educate and adopt the state of the art will be required.

Many advancements have already been made in materials and fuels as a result of DOE-funded programs. Since there have been no advanced reactors built in recent years, there have been no opportunities to gauge the impact of this work. However, sustained efforts still provide tangible and meaningful gains toward commercialization of advanced reactor concepts, not to mention the nuclear industry as a whole.

For example, DOE-NE’s longer term efforts to support the ASME code case qualification of alloys 617 and 709 provide additional opportunities for reactor designers related to the types of materials that can be leveraged for design. However, engineering design and thus deployment are not practical until the code qualification is complete, and even then, beyond laboratory scale, supply chain issues may hamper widespread application. This is more of a concern for alloy 709, which does not currently have commercial applications for nuclear or nonnuclear applications, so the supply chain for large-scale alloy procurement does not exist. Steady progress through DOE-NE programs should provide a shorter path to deployment when advanced reactor deployment opportunities arise. Similarly, significant irradiation data

have been collected for a variety of grades of nuclear graphite that could be leveraged by a vendor for full qualification.

In nuclear fuels, the continued development of TRISO particle fuels is a similar success. High quality (low defect rate) TRISO particle fuels have been redeveloped and are undergoing qualification testing as a direct outcome of sustained DOE funding. The national laboratories were able to take a complex problem and apply the unique characterization and simulation tools within the DOE complex and develop a viable and reproducible process for TRISO fuel fabrication. That technology is now being moved to an industrial-scale process by a fuel vendor working in close collaboration with the national laboratories. When a new gas reactor is ready for deployment or when TRISO is adapted for accident tolerant LWR applications, this technology will now be a viable alternative.

The sustained efforts on TRISO fuel, the advanced graphic creep campaign for graphite, and the qualification of alloys 617 and 709 will yield tangible benefits to community. These are all great examples of what has been successful in DOE-NE and should be replicated in other programs.

A summary of the merits of PTD A3, “Educate and employ the art of what is possible in advanced materials,” is detailed in Table 3.

Table 3. Educate and employ the art of what is possible in advanced materials.

Advanced Materials and Fuels Panel <i>PTD A3: Educate and employ the art of what is possible in advanced materials</i>	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - The art of what is possible in advanced materials (structural fuel, moderator and/or coolant), modern characterization and testing, performance monitoring, high performance computing, machine learning and advanced manufacturing as enabling technologies is changing rapidly - Nuclear industry designers, stakeholders and decision makers traditionally rely on outdated alloys and approaches 	<ul style="list-style-type: none"> - A dedicated and sustained effort to educate researchers, designers, and regulators and to adopt the state of the art of what is possible in advanced materials could enable new designs and missions - Improved safety, reliability, and performance, with improved economics and viability are possible
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Acceptance and adoption of the many advances in modern materials and fuels science by the nuclear industry could bring significant opportunities to accelerate and broaden the deployment of nuclear technologies while enhancing safety and improving new designs. 	<ul style="list-style-type: none"> - Initiate a broad engagement effort to inform different programs and communities on the art of what is possible through agencies, professional societies, or other reliable networks - Communicate best practices across different industries and organizations - Develop a catalogue of examples from other industries to prepare nuclear stakeholders - Demonstrate advanced technologies on a limited scale to build confidence through rapid, numerous, iterative successes and failures

2.2 PANEL B. ADVANCED MANUFACTURING TECHNOLOGIES TO ENABLE NEW DESIGNS

Advanced manufacturing processes cover a broad spectrum of technologies. These processes include additive manufacturing, advanced high-speed/high-accuracy machining, hybrid processes (additive/subtractive), robotic welding, and powder metallurgy. The primary advantage of advanced manufacturing techniques is their ability to enable reduction in manufacturing time through increased levels of automation, sensory feedback, and controls during the manufacturing process while increasing the reliability and complexity of the design to improve functionality. These technologies can enable new designs that combine mechanical and functional performance, adding the capability to operate effectively in an environment not previously possible, even with high radiation levels. Careful design must be implemented with a sound awareness of the strengths and limitations of these newly emerging manufacturing processes.

To encourage rapid adoption and implementation of the technology, there must be clear advantages over existing processes, as well as trust from the professional community. Typical examples of these advantages include the following:

- **Cost reduction** resulting from factors such as
 - Reduction in waste of precious metals and
 - Reduction in manufacturing and qualification times (e.g., reduce nuclear qualification time from 20 years to 2 years)
- **Increased part complexity**, such as the ability to deploy conformal cooling channels for heat exchangers, and
- **Part reduction** for increased reliability and reduction in assembly and maintenance.

Emerging manufacturing processes include higher levels of automation which reduce human error. They also include greater levels of sensory feedback, providing a record of all states of the system during the manufacturing process. These enhancements will create new certification and qualification scenarios based on data and modeling validation through testing. For example, advances in machine tools have allowed us to fabricate complex structures with thin walls (Figure 7) and complex shapes (Figure 8).

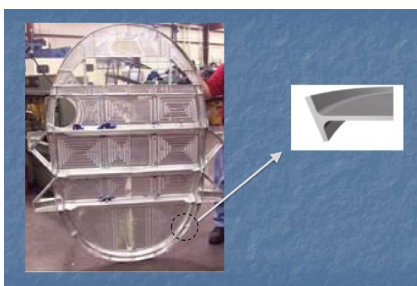


Figure 7. Manufactured aerospace bulkhead with formed edges [courtesy of S. Smith, UNCC].

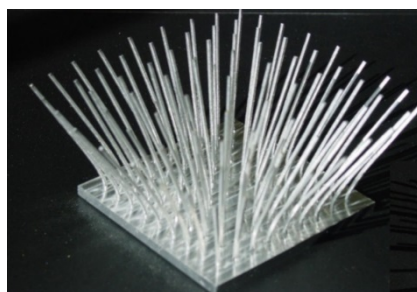


Figure 8. Machined and formed heat sink [courtesy of S. Smith, UNCC].

2.2.1 Application to Accelerate Deployment

To realize the benefits of these advanced manufacturing processes, requirements must be clearly and effectively communicated to the advanced manufacturing community. Enhanced awareness will help establish and expand opportunities. Advanced manufacturing requirements address the following factors:

- Materials, size, scale, shape, properties, and code
- Irradiation data obtained through modeling and experimentation
- Conventional and new reactor designs
- Demand and cost (business case)
- Performance criteria (e.g., temperature, pressure, lifetime)

Access to this set of information will facilitate alignment of manufacturing processes with their potential applications.

A complementary information exchange between the advanced manufacturing community and the nuclear industry is necessary to advance progress. For example, new sensing and control methodologies are expanding the capabilities of existing manufacturing processes. Integration and sensing of fiducial markers on feedstock provide insight into part distortion during the manufacturing process. This can be used to improve machining control (e.g., toolpath, spindle speed, laser power). Hybrid processes such as machining with additive manufacturing can allow for greater complexity while reducing manufacturing time. Innovative methods of localized deformation—or *incremental forming*—may also allow for development of complex shapes without the use of expensive dies and tools.

Nuclear power generation also requires large-scale structures with complex geometries to support pressure retention and fuel elements. Powder metallurgy is enabling the manufacture of large, complex structures with known predictable properties to be used as pressure-retaining structures (see Figure 9). Manufacturing of near net shape, which reduces the need for surface finishing, is impeded by the expensive auxiliary process required to make the powder containment cans needed for hot isostatic pressing (HIP). Large-scale additive processes can be useful in this application. This hybrid approach can be used to deploy high performance material, as the material can be left in place to serve as a high performance skin for the final part. Similarly, emerging laser direct energy deposition additive manufacturing processes can be used to add details to a part that was created using traditional processes. Preliminary work has also shown the possibility of using binder jetting to manufacture a new generation of fuel elements, as illustrated on the cover of this report.

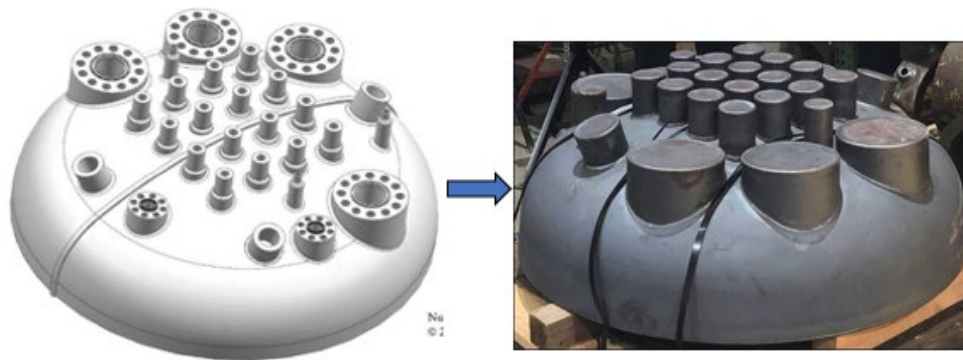


Figure 9. Powder metallurgy and HIP small modular reactor (SMR) component [courtesy of D. Gandy, EPRI].

Additive processes are being developed and deployed in other industries. For example, the aerospace industry has demonstrated success with heat exchangers and fuel nozzles (see Figure 10 and Figure 11). These applications are driven by economics, with cost and lead time as key factors.



Figure 10. General Electric (GE) fuel nozzle made by additive manufacturing [courtesy of GE].



Figure 11. GE heat exchanger made by advanced manufacturing [courtesy of GE].

Hybrid additive/subtractive processes are starting to combine multiple processes to enable rapid manufacture and repair of complex geometries. Many of these systems are becoming commercialized and mass produced by machine tool manufacturers (e.g., Mazak and DMG-Mori, as shown in Figure 12 and Figure 13). Research efforts are focused on developing new design tools and manufacturing process controls such as toolpath generation (Figure 14).



Figure 12. Mazak hybrid additive/subtractive system [courtesy of Mazak Corporation].

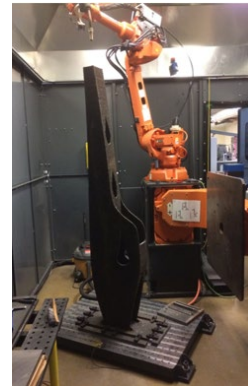


Figure 13. Wolf Robotics robotic advanced manufacturing system [courtesy of ORNL].

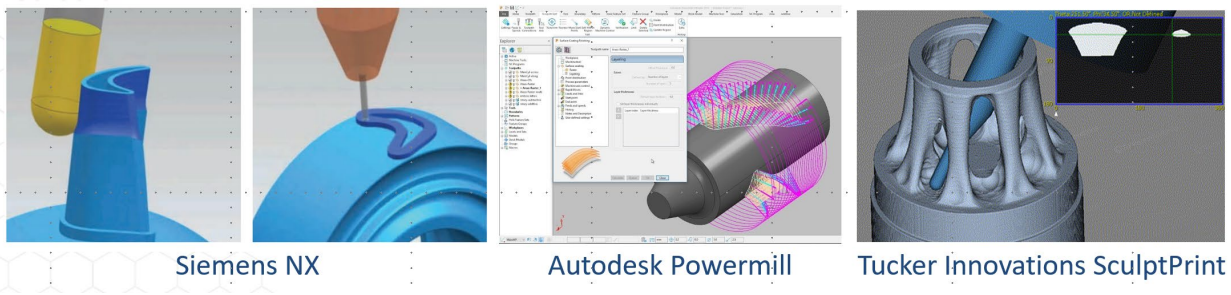


Figure 14. Hybrid process interleaving / optimal trajectory planning [courtesy of C. Saldana, Georgia Tech].

While generative designs and adoption of new advanced manufacturing are being pursued by other industries (e.g., aerospace, defense, biomedical), they have yet to gain traction in the nuclear power industry. There are likely two reasons for this:

1. **Lack of materials information.** Existing nuclear energy manufacturing enterprises do not have access to knowledge and research information on how components made with new manufacturing processes will perform under high radiation conditions.
2. **Lack of verifiable qualification of manufactured components to define their fitness for service.** There is lack of confidence on the qualification of components made by these processes, and there are no case studies demonstrating the effectiveness of the technical and business value proposition for the nuclear industry.

Materials: The nuclear industry has very few materials certified for use. Also, the additive industry only has only a handful of materials suitable for printing. Materials used in additive manufacturing must be available in specific forms such as powders, wires, and sheets of specific size, chemistry, morphology and size distribution. In many cases, material suppliers are limited. Lack of a viable supply chain for these required materials complicates the feasibility of developing and implementing these engineering solutions in a short time. However, these disadvantages are rapidly changing with development of advanced manufacturing systems that use conventional feedstocks such as powders from the powder metallurgy industry, wire from the welding industry, and sheets from consumer products. These developments will increase the likelihood of satisfying the needs of the nuclear energy industry, which has extensive data on mechanical properties with and without nuclear irradiation.

New measurement technologies can be used to monitor the manufacturing process, gathering extensive, highly detailed data in real time. High performance computing can process these data to make rapid certification and qualification a reality.

Certification and Qualification for Fitness for Service: Certification and qualification of processes and/or parts produced through advanced manufacturing presents a significant challenge. The strength of advanced manufacturing lies in *process variability*, which is the ability to change material properties within a single structure through real-time control of processing parameters. This leads to the following fundamental question: *How does one ensure the part or process is operating within a specification that is consistent with the part qualified for service?* Fortunately, this problem is being addressed in many other industries, primarily through in-situ manufacturing process monitoring integrated with big-data analytics. This involves real-time logging of all processing parameters and measurement of temperature, chemistry, and displacement. All information from pre-processing (material, design, geometry, system configuration, etc.), processing (power, speeds, temperatures, gas shielding) and post-processing phases (heat treatment, machining, etc.) is electronically logged and recorded. This provides a full digital thread for every manufactured part. This information can be processed using machine learning and data analytic tools to help establish the required operating conditions necessary to certify and qualify a part. New measurement technologies can be used to monitor the manufacturing process, gathering extensive, highly detailed data in real time. High performance computing can process these data to make rapid certification and qualification a reality. We are moving rapidly in the direction of using sensing techniques and data obtained during manufacturing to ensure part quality, minimizing the potential for human bias and error. Furthermore, in certain cases and in the application of advanced manufacturing, with its requirements for compliance with existing ASTM and ASME

We are moving rapidly in the direction of using sensing techniques and data obtained during manufacturing to ensure part quality, minimizing the potential for human bias and error.

standards, qualification may require testing for extended times under irradiation conditions. At the same time, some reactor companies are taking advantage of current nuclear qualified materials to build reactors with short lifetimes, therefore forgoing extensive irradiation testing (e.g., Terrestrial Energy's 7-year Integral Molten Salt Reactors⁷).

2.2.2 Implications of New Approach

There are clearly many possible opportunities to apply advanced manufacturing processes in the nuclear power industry. First, as discussed earlier, these processes enable greater freedom and flexibility in design and manufacturing. Second, many additive processes enable the emplacement of other components (e.g., radionuclides) with high spatial specificity. The processes do not require any tooling, so the cost and time to market are reduced for low-volume production. New manufacturing processes enable innovative designs, opening up design space and enhanced performance through geometry and materials. An area of growing potential for numerous industries (e.g., construction, aerospace, energy) is the production of replacement parts for applications in which the parts inventory or tooling capabilities no longer exist. These processes are highly automated, digitally enabling the archiving of part genealogy from feedstock to service.

To help ascertain opportunities and challenges, workshop participants responded to five specific multiple-choice questions (see Table 4). The consensus is that the most important tool to be developed is a methodology for rapid certification and qualification. There is great interest in hybrid systems and the ability to integrate sensors within components. Near-term interest in components includes heat exchangers and pressure vessels. By far, the experts assessed that advanced manufacturing can have the greatest impact on the industry in decreased cost and production time.

2.2.3 Further Advances Needed

Topics that require more focus and that received the greatest interest were target platforms to rapidly evaluate the potential for advanced manufacturing. This type of evaluation requires vision, focus, and support. In addition, there is the need for a skilled workforce that understands advanced manufacturing; personnel ranging from technicians to engineers to regulators. Methods are needed to rapidly evaluate materials that are suitable for advanced manufacturing. This evaluation should analyze impurities, test data with radiation under various manufacturing processes (defects), and geometry. The manufacturing industry must not only understand the opportunities (part sizes, geometries, properties), but also the business case (cost savings and market).

Table 4. Results of poll around opportunities and challenges of advanced manufacturing.

What is the most important tool needed for advanced manufacturing?	Very Low	Low	Medium	High	Very High
New design tools for advanced manufacturing	0%				
New manufacturing systems		24%			
New controls on existing manufacturing systems		13%			
New methods for rapid certification and qualification				63%	
What component has the greatest opportunity for cost savings through advanced manufacturing?					
Replacement parts		17%			
Heat exchangers/pressure vessels				54%	
Fuels		17%			
Cement structure		11%			
What manufacturing technology could revolutionize the nuclear power industry?					
Large scale additive manufacturing		15%			
Hybrid additive/subtractive manufacturing				39%	
Integration of sensors into parts				41%	
Additive manufacturing of cement structures	4%				
What should be the greatest impact of a new reactor enabled by advanced manufacturing?					
Increased safety	3%				
Decreased cost and manufacturing time					80%
Increased reliability	0%				
Improved performance			17%		
What is your biggest concern about advanced manufacturing for the nuclear industry?					
Standards will take more than 20 years			28%		
Advanced manufacturing is not proven for nuclear applications				35%	
Public opinion on safety			9%		
Other countries will do this before the United States			13%		

Recommended technology thrusts

Based on this assessment, three PTDs were identified in order of priority:

1. Manufacture and deployment of replacement parts
2. Design and fabrication of new components (clean sheet design)
3. Development of a methodology to rapidly bridge the gap between new designs and materials

2.2.4 Priority Technology Direction B1: Manufacture and Deploy Replacement Parts

The first PTD will provide an early demonstration of advanced manufacturing that will provide confidence in the technology and enable rapid insertion of new technologies, thus reducing cost and lead time while avoiding potential loss of service.

Recommended deployment initiatives

This effort will be phased, starting with lower risk secondary elements (pump housing, heat exchanger), followed by a higher risk demonstration of the primary element. The goal is to have parts that were manufactured using advanced manufacturing processes in operation within a working system. Multiple parts must be evaluated to determine manufacturing options, and multiple processes will be evaluated and compared in terms of processing time, qualification time, cost, and performance. A summary of the merits of the replacement part approach is detailed in Table 5.

Table 5. Manufacture and deploy replacement parts.

Advanced Manufacturing Technologies <i>PTD B1: Manufacture and deploy parts</i>	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - Using conventional technologies (casting, forgings and welding) that have high cost and lead time - Skilled workforce resources are in decline 	<ul style="list-style-type: none"> - The goal is to use advanced manufacturing to replace both primary and secondary components at reduced cost and time: start with secondary aspects (low-hanging fruit) end with moonshot (primary reactor part) - Choose appropriate process to accelerate adoption. For example, use additive manufacturing or an advanced manufacturing part to make a can for powder metallurgy
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Replacement parts are needed to maintain operation - Advanced manufacturing may reduce cost and lead time in areas such as reactor down time - Advanced manufacturing can provide confidence to industry 	<ul style="list-style-type: none"> - New reverse engineering tools are needed to provide CAD models - Large HIP and manufacturing tools are needed to ensure properties of materials at full scale; currently relying on other countries for these capabilities

2.2.5 Priority Technology Direction B2: Design and Fabrication of New Parts (Clean Design Sheet)

The second PTD would focus on new designs made possible through advanced manufacturing. The proposed approach is to implement target demonstration projects through early integration and colocation of subject matter experts (SMEs) in the nuclear power design and advanced manufacturing technologies to ensure rapid information exchange. Teams will iterate on reactor designs with feedback from manufacturing SMEs on manufacturability. In tandem, manufacturing SMEs will provide designers with guidance on relevant requirements. Multiple SMR designs should be evaluated and modified to explore possibilities. Table 6 provides an overview on the motivation, impact, and technical advancements for this effort.

Table 6. Design and fabrication of new parts.

Advanced Manufacturing Technologies	
<i>PTD B2: Design and fabrication of new parts (clean design sheet)</i>	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - Many designs are new and yet to be deployed - There is no consensus on which manufacturing technology to use 	<ul style="list-style-type: none"> - Methodologies can be developed to go from design to manufacturing to service (e.g., digital thread) - Numerous advanced manufacturing technologies being deployed in other industries (fuel nozzles in aerospace, heat exchangers in automotive, pump housings in oil and gas) serve as examples - Advanced manufacturing enables fresh new designs (e.g., increased efficiency in heat exchanger)
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Exploit design, manufacturing, and sensing available with advanced manufacturing for new designs - Bring regulator standards organization into the discussion at the beginning to help educate 	<ul style="list-style-type: none"> - Need collaborative iteration between reactor designers and advanced manufacturing engineers - Collocation of talent is needed to enhance mutual learning: manufacturers need to understand current costs

2.2.6 Priority Technology Direction B3: Develop Methodology to Bridge Gap between New Designs/Materials

The third PTD focuses on the development of a basic methodology to bridge the gap between state-of-the-art concepts and the demonstration of their viability for future reactor designs and manufacture. The goal is to build on the knowledge gained from other industries, which have been focused on creating a full digital thread, beginning with design and progressing through deployment in a way that ensures data can be used to certify and qualify a part and to document all aspects of the manufacturing process.

Table 7 provides an overview of this third PTD.

Table 7. Methodology to rapidly deploy new designs and materials.

Advanced Manufacturing Technologies	
<i>PTD B3: Develop methodology to bridge gap between new designs/materials</i>	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - Existing processes are lengthy and expensive, regulation required at every stage - Not done today with advanced manufacturing 	<ul style="list-style-type: none"> - If digital thread exists and is open to designers, manufacturers, testers, regulators, and users, it will reduce uncertainty for nuclear reactors - Advancements should be leveraged (industry 4.0) as in other areas such as aerospace, automotive, oil and gas
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Reduced time to market - Full digital thread from materials to parts 	<ul style="list-style-type: none"> - Modeling tools for irradiation should be developed for advanced manufacturing (material and geometry) - A demonstration project should be implemented, pulling everything together from materials, process, design, manufacturing and testing

This basic three-phase strategy for staged insertion and infusion of advanced manufacturing components and processes into the nuclear industry follows the same strategy adopted by the aerospace industry. Today, the aerospace industry is flying with parts made through advanced manufacturing, including products made using composites and additive manufacturing.⁸

In both cases, the industry started with supporting parts like simple brackets for wiring harnesses. Mission-critical parts were not candidates for the initial advanced manufacturing efforts. As confidence in the reliability and performance of the parts grew, the industry began migrating to applying advanced manufacturing processes to more mission-critical components such as fuel nozzles. The industry is now starting

to explore integration of flight-critical parts that should have low probability of any catastrophic failure. The US Department of Defense is conducting early testing of this approach. In July 2016, the US Naval Air Systems Command (NAVAIR) successfully flew a V-22 with a flight-critical part made with additive manufacturing.⁹ General Electric Aviation is starting tests on new turboprop engines that were made using additive manufacturing techniques (see Figure 15). This *fresh sheet design* reduced the count from 855 separate parts to only 12 additively manufactured parts. The engine will undergo its first test flights in late 2018, with full-scale production beginning in 2020.¹⁰ A typical new design takes 10 years from start to prototype, whereas the additively manufactured system took only 2 years. GE has publicly stated that “additive manufacturing has changed the way we do business.” In a similar manner, a focused program on exploring the potential for advanced manufacturing in the nuclear power industry may completely change the way the nuclear industry designs and manufactures future reactors.

... a focused program on exploring the potential for AM in the nuclear power industry can completely change the way the nuclear industry designs and manufactures future reactors.

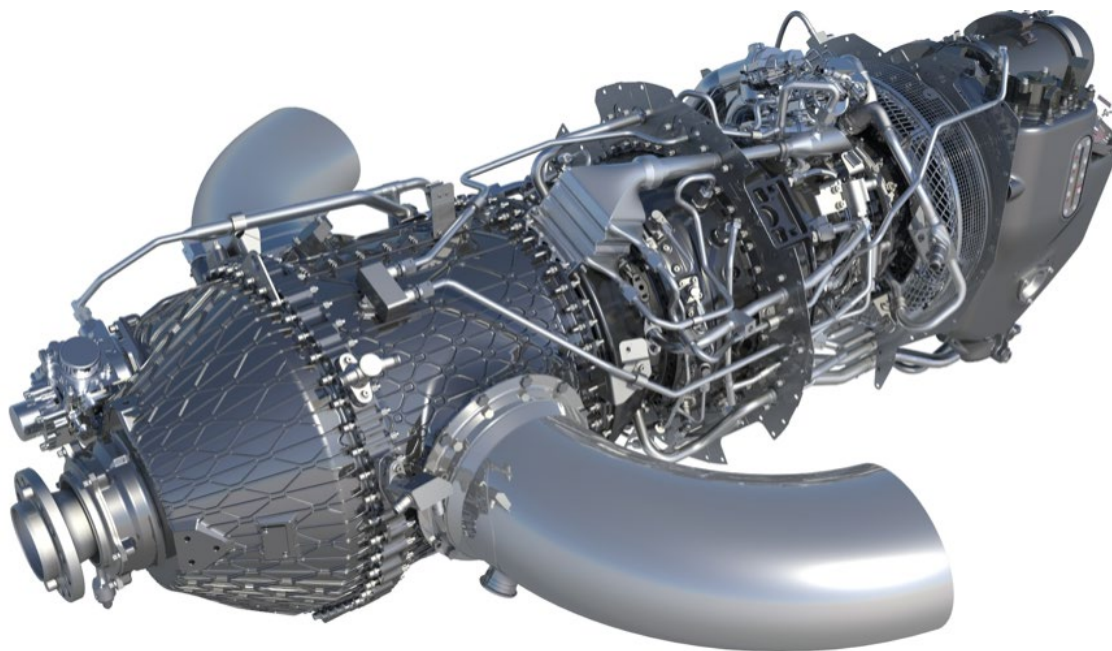


Figure 15. GE additively manufactured jet engine [courtesy of GE].

2.3 PANEL C. SENSORS AND CONTROL SYSTEMS FOR AUTONOMOUS OPERATIONS

Rapid advances in sensing, advanced analytic algorithms, and fast physics-based M&S at the chip and machine-levels are creating a disruptive change across the global economy. Collectively, integrated application of these advances for the purpose of monitoring, managing, and controlling processes and systems at an advanced level—allowing for the system to self-monitor, self-control, and improve its own performance or system state—has been described as *embedded intelligence* (EI).¹¹ The disruptive impact of incorporating EI into transportation, defense, consumer products, manufacturing, energy production, and myriad other areas comes from its ability to extend human performance, automate and integrate processes, uncover system behavior before it is readily apparent, and improve performance through automated learning. This ability can be thought of as *autonomy*, as it drives toward situational or state-space awareness, substantially lowering operational costs and opening frontiers to applications that were not otherwise available. Examples of such applications include

- Very high-performance aircraft that could not fly without such systems,
- Highly automated and remote controlled deep sea drilling platforms,
- Autonomous and hyperintelligent vehicles that are anticipated to completely change corporate business models and consumer behavior, and
- Advanced manufacturing processes that are opening new frontiers in cost-effective precision components.

Because of its implications for machine autonomy, EI is a generational disruptor, moving beyond the incremental advances in automation from decades past to begin a new era of human performance and benefits enhanced through machine autonomy. EI is not only changing how systems operate, but also how designers approach basic design architectures that exhibit autonomy.

As American innovators develop the next generation of nuclear energy systems, autonomy enabled through EI offers the opportunity for unparalleled application flexibility, operational simplicity, resilience, and controllability, allowing for expanded application potential and significantly lower operating costs. Substantial investments in EI are coming from a variety of fields, so next-generation nuclear systems designers can incorporate these advances into their system designs. Defining the extent to which these technologies and approaches can be implemented in advanced nuclear energy applications is essential for making a competitive business case for next-generation systems and will help define competitive niches for US technology in global nuclear energy markets.

The potential of autonomy in advanced nuclear applications, enabled by EI technologies and techniques, can be organized and assessed in three priority technology areas:

- Autonomous control with inherent digital security
- Prognostics and health management
- Sensors enabling autonomous operations

These priority areas are assessed below.

2.3.1 Priority Technology Direction C1: Autonomous Control with Inherent Digital Security

Today, the state of the art is moving from automated control towards autonomous control. These elements can be defined as follows:

Automated control involves self-action, consists of straightforward automatic execution of repetitive basic actions, uses fixed set of algorithms with typically limited global state determination, often implemented as rigidly defined individual control loops rather than as fully integrated process/plant control, and decision-making is left to the human or human-instructed “rules-based.”

Autonomous control involves independent action, integrates control, diagnostic, and decision capabilities, along with the ability to adapt to evolving conditions and operational constraints, and even support self-maintenance over the control system lifetime. Autonomous control encompasses automated control.¹²

Advances in the field of autonomous control and operation over the past decades are evident in robotics,^{13,14} unmanned vehicles like the twin Mars exploration rover developed by the National Aeronautics and Space Administration (NASA),^{15,16} and the driverless car.^{17,18} The autonomous software used in these systems support decision-making abilities and controls to execute commands based on sensory feedback.

A system’s degree of autonomy is determined according to its ability to manage faults, where fault management encompasses fault avoidance, fault detection, fault removal, fault tolerance, and fault forecasting.¹⁹ An autonomous control system requires a top-level planning routine which consists of a goal, a strategy, scenario classification, etc. A planning routine dictates the degree of autonomy and the spectrum of scenarios that the system is capable of handling. Such a planning routine is evident in the autonomous control system being developed for nuclear reactors.^{20,21,22} For cases in which the final decision is left to the human operator, a performance-based decision-making module (prognosis) is used to assess and rank the different decision options²³ according to their associated utility functions and the probability of each outcome.

The technologies identified above have been applied in other industries and offer the potential to facilitate the acceleration of nuclear reactor deployment.

Sensors provide continuous information regarding the state of the system and environment. This information is processed by the intelligent diagnostic modules to generate the necessary course of action. New advances in artificial intelligence (AI) and high performance computing support sophisticated analytic capabilities, allowing for a higher degree of autonomous control. To ensure unambiguous fault detection, it is important to determine the most efficient locations for sensors in the nuclear power plant. An advanced AI algorithm can provide efficient fault diagnosis and help in determining efficient layout for sensor placement. Darling et al.²⁴ have illustrated a technique to determine the key target variables for sensory output using information metrics such as Kullback–Leibler (KL) divergence with machine learning techniques (dynamic Bayesian network).

2.3.1.1 Application to accelerate deployment

The technologies identified above have been applied in other industries and offer the potential to facilitate the acceleration of nuclear reactor deployment. The benefits of adaptation are listed in Table 8 below.

Table 8. Benefits of adaptation of the state-of-the-art in autonomous control to accelerate the nuclear reactor deployment.

Benefit	Description
Simplifies operational complexity	Operational complexity, which is the degree of workload burden placed on a human performing a task, is greatly simplified when these principles are applied.
Automates repetitive operations (reduces human factor)	Autonomous control at the lowest level automates the execution of procedure steps normally performed by an operator. For normal operations, these procedures are highly scripted and performed repeatedly throughout the life of the plant. Automating a procedure relieves the operator from performing repetitive, menial functions, freeing the operator to perform higher level tasks that involve exercising greater judgment, a role for which the operator is better suited.
Expands market	Expanded markets await nuclear power plants that are not designed solely for the generation of base load electricity.
Ensures efficient load following	A premium price is placed on reserves available to the grid operator; these reserves help make up for the variability of other means of electricity, such as renewables. The ability to autonomously load-follow provides access to these markets, with a measure of control that is more efficient than when performed by an operator. Improved control ensures smaller temperature swings, which in turn reduces thermal cycling of plant components.
Ensures improved accident response	Autonomous operation includes machine-based detection of anomalies far in advance of what might be expected from a human operator.
Ensures faster response time	This permits accident mitigation to begin earlier and has the potential to limit the degree of departure from the normal operating point. Plant thermal stress is reduced, and the likelihood that the protection system will be actuated is reduced.
Eliminates human bias	The operator has limited cognitive abilities to correctly perceive fast-moving trends. The current state in the nuclear industry is for the operator to respond to symptoms rather than to diagnose the underlying cause. The capability to diagnose an issue based on conservation law can eliminate unintentional human bias.
Ensures comprehensive state space awareness	Autonomous operation can provide a more informed situational awareness of the plant state and hence a more informed, more accurate basis upon which the machine can proceed with recovery actions.

2.3.1.2 Implications of new approach

Adopting these new technologies in the nuclear industry will improve performance in several areas important to the overall cost of electricity or other products generated. Operational procedures will be performed with greater accuracy by machine, thereby improving operational efficiency. In principle, a machine has a greater capacity for work load and precision of task execution than a human. Autonomous operation has the potential to reduce cost by reducing equipment inspection rounds and eliminating routine calibration of sensors that are not in need of calibration. The number of operators in the control room may be reduced, or multiple reactor control rooms be colocated into a single facility for greater

efficiency. More importantly, the added capabilities from new technologies can improve a plant's risk profile (scenarios, probability, and consequences). These systems could provide measurable benefits and cost savings to the construction, operation, regulatory processes, and licensing for advanced reactor concepts.

2.3.1.3 Further advances needed

It is envisioned that a Nearly Autonomous Management and Control (NAMAC) system has great potential to accelerate deployment of advanced reactors.²⁵ The NAMAC system can provide recommendations to operators during all modes of plant operation except shutdown operations, covering plant evolutions ranging from normal operation to accident management. These recommendations are to be derived within a modern AI-guided system, making use of continuous extensive monitoring of plant status, knowledge of current component status, and plant parameter trends. The NAMAC system will continuously predict near-term evolution of the plant's state and will recommend a course of action to plant personnel.

NAMAC is ambitious, and it presents significant technical and computational challenges, including (1) disparate time scales, (2) large-scale simulation much faster than real time, and (3) data management. Machine learning and data-driven concepts will assimilate plant data and simulation tools to provide information in a timely manner throughout the event. NAMAC will provide prioritized lists of recommended actions and mitigating strategies that could be provided to the operator for action, or they may be acted on automatically by the plant.

Research is required in the development/adaptation/implementation/testing of *digital twins* and associated intelligent functions such as diagnosis, prognosis, and reasoning. A digital twin is the virtual model of a real-world system or process. A sufficiently high-fidelity model that operates in faster-than-real time, to describe a process, can theoretically be used to provide predictive information for control, prognosis, and safety. These functions take modeling and instrumentation uncertainty into account. Research is also required in the development of a formalized, quantitative, computerized safety case, as well as development of approximate reasoning for cases with incomplete information and uncertainty.

The NAMAC concept is conducive to several different deployment strategies. The first strategy is integration during the design and licensing stage. This approach for incorporating NAMAC during the design phase can influence plant instrumentation, initial capital costs, and the overall risk profile for maximum benefit, but it may present some regulatory risk. The second strategy is integration after plant construction. This phased approach allows backfitting NAMAC after design/construction. Consequently, NAMAC would still enhance the plant's safety posture and lengthen coping times, and it would still provide value through reclassification of structures, systems, and components (SSCs), reduced emergency planning zones (EPZs), and reduced operating costs. This flexibility minimizes the deployment risk for NAMAC. Multiple entry points provide opportunities to add significant value to the nuclear industry, as the window for entering the market is not restricted. This strategy can balance cost, risk, and benefit with the feasibility of gaining regulatory acceptance.²⁶

Deployment initiatives:

- Implement and test a digital twin and the associated intelligent functions such as diagnosis, prognosis, and reasoning based on a modern AI-guided system, making use of faster, high-fidelity modeling at component, system, and subsystem levels.
- Develop a testing platform or simulator to evolve cyber defense with digital immunity and resiliency, as well as a qualifying digital control system.

Table 9 provides an overview of this PTD.

Table 9. Autonomous control with inherent digital security.

PTD C1: Autonomous Control with Inherent Digital Security	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - Leverage best practice from other industries (i.e., aerospace and automotive, advanced gas turbine plants with fewer employees) - Combining computational power with ubiquitous sensing and sophisticated analytic capability is fundamentally reshaping whole industries - Embedded intelligence based/model based control systems that allow autonomous operations - Cyber informed design and self-healing is beginning to take shape in the design process 	<ul style="list-style-type: none"> - Simplifies operational complexity by automating repetitive aspects of day-to-day operations (reduces human factor) - Expand market (e.g., efficient load following)
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Enhances operation efficiency - Enhances license case - Reduces cost of operation 	<ul style="list-style-type: none"> - Evolve cyber defense to digital immunity and resiliency - Qualified digital control - Implement and test a digital twin with AI guided system - Faster, high-fidelity modelling at the component, system, and subsystem level

2.3.2 Priority Technology Direction C2: Prognostics and Health Management

Prognostics and health management (PHM) encompasses a suite of modules to support real-time situational awareness and robust decision making. A full PHM system typically includes system and equipment monitoring, anomaly detection and diagnostics, equipment prognostics, and mitigation strategies such as risk assessment, control, and operations and maintenance (O&M) planning. Application of these technologies is a key driver for autonomous operation and control of large industrial systems.

PHM technologies in the nuclear industry and other fields typically differentiate between active components such as pumps, valves, and sensors and passive components like reactor vessels, pipes, and reactor internals. PHM for active components is necessary to support the day-to-day application of autonomous and advanced controls. The current and evolving condition of these components should be closely integrated into real-time control decisions to manage in situ degradation of key components that could challenge the operation or safety of the overall system. PHM for passive components will inform longer term autonomous O&M planning. The evolving degradation of passive components (including materials) under planned operational conditions informs long-term risk assessment, maintenance planning, and outage scheduling.

2.3.2.1 State of the art and use today

PHM is a dynamic, evolving field. Recent reviews of PHM^{27,28,29} summarize the state of the art at this writing. While PHM has not yet seen wide adoption in the nuclear power industry, it is commonly and effectively applied in industries such as aerospace, transportation,³⁰ oil and natural gas, and other energy generation industries.

Online monitoring reduces or eliminates the need for in-person inspection and periodic maintenance, thus reducing radiation exposure to personnel.

Centralized monitoring stations are employed in the energy generating industry for gas turbines³¹ and hydropower.³² These facilities monitor entire fleets of similar systems, and this in turn supports greater integration of operating experience to rapidly respond to emergent issues in common components and systems. Other fleetwide monitoring efforts have leveraged experience across sites to develop pattern recognition-based approaches to fault detection and diagnostics,^{33,34} and to some extent prognostics.³⁵

2.3.2.2 Implications of new approach

Application of a fully developed PHM system supports risk-informed licensing and performance-based O&M. Greater situational awareness may allow plants to reclaim design and performance margins while maintaining and even improving safety goals.

PHM has long been touted for its positive impacts on safety, economics, reliability, and availability. The benefits in nuclear applications are no different. Application and integration of PHM improves the economics of operating nuclear facilities by reducing the need for expensive time-based maintenance, supporting a move to condition-based maintenance. This also improves plant availability by optimizing maintenance and inspection activities during plant outages to speed up the facility's return to operation. It also has the potential to help avoid unplanned outages. In situ monitoring for situational awareness of process and equipment conditions contribute to plant safety and to goals in keeping exposures to ionizing radiation as low as reasonably achievable (ALARA). Real-time equipment condition assessment can be integrated into online risk monitors to provide a more accurate representation of operational risk.^{36,37} Online monitoring reduces or eliminates the need for in-person inspection and periodic maintenance, thus reducing radiation exposure to personnel.

Besides operational concerns for a specific facility, PHM technologies support the move toward a holistic *digital thread*, which includes design, manufacturing, and operation. Online monitoring of the current and evolving condition of SSCs provides insight into previously opaque regions of operation and control. Data obtained during this monitoring will inform the design and manufacture of future generations of components and systems. PHM technologies have the ability to close the loop on cradle-to-grave monitoring of components by improving and tuning the next iteration based on operating experience.

2.3.2.3 Further advances needed

Significant research has been undertaken to develop PHM systems for nuclear applications. Limited pilot applications and implementations have resulted in success.^{38,39} Implementation of fully developed PHM systems, however, has been stymied by several persistent gaps in the technology.

Modeling and Simulation

PHM technologies rely on physics-based and data-driven modeling. For first-of-a-kind systems and components, no lifetime data are available to develop empirical PHM models. High-fidelity physics-based models will be necessary at the component, subsystem, and system levels to understand the evolution from initial fault or degradation onset to failure in key equipment, the impacts of that degradation on component and subsystem performance, and the integrated impacts on system operation. These high-fidelity physics-of-failure models can be used to support PHM in two ways: the models themselves can be directly used in an online PHM system, or they can be used as simulation tools to provide data to develop empirical PHM tools.

To apply physics-based models for online PHM, the model must be of sufficiently high fidelity, robust to real-world noise, and computationally appropriate for real-time simulation and prediction. Depending on the scope of the PHM system, these models will be required to simulate the effects and evolution of degradation at multiple scales under multiple potential future operating regimes; this simulation must be

deployable on available computational resources and must run faster than real time in order to be integrated into near-term autonomous control.

Alternatively, high-fidelity physics-based simulation of components and systems can be used to generate operational data under a variety of scenarios. These data can then be used to develop empirical models for monitoring, detection and diagnostics, and prognostics. More likely, a hybrid approach combining physics-based, data-driven analysis will be employed.⁴⁰

Physics-based and empirical PHM models must provide accurate and robust uncertainty quantification in order to be useful for short-term autonomous control decisions and long-term autonomous operation planning. Work remains to be done to define and develop appropriate approaches to uncertainty quantification for autonomous decision making.

PHM-Informed Sensor Suite Design

Most applications of PHM across industries rely on the retrofitting of necessary sensors and instrumentation to provide the necessary measurements. Thoughtful design of sensor suites is critical to enable accurate, robust PHM for active and passive components. PHM requirements can help drive specification of measurement needs, sensor placement, and sensor performance.

Both physics-based and empirical approaches to PHM require accurate, sensitive in situ measurements of key parameters and indicators. System-level M&S of the plant can provide input on the minimum set of process measurements (temperature, pressure, flowrate) that may indicate degraded performance of key components and allow for diagnosis and differentiation of fault modes. Additional permanently mounted instrumentation will replace periodic inspection such as permanently installed accelerometers on pumps and motors. These data sources provide complementary indicators to process measurements to support very early detection of faults and further diagnosis of fault modes.

Integrated sensors may be a viable option for many components. Electromagnetic pumps have been designed with embedded instrumentation.⁴¹ Advanced manufacturing of passive components and structures may allow for embedded sensors to support long-term health monitoring such as embedded strain gauges in reactor vessels.

In addition to designing the types and locations of sensors, the PHM sensor suite must be paired with a robust signal validation system to ensure that measured and stored data accurately represent the physical condition of the system and components.

Large data management and storage

The proposed sensor suite, which includes process and inspection instrumentation, will generate significant volumes of data. This may challenge bandwidth limitations for data transmission, analysis, and storage. A well-defined approach to data management to support PHM and autonomous operation must include:

- Transmission guidelines for moving data from the sensor to the computer over wired and wireless communication channels
- Specification of the specific data to be stored (e.g., raw data streams, post-processed data features)
- Archive guidance on the length of time and amount of data to store
- Communication between data storage systems and PHM and M&S systems

Recommended technology thrusts and deployment initiatives

The prevailing experience in backfitting PHM solutions to the current fleet of nuclear plants suggests that closely integrating PHM in the design of both the facility and the instrumentation and control (I&C) system is paramount for success. Design for reliability and design for maintainability have become

common considerations in industrial design; the new requirement is to *design for monitoring/observability*. As-designed risk models can be used to identify high-value, high-consequence SSCs. Failure modes and effects analysis (FMEA) evaluation of these target SSCs then drive the monitoring needs to ensure online situational awareness of the evolving health state and probability of failure. With this information in hand, instrumentation systems can be thoughtfully designed to provide the necessary information and indicators to support fully integrated PHM.

Given a robust monitoring instrumentation suite and well-developed prognostic models, prognostic results can be integrated into near-term control decisions and long-term O&M planning. With accurate, precise estimates of remaining useful life or probability of failure, integrating prognostic information into control and decision making can be straightforward. However, prognostic information is rarely both accurate and precise. A framework for decision-making and controls must be developed that accounts for uncertainty in the condition assessment and prognostic estimates and provides the confidence necessary for meeting operational objectives, such as safety, availability, and flexibility.

Deployment initiatives:

- Measurement requirements for system control, online process and equipment monitoring, and equipment and system prognostics must be enumerated, and technology gaps must be identified for measurements that are not currently available off the shelf for proposed reactor designs and missions.
- Online monitoring and prognostic routines must be developed to leverage both measured data and physics-based models to provide accurate, robust estimates of remaining useful life.
- A hierarchical, autonomous monitoring and control framework should be developed to incorporate remaining useful life estimates for key components, along with mission goals and maintenance logistics, to ensure safety, economic operation, and plant availability.

Table 10 provides an overview of this PTD.

Table 10. Prognostics and health management.

PTD C2: Prognostics and Health Management	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - Look to aerospace, defense, energy, and oil exploration industries - Digital thread which gives insight into previously opaque regions of control - Digitization of design, manufacturing, and operations is allowing for incredible advances in predictive techniques (e.g., centralized monitoring, data aggregation, fleetwide monitoring) 	<ul style="list-style-type: none"> - Necessary for risk informed and performance-based licensing by regulatory agencies, reclaims margin - Develop a hierarchical, autonomous monitoring and control framework
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Techniques could substantially reduce maintenance costs, shorten outage duration, increases plant availability - Increases safety and meets ALARA goals 	<ul style="list-style-type: none"> - Faster, high-fidelity modelling at the component, system, and subsystem level - Integrated, ubiquitous, cost-effective sensing (e.g., through advanced manufacturing) - Large data management techniques (what to do with data, how long do you maintain, how do you analyze?)

2.3.3 Priority Technology Direction C3: Sensors for Autonomous Operation

State of the art sensor networks are the confluence of two trends in engineering: miniaturization of high computational power and networking, both of which are enabled by the concept of the smart sensors with embedded processing. To provide the data necessary for complete state-space awareness of nuclear power plant operations, designers must deploy inexpensive, standalone sensing in as many safety-critical and noncritical components as possible. These sensing capabilities have several desirable qualities to enable broad deployment in a power plant, including reduced fabrication cost, low or self-powered components, a small design footprint, embedded, and ubiquitous deployment. Other industries have moved to incorporate sensors with these characteristics for improved operational performance. Several of these sensors could be adapted in a novel reactor design through proper modification. For example, Sazonov⁴² has worked to develop wireless monitoring systems for highway bridges using vibrational energy harvesting technology to aid engineers in inspecting the nearly 600,000 bridges in the United States. The “low cost of the sensors, ease of installation and maintenance, and ability to be applied to existing” structures make these an ideal candidate for applications in a nuclear reactor, depending on the application and frequency of the vibrational source, piezoelectric, electromagnetic, electrostatic mechanisms, or radiation energy can be used to harvest energy.⁴³ More broadly, researchers have developed a low-cost impedance sensor for monitoring the oil condition of lubricants in mechanical pumps, allowing plant management to analyze the real-time condition of mechanical components.⁴⁴ Connecting these various sensors to form a network helps to understand the state of a system in real-time. The scale of these networks can be quite large, such as those used in monitoring natural disasters,⁴⁵ or it can be quite small, such as those used in biomedical applications.⁴⁶

Many of these sensors can be adapted for use in advanced reactors with little or no modifications.

Harsh Environment Applications

The advanced reactor concepts for autonomous operation present new challenges that call for radically new sensor and instrumentation technologies for monitoring, control, protection, prognostics, and reactor health monitoring. Sensors for traditional I&C technologies (thermocouples, fission chambers, pressure sensors, etc.) have satisfied the design criteria of current light-water reactors (LWRs). The concept of a sensor-rich environment for ubiquitous sensing deployment has driven the advancement of other industries. While the nuclear reactor application puts its unique requirements for sensor resistance to extreme conditions, many access points share certain similarities with those in the space industry, the defense industry, and high energy physics communities where rad-hard sensors and front-end electronics are commercially available. Many of these sensors can be adapted for use in advanced reactors with little or no modifications.

Advanced manufacturing technologies are being considered more and more for embedding sensors inside of structural components. One additive manufacturing technology that is particularly attractive for embedding sensors is ultrasonic consolidation, or ultrasonic additive manufacturing (UAM). UAM is a low-temperature (<150°C) tape-layering process whereby thin metal foils are built up from a substrate.⁴⁷ A sonotrode or horn applies downward pressure on the foil while vibrating at ultrasonic frequencies. This causes breakdown of surface oxides and collapsing of local surface asperities, resulting in true metallurgical bonding. After building up enough layers, a slot can be machined in the component, and sensors are then placed inside the slot. Consolidating over the sensor in the machined slot results in a sensor that is embedded inside the part. An example of embedding fiber optic sensors is shown in Figure 16.

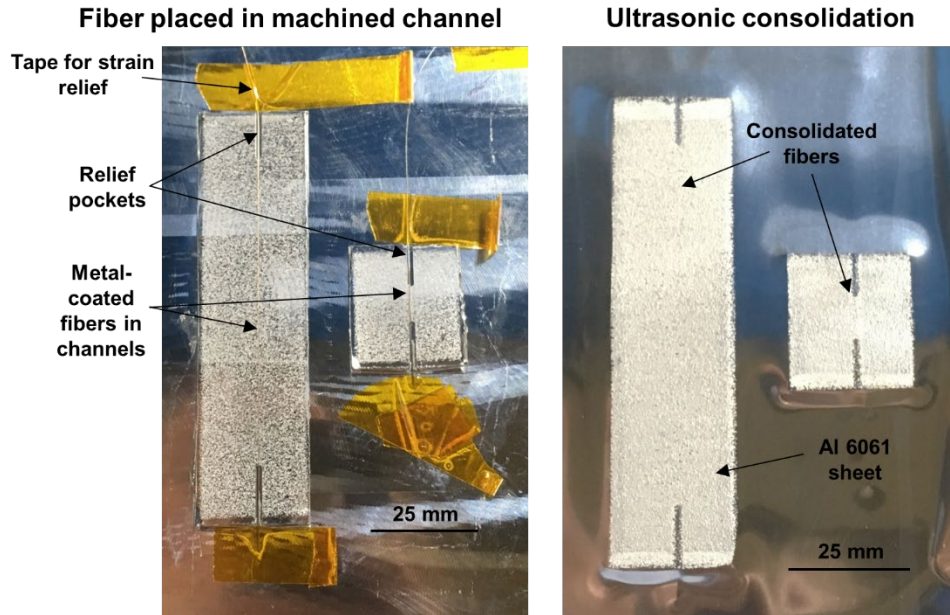


Figure 16. Embedding of fiber optics using ultrasonic additive manufacturing [courtesy of C. Petrie, ORNL].

Figure 17 shows results from work being performed at Oak Ridge National Laboratory including a finished UAM part with an embedded optical fiber that is flush with the surface of the part.^{48,49}

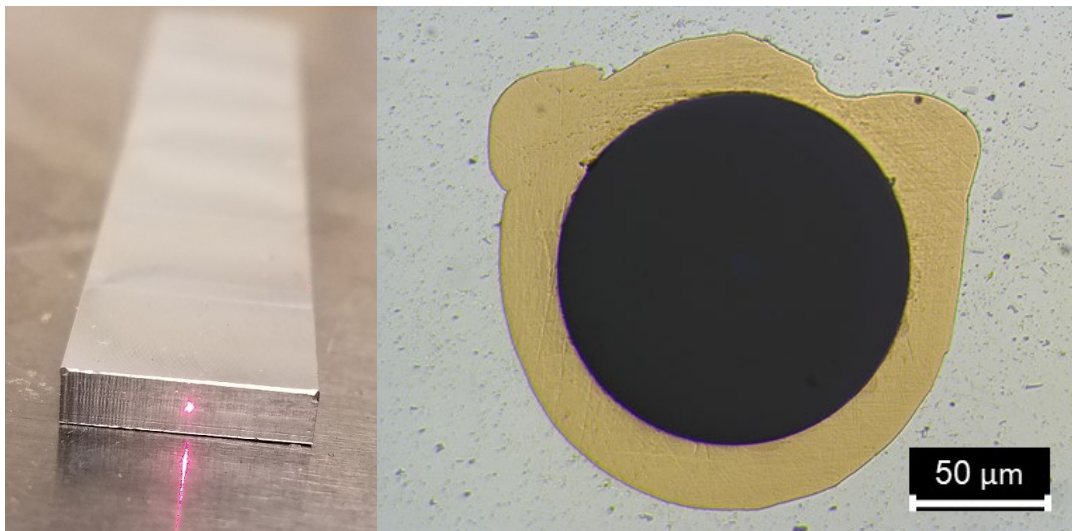


Figure 17. Finished part with embedded optical fiber (left) and optical micrograph showing a copper-coated optical fiber embedded in aluminum (right) [courtesy of C. Petrie, ORNL].

Also shown is an optical micrograph of an embedded optical fiber with a copper coating. The ability to embed fibers with metal coatings is important for harsh environment applications where traditional polymer coatings will not survive. Embedded fiber optic sensors can perform spatially distributed sensing of temperature and strain.^{50,51} This capability could be particularly useful for structural health monitoring of critical nuclear components.

Wireless Communications (Radio Frequency, Acoustic, Magnetic, Inductive, Through-Wall Communication)

Wireless transmission of data is pervasive in modern society and in industrial applications such as fossil fuel and chemical plants, where comprehensive infrastructures have been deployed to improve operational efficiency and reduce cost. The sensors employed for automating a plant do not necessarily need to be wireless, but to deploy the quantity and variety of sensors needed, routing cable could become cost prohibitive. Commonly used wireless transmission technologies include but are not limited to radio frequency (RF), acoustic, magnetic, and inductive options. Within these communication technologies, matured data protocols (e.g., Institute of Electrical and Electronics Engineers [IEEE] 802.11, 802.15.4 and International Society of Automation [ISA]-100) offer cyber-secure, low-power data transmission schemes.

2.3.3.1 Application to accelerate deployment

Ubiquitous sensing supported by low-cost and high-volume sensors can provide more information on the state of many more components than currently provided for nuclear power plants. By providing the real-time temperature distribution through the reactor core, the vibrational frequency of auxiliary pumps, and the thermal signature of support components, a digital twin model of the plant can be continuously informed. Additionally, deploying low-cost, high-volume sensors can improve plant defense-in-depth through redundancy in monitoring.

Wireless transmitters/sensors. A multitude of sensors such as thermocouples, resistance temperature detectors (RTDs), accelerometers, radiation monitors, etc., can be integrated with wireless transmitters using commercial-off-the-shelf components for applications in mild environments. For these types of environments, critical components throughout the plant can be instrumented to assist the designers and operators in verifying design parameters, monitoring normal operation, aiding in maintenance planning, and potentially predicting component degradation. Wireless transmitters and sensors may also be used for harsh environments, but they are not as widely available as for mild environments. Other sections of this report describe further developments needed for their use in harsh environments, but semiconductor-based radiation-tolerance for in-containment components has been investigated,⁵² while self-powered, in-core thermo-acoustic sensors⁵³ and vacuum micro-electronic-based wireless transmitters⁵⁴ have been demonstrated to be capable of operating in a high neutron flux and high temperature environment such as the interior of a reactor vessel. Advanced reactor design must incorporate wireless transmitters/sensors, along with a distributed antenna system⁵⁵ in the initial design. This would reduce the cost of retrofitting the hardware into the plant as is typically done. New plant designs have the potential to (1) significantly improve operating margins by reducing in-core power distribution uncertainty and (2) significantly reduce operating cost by eliminating some of the typical recurring maintenance practices.

Integration with M&S: model-based predictive control. M&S programs and experts are perpetually data-starved when endeavoring to recreate real-world systems. Distribution of more sensors throughout a plant can make data available so that models can be developed to predict component failure.

Real-time, in-situ performance of fuel/components: creep, fluence. Real-time, in-situ performance monitoring of fuel (e.g., creep) is not currently deployed for a commercial power plant operation, although in-pile creep test capabilities are available at some test reactors, including ongoing research for instrumented creep testing capability at the Advanced Test Reactor (ATR) at Idaho National Laboratory.⁵⁶

2.3.3.2 Implications of new approach

Sensors (e.g., fission chamber and solid-state approach for neutron flux) are an indispensable safety feature of the reactor control system. Not only do they measure reactivity change at short time intervals; they also should enable the system to sense the reactor's healthy conditions for prognostics and lifetime performance monitoring. Advanced manufacturing technologies have made it possible for embedded sensing: sensors or sensing mechanisms can be embedded into reactor structures, fuel configurations, pumps, etc., to provide stage awareness signals at various temporal scales for enhanced maintenance and health monitoring. A distributed sensor network (e.g., SiC sensors and electronic circuits in hostile environments⁵⁷) has been used to improve engine efficiencies and reduce emissions while maintaining safety in aerospace systems. Further development of sensor technologies for harsh environment applications such as nuclear reactors could ultimately improve performance, increase reliability, and allow for staff reduction.

Sensitivity and uncertainty quantification. Quantifying the range of sensitivity and measurement uncertainty for new, ubiquitously deployed sensors will be a key area of focus for licensing and regulatory agencies. Efforts to determine these values will be necessary before sensors can be incorporated into a new reactor design.

Long-term performance (e.g., signal drift). Additively manufactured sensor technology has enormous potential for in-situ monitoring of reactor components. However, a number of limitations are associated with the properties of sensors requiring further study. For example, traditional thermocouples (e.g., Type-K and Type-N) normally suffer from temperature drift, which is exacerbated under neutron irradiation. The impracticality of replacing an embedded sensor during the lifetime of the reactor's components will likely demand stable, long-term performance.

Further irradiation tests in test reactors and especially in commercial reactors. As discussed previously, to apply wireless sensor/transmitter or wired sensor technology to the advanced reactor environment, qualification tests under high radiation and high temperature will be needed. These types of tests should build on the wealth of material science knowledge available for electronics, drawing on data for technologies such as high-temperature fission chambers⁵⁸ and fiber optic sensors.⁵⁹ These technologies allow the simultaneous measurement of at least two parameters with a single cable strand. Test reactors will play a critical role in the rapid deployment of new technology given the complexity of installing a first-of-a-kind sensor in a commercial reactor. In addition to the relatively lower cost of a test reactor, facilities such as INL's ATR, ORNL's High Flux Isotope Reactor (HFIR) and the Massachusetts Institute of Technology (MIT) Reactor (MITR) offer the flexibility in regard to radiation levels and instrumentation that are paramount to verifying the proper operation of the new hardware. Other test reactors such as those operated in university environments also offer flexible, inexpensive and simple avenues to test technologies with low technology readiness levels (TRLs).

Figure 18 shows a high-temperature capsule containing molten chloride salt being irradiated at the OSU research reactor.



Figure 18. High-temperature molten chloride salt capsules being irradiated at OSU research reactor [courtesy ORNL and OSU Nuclear Reactor Lab].

Cybersecurity implications and recommended approach. From a digital security perspective, increasing the use of embedded intelligence (EI) in nuclear systems requires a significant digital transformation of technology infrastructure and resources. This digital transformation may increase attack surface exposure and the likelihood that digital events of any kind may impact operations. In particular, multiple challenges arise when implementing highly digitized monitoring and control (M&C) systems in high-consequence applications including the following:

- Disturbances in traditional M&C applications are assumed to act exclusively on physical assets and consequently can (generally) be well characterized. On the contrary, malicious attacks, which are intrinsically ill-characterized, may involve manipulating both physical and digital assets, making attack and risk determination more complex in terms of devising security and resiliency solutions.
- Digital information is typically consumed in a deterministic manner. When responding to a digital event—regardless of origin but after recognizing the possibility of malicious data manipulation—information may need to be consumed probabilistically and could require some analytic considerations prior to implementation of the response. For example, operational systems must account for whether process deviations are a result of natural or malicious actions. If the deviations continue and reach unacceptable boundaries or thresholds, then threat evaluation and proactive defense mechanisms should be triggered to deliver corresponding security and resiliency analyses and responses.
- Control information typically involves a fixed set of sensor and control resources. However, digital security, along with resiliency architectures and frameworks for modern M&C implementations, may involve time-varying sets of resources. This challenge should be explicitly addressed in the risk management plan and considered when security life cycle (design, implementation, maintenance, end-of-life) tasks are performed.

Operational and cyber security risk assessments support the premise that well-considered, carefully implemented EI capabilities may improve digital security risk management, and they also may enhance operational performance. Incorporating automation techniques into the existing reliability and continuous improvement processes will not only increase operational resilience but will also address potential security concerns. To effectively address digital security considerations resulting from hybrid (cyber plus physical) threats in high-consequence, highly digitized applications, modern M&C systems should be restructured to include the following intrinsic properties in their architectural designs:

- effective management of ill-characterized threats
- effective accommodation of partial, probabilistic, unexpected, unreliable, and/or imprecise information
- predictive and risk-informed dynamic selection of sensing and control resources
- adaptive information generation and collection based on assessed conditions
- graceful performance degradation as opposed to sudden collapse when facing severe insults

More research is needed in these areas to further strengthen and develop new guidelines, practices, and standards beyond the administrative threat-centric conceptualization of security concerns and their preventive risk identification, quantification, and mitigation. In particular, research focused on creating predictive, adaptable, digitally secure, resilient architectures with proactive defense mechanisms for nuclear environments is needed to support secure digital transformation.

With no plan to abandon the tremendous gains in flexibility, productivity, and efficiency that EI offers, most, if not all, industries (e.g., oil and gas, manufacturing, transportation, power) are moving forward with the ubiquitous use of EI in their processes and systems while managing digital security concerns with the implementation of diversified portfolios of security controls in tailored security architectures and with the recognition of the differing security and resiliency goals. An instructive example from high-cost,

high-consequence industries is provided in the creation of the world's first autonomously operated offshore oil robot.⁶⁰ The rapidly moving digitization strategies may entail deploying advanced administrative (e.g., role-based access controls, strong passwords, patch and update management, cybersecurity incident response plan and training), static mitigation (e.g., encryption, secure protocols, network segmentation, firewalls, secure network architectures), proactive mitigation (e.g., digital twins, proactive defense, hybrid intrusion detection and prevention systems), and cyber supply chain (e.g., firmware malware inspection) measures to secure digital assets for availability, integrity, and confidentiality. With continued significant contributions and lab–industry partnerships for assessing and resolving cyber-resilience issues, the national lab system is anticipated to be key in the development, demonstration, validation, and delivery of advanced techniques and technologies in digital security and resiliency for intelligent nuclear systems, including micronuclear reactors and the nuclear industry at large.

DOE and public and private stakeholders developed a Roadmap to Achieve Energy Delivery Systems Cybersecurity. The five high-level strategies discussed in the plan are as follows:

1. Build a culture of security
2. Assess and monitor risk
3. Develop and implement new protective measures to reduce risk
4. Manage incidents
5. Sustain security improvements

This roadmap was updated in September of 2011.⁶¹

Since 2010, the federal Cybersecurity for Energy Delivery Systems (CEDS) R&D Program has been assisting energy sector owners in research partnerships for cybersecurity tools and practices to support high-level strategies. Several DOE labs continue to be involved in these R&D partnerships.

The newly formed Office of Cybersecurity, Energy Security, and Emergency Response (CESER) recently shared a multiyear plan establishing an integrated strategy to reduce cyber risks in the US energy sector.⁶²

We recommend that advanced nuclear plants address cybersecurity in alignment with these strategies and plans. An early demonstration could be a prototype monitoring and advisory system developed and tested following the strategies within CEDS. National laboratories familiar with CEDS could participate in this prototype demonstration.

2.3.3.3 Recommended technology thrusts and deployment initiatives

Autonomous control of reactor operation will not be achieved without a thoughtfully designed, digitally secure, sensor-rich environment. To enable the accelerated deployment, low cost, self-powered, high temperature resistant, and rad-hard sensors and instrumentation demands accelerated development and testing. While sensors successfully utilized in the other industries that share some similarities with nuclear (e.g., aerospace) should be considered, the sensors that have successfully supported the LWR fleet could also be reengineered with technologies that did not exist in the first nuclear era. These technologies include advanced new materials, modern simulation and modeling-guided design strategy, and the latest additive manufacturing technologies etc. Integrated multi-mode sensors should be a top priority, including those with the embedded miniature design needed for distributed, networked, or embedded sensing. A new method for data transmission should be developed to reduce the cable cost and the undesired cable penetration through reactor vessels. Accelerated in-pile testing for sensor and sensor materials should be running in parallel with development efforts to ensure rapid deployment.

Deployment initiatives

- Reengineer sensors that have successfully deployed in LWRs with advanced new materials and advanced manufacturing technologies on functional materials, aiming for enhanced sensitivity and improved long-term performance
- Develop low-cost, miniature, multi-mode, and/or embeddable solid-state sensors for pressure, strain, temperature, radiation, etc., at a reduced power consumption or self-powered capability, with a considerably reduced cabling requirement (such as having a wireless option and using multi-mode)
- Expand accessibility to the in-pile testing capabilities available at national lab and university research reactors for sensor and sensor materials testing and for testing of digital security of sensors and associated data transmission.

Table 11 provides an overview of this PTD.

Table 11. Sensors for autonomous operation.

PTD C3: Sensors for Autonomous Operation	
<p>What is the state of the art of this specific priority technology direction?</p> <ul style="list-style-type: none"> - Other industries are using low cost, low or self-powered, small footprint, ubiquitous sensors - Expertise available for harsh environment applications - Wireless communications (e.g., RF, acoustic, magnetic, inductive, through-wall communication) - Smart sensors with embedded processing 	<p>How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?</p> <ul style="list-style-type: none"> - Potential for ubiquitous sensing (i.e., low cost, high volume sensors) - Wireless transmitters/sensors - Integration with M&S to support model based predictive control - Real-time, in-situ performance of fuel/components (creep, fluence)
<p>What are the implications of taking new approaches in this technology area?</p> <ul style="list-style-type: none"> - Real-time sensor-based data analytic techniques will allow improved operator situational awareness and create a gateway to M&S - Application of appropriate sensors for various temporal scales to support different operational needs (i.e. day-to-day control, prognostics, lifetime performance) 	<p>What further advances are needed?</p> <ul style="list-style-type: none"> - Advanced manufacturing to fabricate embedded sensors - Long term performance (e.g., signal drift) - Further irradiation tests in test reactors and especially in commercial reactors

2.4 PANEL D. HIGH FIDELITY MODELING AND SIMULATION AND DATA ANALYTICS FOR DESIGN, MANUFACTURING, LICENSING, AND OPERATIONS

In recent decades, rapid growth in computing capacity—including growth of technologies ranging from mobile phones to supercomputing centers—has been at the heart of several disruptive waves of technology advancement. Recent progress in highly parallelized computing technology, solution algorithms, and software architectures has led to realization of three long-term goals in advanced M&S:

- Robust, inline integration of multiple physics models and/or codes to directly evaluate multiphysics phenomena such as fluid-structure interaction and Doppler broadening of neutron cross sections,
- Hierarchical integration using data from high-resolution, small-domain models to inform lower resolution models of larger domains or complete engineering systems
- Direct data integration methods leveraging AI algorithms to predict system performance based on the combination of data from experiments and high-resolution numerical simulations

Application of advanced mechanistic M&S methodologies, especially those that approach so-called “first principle” representations of physical phenomena, enable engineers to better evaluate performance and optimize complex engineering designs for a wide variety of systems ranging from high-power electronics to diesel engines to aerospace vehicles to medical devices.

As a consequence of the far-reaching effects of advanced M&S capabilities, potential impacts have been evaluated by several notable panels in the past decade. The 2006 Report of the National Science Foundation Blue Ribbon Panel on Simulation-Based Engineering Science⁶³ reviews potential impacts of increased emphasis on advanced M&S research. The panel considered far-reaching impacts in a broad sampling of applications, including medical practice and engineering, homeland security, energy and environment, materials, and industry processes. The report identifies the need for investment in multiphysics simulation, real-time integration of simulation and measurement, verification and validation methods, and visualization. The report has been instrumental in establishing and shaping US DOE Leadership Computing programs and facilities.

In 2016, a National Science Foundation workshop reviewed the progress made since the 2006 Blue Ribbon Panel convened. Participants identified priorities for continued investment in research⁶⁴ and considered impacts in five example applications: urban infrastructure, healthcare delivery, automated vehicle manufacturing, deep space missions, and acquisition enterprise. The findings of this follow-up report focus on emerging challenges that are direct consequences of the progress achieved since the 2006 Blue Ribbon Panel. The workshop report concludes that there is a growing need for development of new conceptual models and tools to address the growing complexity of applications, the growing scale of computing platforms, and the mounting challenges associated with big data. The need for new approaches to address verification and validation of models and methods was also augmented with increasing emphasis on understanding and quantification of M&S uncertainty.

Other studies have focused more closely on specific fields. For example, a 2012 NASA study focused on the role of M&S, and more specifically on computational fluid dynamics (CFD), in aeronautics research.⁶⁵ The panel sought to define a pathway to achieve significant reductions in wind tunnel testing. The panel also agreed that wind

tunnels are typically used for final design configuration confirmation tests of cruise conditions, with minimal separation by the time of the 2012 report. The report focuses on the need for improved closure modeling strategies, including hierarchically coupled high- and low-resolution methods, for more complex flow fields, and it also focuses on the need for more efficient simulation methods to enable

Ultimately, the adaptation of advances in M&S hardware and software technologies to accelerate advanced reactor deployment must focus on industry needs to first optimize and then license their designs.

large-scale design optimization studies. The study projects that if identified challenges are addressed, then CFD simulations could largely replace wind tunnel testing for most applications within 20 years.

In reality, abrupt transitions from conventional engineering design methods to new approaches are not ubiquitous. As a result of more common evolutionary adoption of new methods, economic benefits of M&S can be difficult to quantify. The European Materials Modelling Council (EMMC) and the International Materials Modelling Board (IM2B) commissioned a study of the “The Economic Impact of Materials Modelling” in 2016. The study used a multi-part, survey-based approach to gather responses from 29 companies. Companies reported impacts including product innovation, cost savings, job creation, and direct revenue generation. Overall results suggest a greater-than-linear relationship between investment in M&S technology and return on investment in materials projects.⁶⁶

2.4.1 State of the Art in Nuclear Energy Modeling and Simulation

An overarching lesson from prior evaluations of M&S research priorities can be summarized as *begin with the end in mind*. Ultimately, adaptation of advances in M&S hardware and software technologies to accelerate advanced reactor deployment must focus on industry needs to first optimize and then license their designs. Figure 19 is a timeline of the evolution of nuclear engineering design approaches. Although the earliest nuclear reactors were designed by exceptionally talented engineers and scientists with slide rules, M&S tools were adopted fairly early on. This is because it is an inherently multiphysics optimization problem that must be used to resolve a challenging range of length and time scales. The safety consequences of these engineering analyses require that the models used be thoroughly verified and validated against experimental data. Reliability resulting from the availability of well-validated tools enables design optimizations that drive down costs in many ways. For example, since the 1980s, lattice method approaches to core design have enabled fuel cycles to be extended and power uprates to be authorized for today’s LWR fleet. However, as confidence grew in these tools, innovation in reactor design and in the tools became increasingly stagnant. Construction costs and schedules have ballooned, and in response to a variety of drivers.⁶⁷

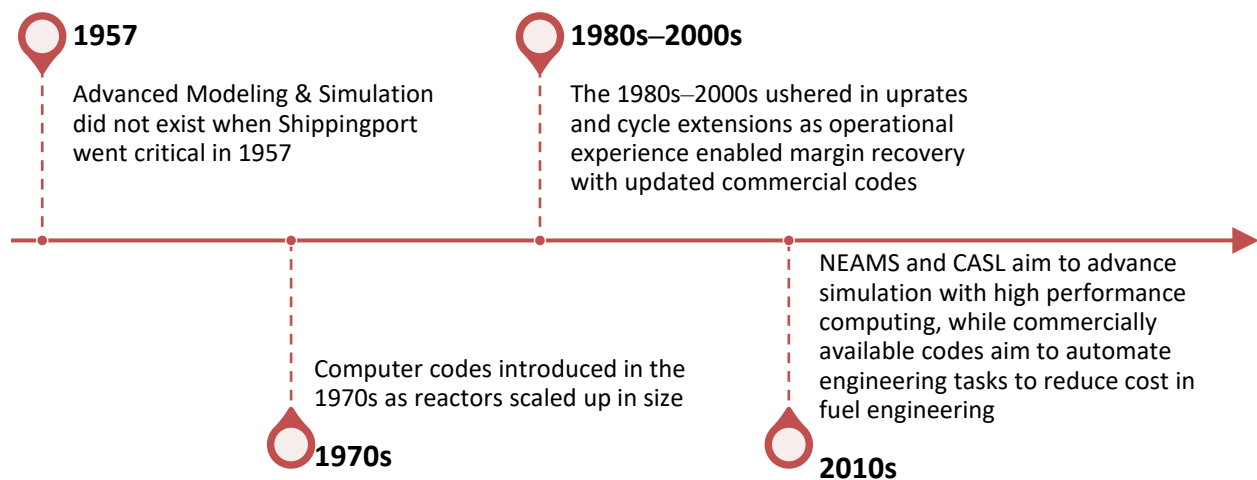


Figure 19. Timeline for nuclear reactor M&S development [courtesy of W. D. Pointer, ORNL]

For LWRs that use pressurized water as the coolant and ceramic uranium oxide fuel, thousands of reactor-years of operating experience has enabled us to identify and fill gaps in our knowledge and to increase understanding of the important physical phenomena in LWR safety. Well verified and validated codes are

supported by nuclear vendors and accepted by the regulator for a broad range of operating and accident conditions. Commercial software solutions are readily available for analysis of neutronics, thermal hydraulics, fuel performance, and source-term characterization. Commercially available finite element analysis (FEA) capabilities are commonly applied for mechanical design of components and development of manufacturing process requirements. These methods are inherently dependent on calibration to experimental data in many ways. As a result, significant databases of experimental, operational, and numerical analysis data have been amassed to provide the necessary confidence in the predictions obtained using these tools.

The DOE Office of Nuclear Energy’s Consortium for Advanced Simulation of Light Water Reactors (CASL) M&S hub was established with the mission to leverage recent advances in high performance computing hardware and middleware to enable the much-integrated multiphysics virtual reactor simulation environment of LWR nuclear reactor cores. CASL seeks to provide tools that enable industry to further optimize fuel designs and core loadings in order to reduce or eliminate the fuel performance issues that (1) limit fuel life and (2) reduce operational efficiency. CASL’s Virtual Environment for Reactor Applications (VERA) integrates neutronics, thermal hydraulics, fuel performance and coolant chemistry models within a common data framework. CASL’s challenge problems focus on fuel performance issues such as crud-induced power shift (CIPS), crud-induced localized corrosion (CILC), pellet-clad interaction (PCI), and grid-to-rod fretting (GTRF). Since the phenomena that drive these issues are highly localized to the conditions at a particular position on a particular fuel pin’s surface, the tools developed by CASL rely on pin-by-pin resolution simulations of the reactor core rather than the lattice methods and characteristics pin/channel strategies used in conventional methods. CASL models are validated against new and legacy separate-effects experiment databases, as well as operational plant data.

For advanced reactor technologies that use alternative coolants and fuels, commercial infrastructure is much less well developed. Although the earliest reactor designs and prototype reactors used gas, liquid metal, and other coolants, few research reactors in these categories continue to operate today. Significant M&S capability development efforts that use approaches similar to those applied to LWRs are associated with past research reactors and those that continue to operate. Some commercial analysis capabilities have been established for specific commercial reactor designs. Today it is reasonable to expect that vendors can directly apply the same commercial FEA capabilities applied to LWRs for structural component design, but it has not been demonstrated that sufficiently developed and validated commercial software infrastructure and quality assured experimental validation databases exist to support licensing and construction of an advanced reactor concept in today’s regulatory environment. An updated, simulation-based test and verify approach (Figure 20) can contribute to closing these gaps and enabling the deployment of advanced systems.

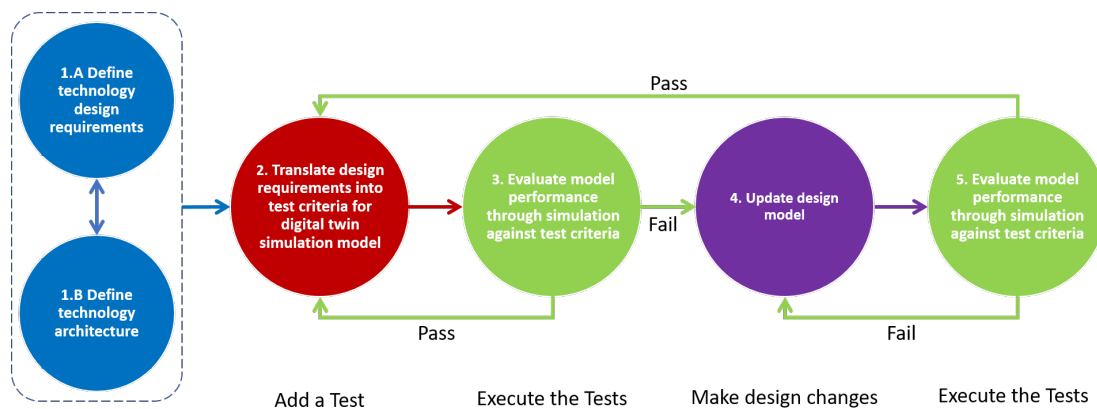


Figure 20. Notional model development and validation process [courtesy of W. A. Wharton, Studsvik, and W. D. Pointer, ORNL].

The DOE Office of Nuclear Energy’s Nuclear Energy Advanced Modeling and Simulation (NEAMS) program seeks to leverage recent advances in high performance computing hardware and middleware to provide a new class of high resolution methods to support development, optimization, and licensing of advanced nuclear reactor core designs. NEAMS supports a wide range of nuclear reactor types using a variety of coolants, fuel forms, and operating strategies. To support this broad range of applications, a multiscale, multiphysics suite of tools has been developed that provides capabilities for neutronics, thermal hydraulics, fuel performance, and source-term characterization analyses. NEAMS tools are validated against available separate effects experimental data and the operational data from operating research reactors, as well as data from past test and prototype reactors.

2.4.2 Modeling and Simulation for Advanced Reactor Deployment

However, advanced M&S must ultimately enable aggressive reactor design optimization to address the economic competitiveness of new designs. Workshop participants were asked to identify specific challenges in the development and deployment of new advanced reactor designs based on their own experience (Figure 21). The challenges were further discussed and distilled during the workshop, resulting in identification of three priority technical directions (PTDs) for further investment. These are discussed in the following sections.

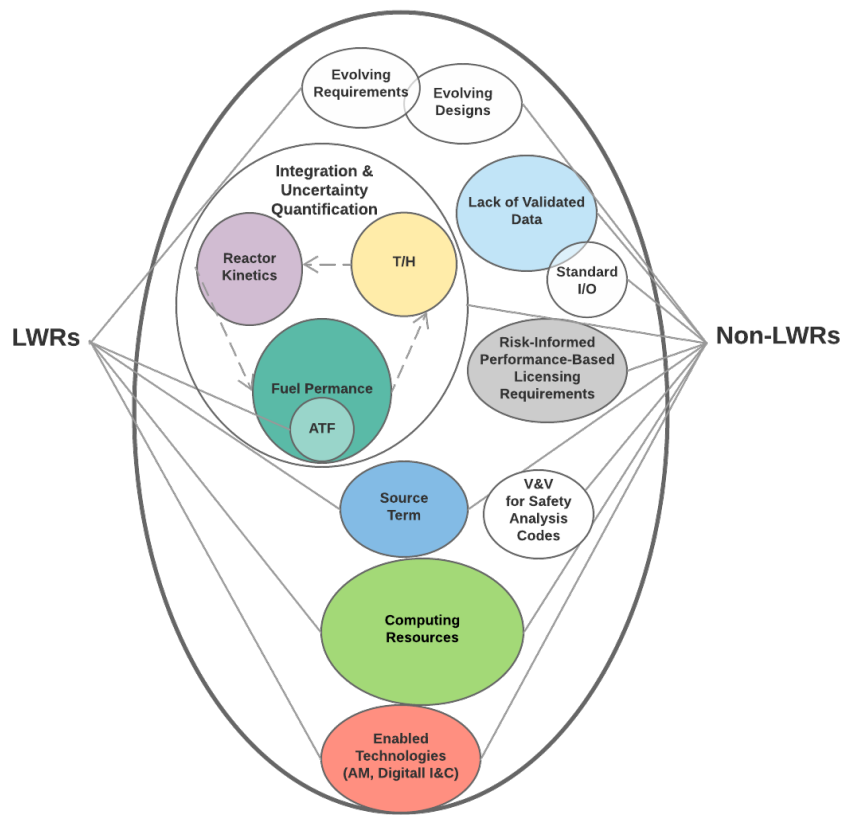


Figure 21. Summary of M&S challenges that must be addressed in deployment of new reactor designs [courtesy of A. Guler Yigitoglu, ORNL].

While no knowledgeable customer should expect a first-of-a-kind advanced reactor design to be as well optimized as the current fleet of LWRs, any reactor design must ultimately be economically competitive in a rapidly evolving electricity generation market. Lack of confidence in engineering models leads to

implementation of larger design and safety margins in first-of-a-kind plants, which consumes economic margin. Currently, licensing an efficient reactor requires significant operational data, as well as a substantial database from separate effects testing for that specific reactor design. This in turn requires that the design be licensed, built, and operated for an extended period of time. In the very near term, the promise of advanced M&S is a shortcut of this logical loop in which high fidelity models enable execution of a smaller number of much more targeted experiments, with more emphasis on separate effects testing with high resolution instrumentation to validate prediction of fundamental phenomena. In the intermediate term, verified, validated, and version-controlled advanced M&S capabilities that significantly reduce dependence on experimentally calibrated engineering models with very limited ranges of applicability may have the potential to streamline licensing processes.

2.4.2.1 Priority Technical Direction D1: Expanding Design Optimization Beyond the Core

Today, efficiently operating nuclear power stations are being shut down because high staffing costs, restrictive operational paradigms, and tumultuous electricity market spot prices combine to make transitioning to decommissioning activities more economically favorable than operating the facility. If we are to overcome the economic challenges faced by new advanced nuclear reactor designs in today's energy and monetary markets, we must quickly adopt a more comprehensive approach to design optimization. Design optimization must consider a variety of operational paradigms that fit within the context of the modern energy mix and the rapidly advancing grid management and energy efficiency strategies. We must enable plants to operate within the context of extended hybrid energy systems. The tool development efforts of the CASL innovation hub and the NEAMS program open the door to optimization of designs for operational environments that are quite different from the operational environments used in the current fleet.

Furthermore, a 2012 report commissioned by the National Renewable Energy Laboratory evaluated the cost of deployment for a wide variety of electric generation options (Figure 22).

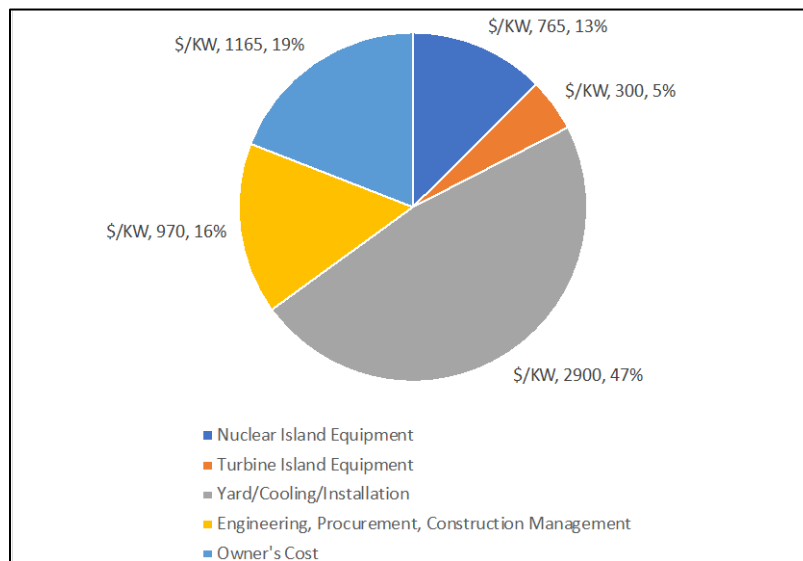


Figure 22. Projected cost of new nuclear power generation capacity [courtesy of W. D. Pointer, ORNL].⁶⁸

In this report, the contribution of the cost of nuclear island equipment is projected to be less than 14% of the total deployment cost.⁶⁹ This implies that a nuclear vendor could reduce the price of nuclear reactor components to zero but could only reduce the cost of deploying a new plant by 14%. The optimization of new reactor designs must extend beyond the reactor vessel and even beyond the containment boundary to fit within the optimization of the construction process itself to have a substantial impact on the cost of

deployment. Indeed, the entire lifecycle of the facility should be considered, from construction through startup testing, maintenance, and decommissioning. Product lifecycle management (PLM) strategies have been widely used to formalize industrial production processes for much of the last decade, and several robust commercial software systems are available to support this approach. In a PLM workflow, changes to reference design documents automatically propagate to designers of connecting components and analysts of overall system performance and safety. These concepts have also been further extended to the construction of large infrastructure projects in the form of building information management (BIM) tools which seek to optimize designs to minimize construction schedules and long-term maintenance costs.

The integration of these available approaches can be applied to optimize the overall deployment strategy of an advanced nuclear reactor design. This might look like the process shown in Figure 23.

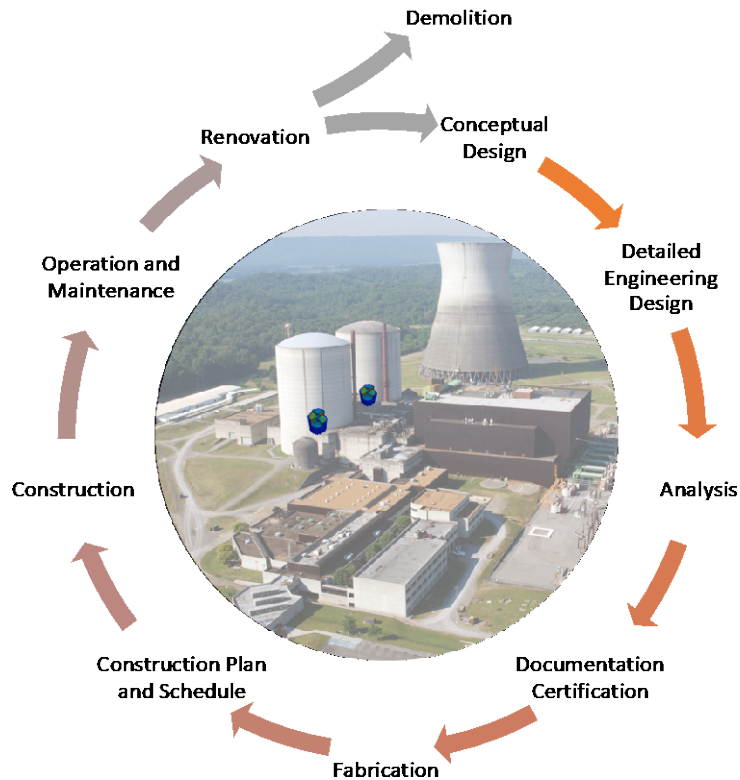


Figure 23. BIM lifecycle approach to facility design optimization [adapted from Wikimedia Commons image at [Wikimedia.org: Bellefonte Nuclear Power Plant](https://commons.wikimedia.org/wiki/File:Bellevue_Nuclear_Power_Plant.jpg), W. D. Pointer and B. Collins, ORNL].

Such an approach could have a much more significant impact on the economics of new design deployment than the standalone optimization of nuclear island component designs. This PTD is summarized in Table 12.

Table 12. Expanding optimization beyond the core.

High Fidelity Modeling and Simulation and Data Analytics	
<i>PTD D1: Expanding optimization beyond the core</i>	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - Reactor modelling and simulation tools: NEAMS, CASL, industry codes - BIM fabrication/construction models used by engineering, procurement, and construction (EPC) - Model input development and output data management e.g., NEAMS Workbench, ICE - Workflow and configuration control data management: Siemens PLM - Fundamental databases: GenIV Material Handbook, International Association for the Properties of Water and Steam (IAPWS), NE-KAMS 	<ul style="list-style-type: none"> - PLM processes have been actively deployed for other manufacturing and construction processes - BIM methods are applied to other large-scale construction projects to manage cost and schedule - Some aspects have been applied to nuclear technology, but comprehensive implementations have not yet been demonstrated
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Better target designs to impact the real economics of deployment and operation 	<ul style="list-style-type: none"> - Hold a focused workshop on BIM with EPCs to clarify demonstration - Identify gaps in tools to tie workflows together and develop plans to close them - Demonstrate automated workflows that pass reactor design change to next evaluation step(s) leveraging available tools - Develop a reduced order modeling strategy to examine state space without fully resolving details - Demonstrate propagation of VVUQ data through the process

Application to Accelerate Deployment

All advanced nuclear reactor vendors participating in the workshop reported that they are already adopting product lifecycle management and digital twin strategies to establish design version control and to ensure consistency across all aspects of the engineering system design. A notional deployment optimization workflow is shown in Figure 24.

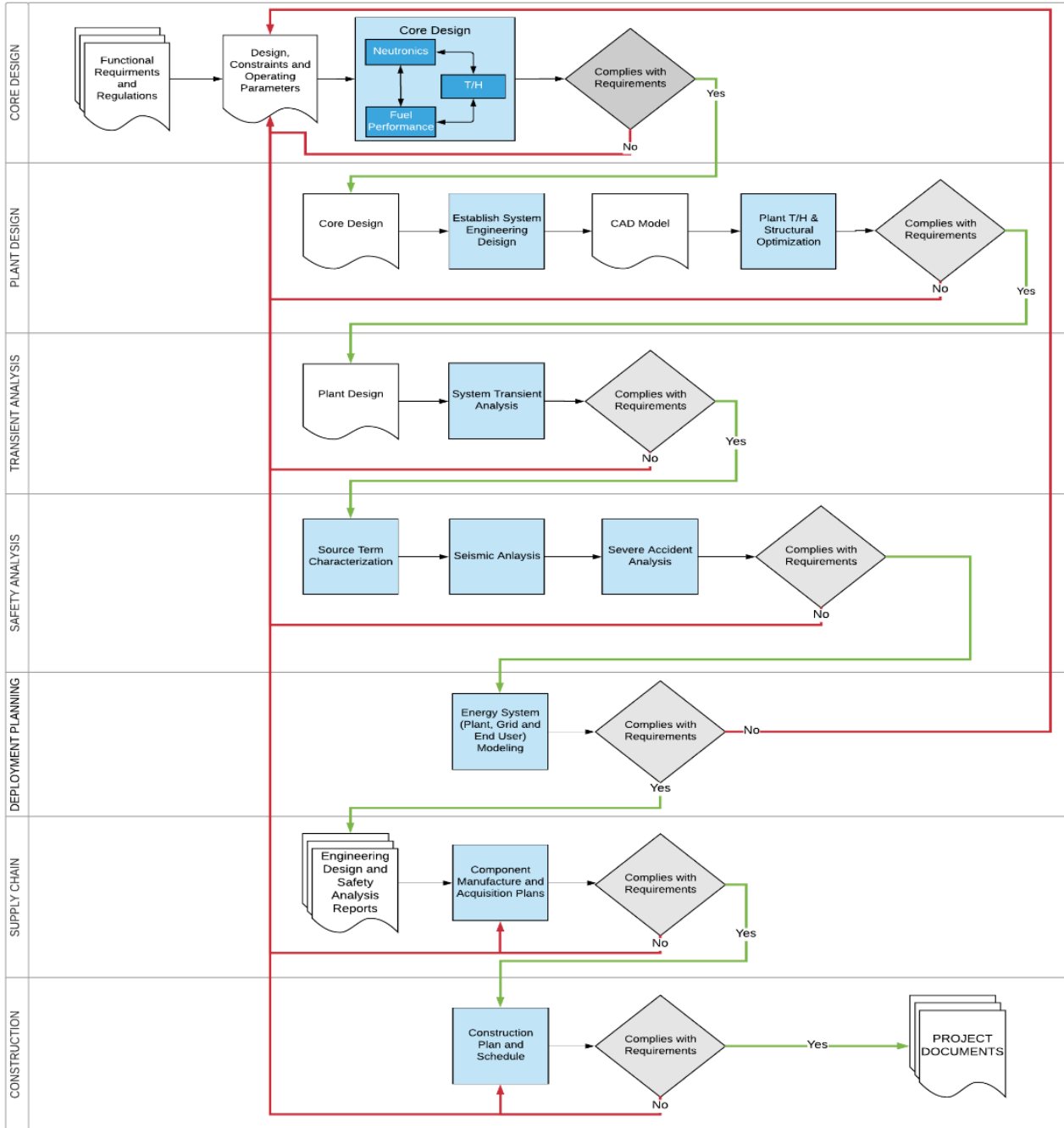


Figure 24. Notional comprehensive deployment optimization workflow [courtesy of D. Pointer, ORNL].

Recommended Deployment Initiatives

- Hold a focused workshop on BIM with EPC firms to clarify demonstration objectives and requirements
- Identify gaps in tools to tie nuclear reactor deployment optimization workflows together and develop plans to close them that leverage existing PLM and BIM tools
- Demonstrate automated workflows that pass reactor design change to next evaluation step(s) leveraging available tools

- Develop a reduced order modeling strategy to examine state space without fully resolving details
- Demonstrate propagation of VVUQ data through the process

2.4.2.2 Priority Technical Direction D2: Enable *Robust, Automated Optimization of Reactor Designs*

Opportunity

Consideration of a wider range of operating strategies and the expansion from design optimization to deployment optimization suggested in PTD D1 push development costs in the wrong direction: upward. In order to begin to optimize new designs for deployment, performance, and safety, we must advance the state of the art in design optimization to reduce the manual workload required to complete the reactor design optimization cycle. Furthermore, the optimization strategies must be adapted to incorporate and carry forward solution verification and uncertainty quantification as an integral component of the design optimization. This will support accelerated licensing and will facilitate demonstration of compliance with applicable quality standards. Commercial and national laboratory solutions for design optimization, uncertainty quantification, and product life cycle management exist, but they have not yet been integrated for application to the design of a nuclear energy system. This PTD is summarized in Table 13.

Table 13. Enable robust, automated optimization of reactor designs.

High Fidelity Modeling and Simulation and Data Analytics	
<i>PTD D2: Enable Robust, Automated Optimization of Reactor Designs</i>	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - A manual, iterative process for performing system-level design (neutronics, fuel, thermal-hydraulics) - Component-level optimization coupled with finite element analysis - Product lifecycle management systems to integrate all workflows (databases, design, analysis, procurement, etc.) but lack application to nuclear 	<ul style="list-style-type: none"> - Integrated workflows allow for more rapid design iterations that focus simultaneously on all aspects of the system (safety, economic, etc.) - Allows for ready transition to licensing as designs evolve through incorporation of uncertainty quantification (UQ) workflows (compliance gaps addressed during the design phase) - Component-level design is integrated with manufacturability
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Economic: M&S aspects of design informed by product lifecycle, resulting in reduced development time and final cost - Safety: safety incorporated directly throughout the design lifecycle, including robust instrumentation - Regulatory: UQ incorporated as part of robust design, allowing accelerated licensing and NQA-1 compliance 	<ul style="list-style-type: none"> - Integration of multiphysics-based capabilities with engineering design processes - Common data interfaces between M&S codes and engineering product lifecycle tools

Application to Accelerate Deployment

To accelerate deployment, there is a clear need to enable more rapid, automated completion of reactor design cycles. These cycles must be completed within the context of integrated workflows that focus simultaneously on all aspects of the system including, safety and performance. Furthermore, the automated design cycle should allow for ready transition to licensing as designs evolve. This can be accomplished through incorporation of solution verification and UQ workflows so that compliance gaps can be addressed during the design optimization phase.

A wide range of multi-objective, multi-modal design optimization algorithms has been developed in recent years for application to a wide range of scientific and engineering problems. Heuristic methods such as genetic algorithms offer opportunities to discover new options that extend beyond the experience base. A wide variety of optimization software tools is available commercially from the academic open source community and in the development programs of US national laboratories. These tools are commonly applied in the development of aerospace/aeronautical systems, high power electronics, and high-efficiency engines; they have not yet been widely applied to design challenges related to new nuclear power deployment.

Several obstacles to the broad deployment of robust automated design optimization approaches to nuclear power can be identified. First, the complexity of nuclear power plant design analysis requires that many discrete assessments be conducted by expert analysts who contribute individually to the evaluation of a design. As a result of the adoption of product lifecycle approaches, many of these steps have already been automated to some degree by nuclear reactor developers.

The NEAMS and CASL programs have taken the further step by developing more rigorously integrated multiphysics analysis toolsets that can provide pin-by-pin resolution simulations of multiphysics phenomena to advanced and conventional LWR cores. Although much work remains to reach the fully integrated capability envisioned in Panel D's PTD D1 above, fundamental toolsets are available in the academic, industrial, and laboratory communities to support fundamental development of optimization capabilities based on integrated analyses.

As a result of the adoption of product lifecycle approaches, many of these steps have already been automated to some degree by nuclear reactor developers.

The second challenge lies in the extreme diversity in fundamental solution methods, data formats, and geometry description requirements currently used by industry, the national laboratories, and academia. It is often quite difficult to share common material property libraries from one code to another. Significant challenges lie in the definition of common processes and common tools for the evaluation of simulation results, the assessment of uncertainty sources and propagation, and the use of this information to drive design optimization. The recommended deployment initiatives include some initial steps toward simplification of data and tool sharing.

The third challenge lies in the high consequence significance of nuclear reactor design performance and safety evaluations. Design optimization approaches must preserve information defining the uncertainty in simulations that serve as the basis for design evaluation. Currently, uncertainties are established through a manual process defined by various national and international regulatory authorities. The necessary transitions in the approach to uncertainty quantification are discussed further in PTD 3.

Recommended Deployment Initiatives

- Increase prioritization of integration of multiphysics, multiscale analysis capabilities with engineering design optimization processes in US nuclear energy M&S programs
- Develop standards for nuclear simulation code input and output formats to facilitate simpler component sharing without requiring community consensus definitions of common input and output formats
- Demonstrate common data interfaces between M&S codes and engineering product lifecycle tools for nuclear applications
- Establish an archival online reference data (e.g., material property) repository for advanced reactor design that can be accessed directly by simulation tools with appropriate access controls

2.4.2.3 Priority Technical Direction D3: Intersect VVUQ and Margin Characterization for Maximum Return on Design Optimization

Opportunity

As previously stated, no knowledgeable customer would expect a first-of-a-kind deployment of a new design to exhibit the same level of performance optimization as an LWR plant currently operating in the commercial fleet. However, extended operating margins that account for hypothetical uncertainties in predictive tools, validation data, and component reliability (see Figure 25) are immediately translated into real-world revenue losses. Uncertainty quantification methods are rapidly evolving to include more efficient algorithms as advances in computing to enable consideration of larger and larger samples of the uncertainty space.

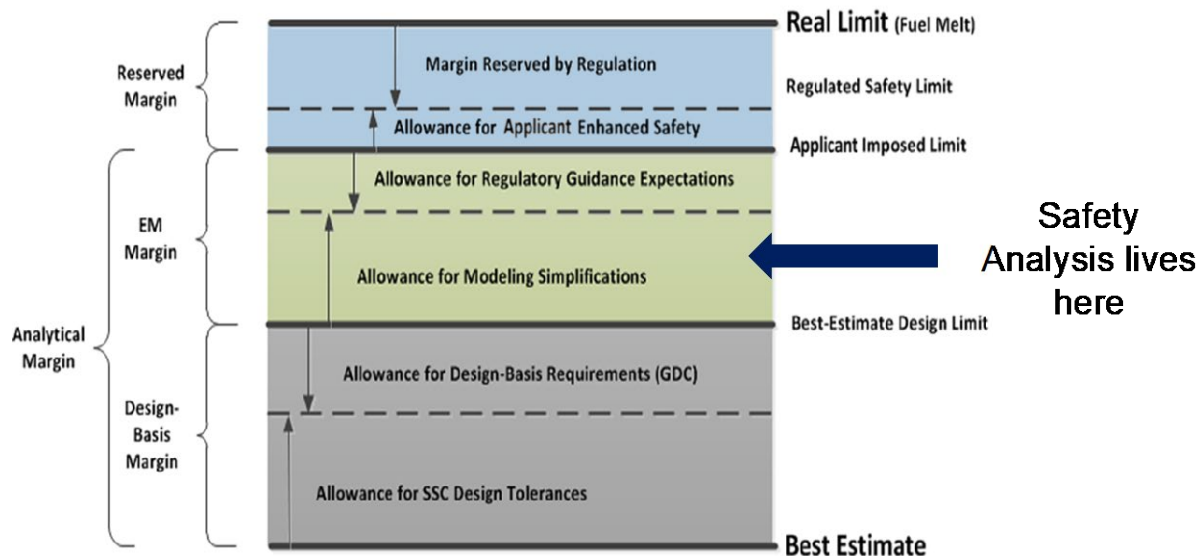


Figure 25. Margin contributors in the evaluation of new designs [courtesy of R. Martin, BWXT].

Formalized uncertainty quantification methods were originally developed for aeronautics applications, and developments in this field continue to lead the way for engineering uncertainty quantification. The Wilks formula⁷⁰ is widely used to quantify the number of samples required to establish safety margins. Scaling/similarity approaches, including Zuber’s hierarchical two-tier scaling (H2TS)⁷¹ and Reyes’s Dynamic System Scaling (DSS),⁷² have long been used to assess the applicability of experimental results to plant designs in the thermal hydraulics field, and the concept of representativity has long been used in reactor physics and criticality safety.⁷³ Monte Carlo approaches are used to assess sensitivity in single

physics thermal hydraulics and structure mechanics models, and perturbation theory is widely used to assess uncertainty in neutronics models. Approaches that make use of uncertainty information from experiments, operational data, or higher resolution simulations are much less common, as are model calibration methods such as Bayesian calibration methods that make use of available uncertainty information. Computing capacity limitations have traditionally restricted the applicability of such methods to large complex systems, but advances in high-performance computing are now enabling studies of similar complexity. This priority technical direction is summarized in Table 14.

Table 14. Intersect VVUQ and margin characterization for maximum return on design optimization.

High Fidelity Modeling and Simulation and Data Analytics	
<i>PTD D3: Intersect VVUQ and Margin Characterization for Maximum Return on Design Optimization</i>	
What is the state of the art of this specific priority technology direction?	How can it be deployed to accelerate design, manufacture, licensing, and operation of nuclear reactors?
<ul style="list-style-type: none"> - This technology is used today in design and licensing - Growing acceptance of the science and engineering basis for the technology: scaling/similarity, representativity 	<ul style="list-style-type: none"> - The state of the art can be adapted to the reactor environment through VVUQ methods which have been demonstrated in nuclear reactor applications, including safety-related loss-of-coolant accident analysis, and new methods are available to do more - This research, development, and/or demonstration can be done now because all the pieces exist; they simply need to be put together in an application
What are the implications of taking new approaches in this technology area?	What further advances are needed?
<ul style="list-style-type: none"> - Economic: less expensive to analytically probe design space vs. experiment. VVUQ provides insights that accelerate process - Safety and regulatory: methods originated in the nuclear safety and regulatory communities 	<ul style="list-style-type: none"> - Recommended technology thrusts: focus on design engineering vs. design verification - Recommended deployment initiatives: methods standardization and automation

Application to Accelerate Deployment

Ultimately, the technological advancements enabled by the two proposed PTDs outlined above will only be successful if the outcomes can be accepted by the regulator. Acceptance requires the developer to be able to establish the robustness and accuracy of the methods employed and to define the impact of modeling uncertainties on the margin between expected reactor conditions and threshold values of parameters that define the limit of safety. Adapting the state of the art in uncertainty quantification to safety margin characterization may provide a path to greater confidence in predicted performance. However, these uncertainty quantification methods must be accepted by the regulator.

To enable the broad application of contemporary uncertainty quantification methods, software platforms that allow new methodologies to be evaluated against knowledge captured in existing tools must be built, deployed, and tested. Standards for the documentation of such methodologies and the results that they produce must be established. Finally, developers must work with regulatory bodies to achieve acceptance of these new approaches.

Recommended Deployment Initiatives

- Formulate a more rigorous theoretical foundation of propagation of uncertainties to the design application
- Build an application-specific workflow capable of comparing high TRL, old approaches with the new proposed approaches
 - To prove better margin estimation with lower computational burden
 - To quantitatively identifying relevant experiments
 - To suggest aimed experiments
- Establish a working group, including all stakeholders, to document the methodology framework
- Accelerate the deployment of a risk-informed regulatory practice

2.5 PANEL E. CROSSCUTTING TECHNOLOGY INTEGRATION

The opening industry-led discussions framed the workshop. These discussions pointed to a need for reactors that are highly responsive, more predictable, more affordable, and more flexible to ensure that they are competitive with other forms of energy generation. Advanced technologies such as manufacturing techniques, novel materials, and control systems are being implemented in other industries, and these technologies have the potential to significantly improve nuclear plant performance, safety, and operational efficiency by lowering costs, implementing passive safety, mitigating accident consequences, expanding sizing and siting options, and increasing resource utilization. Implementation of many of these advanced technologies requires coordination across several scientific and engineering disciplines. As part of the workshop, a separate panel was organized to look for cross-cutting technologies that benefit multiple topic areas and that also require collaboration across the following areas: advanced manufacturing technologies, sensors and control systems for autonomous operations, materials and fuels, and high-fidelity M&S and data analytics. Panel E functioned by providing each of Panels A–D with an observer from Panel E that identified crosscutting topics. The Panel E Chair then reviewed the observations of the panel with the workshop participants during the readout elements of the workshop and received feedback and clarification that was included in this section.

2.5.1 Advanced Manufacturing Technologies to Enable New Designs

Deploying advanced manufacturing for nuclear applications is inherently cross-cutting, and it involves all other focus areas: materials, sensing, and simulation.

One cross-cutting technology that was identified early in the workshop is the need for in-situ process monitoring during fabrication of advanced manufactured components to enable a *born-qualified* manufacturing approach. This type of process monitoring requires instrumenting the manufacturing equipment with sensors to measure variables such as layer-by-layer thermal history during additive processes and process variables such as material feed rates and heat input. ***Control teams from advanced manufacturing and instrumentation and control (I&C) should work closely with one another to identify the appropriate sensors and feedback control systems.*** Furthermore, the materials team must be involved to determine how in-situ process monitoring can be correlated with material performance. For example, when M&S is used to predict and correct for warping due to thermal gradients during the fabrication process, data analytics would be implemented in an effort to diagnose common metrics that contribute to any potential issues with components. Therefore, developing and deploying born-qualified components is a multidisciplinary effort across all of the specialized areas.

The ability to embed instrumentation into parts would provide unprecedented knowledge of the time-history and environment of a component. This information could be used to validate a digital twin of a component, to ease regulatory acceptance (e.g., availability of in-situ knowledge of condition instead of data drawn from testing from post-use examination), and to inform and reduce maintenance needs and

costs. Sensors could be embedded in critical locations within the reactor system (determined in the design process) to enhance operator awareness of the health and status of components and systems in the locations most vulnerable to failure. M&S will provide valuable input for determining which components and locations are most critical. Embedding sensors could also be considered as a supplement to longer-term qualification testing. This is typically performed in test reactors prior to implementing the components in commercial reactors. For example, if embedded strain sensors could be used to monitor structural components during service, then the component could be replaced at the earliest indication of degradation. This active monitoring could replace the need for long-term testing for material aging, irradiation creep, or other phenomena that traditionally must be addressed prior to qualification. The challenges to realizing the application of embedded sensors in reactor components and systems include (1) determining suitable manufacturing techniques to embed sensors, (2) ensuring that the embedding process does not significantly alter the sensor performance, and (3) designing ways to route power to a sensor and signals from it.

Advanced manufacturing provides a means to redefine the approach to nuclear reactor design. Advanced material modeling can also help alleviate fabrication challenges by minimizing the impact of welding or heat on superalloy properties and grain sizes. Advanced manufacturing enables the use of tailor-made materials which open up new design possibilities. For example, material composition and properties could be varied across a component. These geometries and complex material variations can be determined from high-fidelity M&S capabilities.

Demonstrating advanced manufacturing in existing plants through the use of replacement parts (i.e., an early demonstration of putting a part into service), designing and fabricating a new part (i.e., a clean sheet approach), and developing a methodology to bridge the gap between a new part's design and materials was also discussed. With additional insight from recent new nuclear builds, two areas that may warrant further investigation include reinforced concrete and modular construction. Beyond singular components, advanced manufacturing of system(s)-level components or modules may help reduce costs and accelerate new builds. Areas to investigate may include the fabrication of the module and/or the design and logistics, as in building information modeling (BIM). Reinforced concrete is a large upfront cost and is a time-consuming effort for new nuclear builds. Advanced techniques in the fabrication of the steel reinforcement for concrete structures or improvements in the production, transport, and placement of concrete have the potential to reduce cost and accelerate new builds. While these demonstrations rely heavily on advanced manufacturing, materials and M&S focus areas both contribute to the deployment of these technologies for actual nuclear systems.

2.5.2 Sensors and Control Systems for Autonomous Operations

Cross-cutting elements include using sensors for born-qualified components and embedding sensors using advanced manufacturing techniques. Another cross-cutting technology in this area is model-based autonomous control. Autonomously controlled reactors could potentially allow for reductions in staffing costs and improved safety related to human factors. They may also allow for improved load following. Embedded sensors have the potential to indicate stress in a component; stress data from embedded sensors can be used to optimize load-following ramp rates while avoiding potential damage. These time-evolved profiles can be integrated over the component's lifetime to track how regular and routine power or temperature changes affect the component's lifetime.

Some of the major challenges to implementing autonomous reactor control are (1) integration of model-based control systems that operate in real time, as these systems cannot rely on computationally expensive simulations, (2) integration of machine learning technologies to be able to interpret sensing inputs and system responses, and (3) cybersecurity concerns. Research to address these issues will require close collaboration between the instrumentation and control team and the M&S team.

2.5.3 Accelerated Development and Qualification of Materials and Fuels

Cross-cutting technologies for accelerating the development of new materials already discussed include embedding sensors to provide real-time in-situ surveillance of materials for (1) implementing a born-qualified advanced manufacturing approach, (2) informing lifetime performance predictions, and (3) reducing the time burden for material qualification.

As in the deployment of advanced manufacturing to redefine the reactor design paradigms, exploring and adopting high-performance materials could enable the development of new reactor designs with improvements in operating margins, performance, and economics. This would leverage high performance computing and machine learning in combination with advanced characterization and testing as an integral part of the material discovery and design cycle. Some elements of advanced manufacturing may also help accelerate iterations on existing materials, with improved performance for current and future deployment. Practice and experience are needed to develop and understand the range of possibility for accelerated development of advanced materials.

2.5.4 Impact and Takeaways

The most impactful gains from these individual emerging technologies can be expected from coordinated, multidisciplinary efforts across multiple focus areas. For the nuclear industry, the anticipated impacts include (1) reducing cost by shifting construction to manufacturing, (2) reducing touch labor for production and inspection and eliminating or merging components, (3) reducing operating costs using integrating monitoring and autonomous control and reporting systems, (4) and developing new designs that eliminate the potential for significant consequence beyond the site boundary, reducing licensing uncertainty and costs and also increasing the number of potential operating sites while reducing the size and scale of the necessary emergency planning zone.

Reducing material development time with high performance computing, improved and targeted instrumentation, and advanced manufacturing (Table 15) can potentially allow quicker deployment of advanced materials into reactor systems. The lengthy testing and qualification time must be reduced to support the necessary iterative design and development cycles.

Table 15. Cross-cutting elements for material development.

	Materials	Manufacturing	Sensing	Simulation
Materials				
Manufacturing				
Sensing			Shorter time to new materials	
Simulation				Shorter time to new materials

Along with new materials, the combination of data analytics, instrumentation methodology, and rigorous quality control practices can be used to ensure a given advanced manufacturing component is born qualified (Table 16). This capability would provide a revolutionary approach to making optimized nuclear system components with new materials.

Table 16. Cross-cutting elements for born-qualified components.

	Materials	Manufacturing	Sensing	Simulation
Materials				
Manufacturing	Born qualified			
Sensing	Born qualified			
Simulation	Born qualified			

With new materials and advanced manufactured, born-qualified components, the nuclear system design paradigm shifts (Table 17) to allow innovative, complex designs. The use of traditional components such as axially uniform fuel elements can be expanded to include variable shapes, loadings, strengths, coatings, etc. Once this is possible, current nuclear M&S tools and the current reactor design paradigm become the limiting design capability. Experience with new materials and manufacturing capabilities will drive the M&S tools development necessary to design modern, complex, and optimized nuclear systems.

Table 17. Cross-cutting elements for redefining design efforts.

	Materials	Manufacturing	Sensing	Simulation
Materials	Integrated design			
Manufacturing				
Sensing				
Simulation	Integrated design			

New materials, manufacturing, and design approaches lead to innovative designs with improved operations, safety, and economics (Table 18). Robust components and systems with advanced materials improve operability and safety. Autonomous operations with embedded sensors allow the development of real-time digital twins of physical reactor systems. Embedded sensors allow detection of approaching issues and provide integrated and accessible real-time characterization of components and systems. Advanced manufacturing allows replacements to be fabricated on demand and permits improvement of designs if necessary.

Table 18. Cross-cutting elements for improved operations.

	Materials	Manufacturing	Sensing	Simulation
Materials	Robust components and systems			
Manufacturing	Make replacements on demand		Early detection of issues	
Sensing	Make replacements on demand			Autonomous operation, real-time digital twin
Simulation	Make replacements on demand	Ability to replace (and improve)		

3. SUMMARY OF RECOMMENDATIONS

Combining emerging capabilities and technologies in materials, manufacturing, instrumentation, data acquisition and analytics, and design and analysis tools can improve capabilities in reactor development, deployment, safety, and economic operation. These new capabilities have the potential to revolutionize the nuclear industry. They will allow advanced alloys to be designed for specific applications and for components to be manufactured and inspected in a single operation to become born-qualified components that are made on demand and ready for use. The entire life history of every critical component can be recorded through the use of embedded sensors, which can instantaneously alert an automated control system to adverse operating conditions and track component performance over its lifetime to detect early signs of degradation, thus allowing for optimal replacement strategies. New, fully integrated fuel forms and structural elements can be varied in composition and shape to allow for previously unachievable reactor designs. These designs can have fewer components, thus resulting in lower costs. They can provide greater resource utilization with an improved safety posture. The potential impacts on reactor design and development are greater than we can imagine today.

An essential element of nuclear revitalization is the establishment of effective and efficient approval processes that result in productive iterative design cycles. New reactor designs that reduce the probability of severe accidents and that can be easily monitored and maintained can be enabled with this combined advanced technology. Accident-tolerant fuel forms, integrated fuel and structural elements, embedded sensors, and autonomous control systems can be combined to generate these new designs. However, to achieve the full potential, the combination of these individual technologies must be practiced, perfected, and expanded. We only learn by doing.

The first step toward the realization of this vision requires the combination and extension of current practices. Today, advanced material performance can be predicted prior to production. Components can be designed with multiphysics evaluation tools and printed with advanced manufacturing methods. Sensors have already been embedded into materials through the use of these advanced manufacturing methodologies. Automated, autonomous control systems are common in industrial practice today and their applications to reactor operation have been studied for decades. These fundamental building blocks are available today to use in the initial begin developing and demonstrating the combined technology that will generate innovative, economically attractive, and market-expanding advanced reactor systems.

Because it will take many years to fully develop these new capabilities, development must be started now to verify the capabilities needed to revitalize the nuclear power industry and to establish American leadership in growing nuclear energy markets. The United States is perhaps the only country positioned to undertake such a bold initiative, and if it does, it can again lead the world in nuclear reactor technology design, development, and deployment. That journey can begin today. The panelists recommended that the federal government, nuclear industry designers and operators, and researchers in federal laboratories and universities combine efforts to (1) develop initiatives that can start quickly, (2) demonstrate straightforward examples that effectively combine these technologies, and (3) provide a basis for characterizing benefits and remaining gaps to enhance deployment in the nuclear industry. These initiatives should transform the processes for reactor designed, licensing, and operation.

One cross-cutting initiative that would combine most technologies described herein is to demonstrate production and operation of an advanced manufactured nuclear reactor core with data generated throughout its design, manufacture, and testing. Through this data, this initiative would demonstrate the science behind born-qualified nuclear reactors and would provide a design-agnostic blueprint. This blueprint would codify the effective combination of advanced manufacturing and I&C technologies with materials and computational sciences to deliver born-qualified reactors of any design to meet specific energy needs.

To be successful, existing domestic capabilities in these science and technology areas must be applied. Unique, carefully coupled proficiencies must be leveraged across the national laboratory and industrial complex. The outcome of this success will be a new paradigm, allowing for rapid innovation, improved safety, and dramatic reductions in costs and timelines of nuclear energy systems.

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APPENDIX A. WORKSHOP PARTICIPANTS

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Chair: Ken Tobin (Oak Ridge National Laboratory)

Co-chair: Steven Aumeier (Idaho National Laboratory)

Keynote Speakers:

Rob Ivester, US Department of Energy Office of Energy Efficiency and Renewable Energy

Mike Case, US Nuclear Regulatory Commission

Industry Panel:

Shane Johnson, US Department of Energy Office of Nuclear Energy

Dan Stout, Tennessee Valley Authority

Jonathan Cirtain, BWX Technologies, Inc.

Andrew Sowder, Electric Power Research Institute

Stage Setters:

Kevin Field, Oak Ridge National Laboratory

Suresh Babu, University of Tennessee-Knoxville

Rick Vilim, Argonne National Laboratory

Jess Gehin, Idaho National Laboratory

Panel A: Accelerated Development and Qualification of Materials and Fuels

Chairs: Jeremy Busby, Oak Ridge National Laboratory/Micah Hackett, Kairos Power, LLC

Sam Sham, Argonne National Laboratory

Ryan Dehoff, Oak Ridge National Laboratory

Stuart Maloy, Los Alamos National Laboratory

Doug Crawford, Idaho National Laboratory

Steve Zinkle, University of Tennessee-Knoxville

Kevin Field, Oak Ridge National Laboratory

Panel B: Advanced Manufacturing Technologies to Enable New Designs

Chairs: Lonnie Love, Oak Ridge National Laboratory/Suresh Babu, University of Tennessee-Knoxville

Bob Hathaway, Oshkosh Corporation

Dave Kennedy, Mazak Corp.

Tom Matthews, Lincoln Electric

Rick Lucas, The ExOne Company

Chris Saldana, Georgia Institute of Technology

Scott Smith, University of North Carolina-Charlotte

Dave Gandy, Electric Power Research Institute

Kurt Terrani, Oak Ridge National Laboratory

Joe Miller, BWX Technologies, Inc.

Badri Narayanan, Lincoln Electric

Katherine Gaul, Oak Ridge National Laboratory

Panel C: Sensors and Controls for Autonomous Operations

Chairs: Ken Tobin, Oak Ridge National Laboratory/Raymond Cao, The Ohio State University
Steve Aumeier, Idaho National Laboratory
Jorge Carvajal, Westinghouse Electric Co.
Paul Tobin, Rolls-Royce
Rick Vilim, Argonne National Laboratory
Jamie Coble, University of Tennessee-Knoxville
Nam Dinh, North Carolina State University
Heng Ban, University of Pittsburgh
Venkat Krovi, Clemson University
Pat Mulligan, Oak Ridge National Laboratory
Scott Greenwood, Oak Ridge National Laboratory

Panel D: High-Fidelity Modeling and Simulation and Data Analytics for Design

Chairs: Dave Pointer, Oak Ridge National Laboratory/Art Wharton, Studsvik
Hussein Khalil, Argonne National Laboratory
Cristian Rabiti, Idaho National Laboratory
Tom Downar, University of Michigan
Dave Kropaczek, North Carolina State University
Paul Wilson, University of Wisconsin-Madison
Martin van Staden, Aerotherm Computational Dynamics USA LLC
John Kutsch, Terrestrial Energy USA
Jeff Whitt, Framatome, Inc.
Nick Bobolea, Framatome, Inc.
Bob Martin, BWX Technologies, Inc.
Askin Guler Yigitoglu, Oak Ridge National Laboratory
Marco Delchini, Oak Ridge National Laboratory

Panel E: Technology Integration Cross-Cut

Chairs: Lou Qualls/Ben Betzler, Oak Ridge National Laboratory
Kevin Robb, Oak Ridge National Laboratory
Chris Petrie, Oak Ridge National Laboratory
Nidia Gallego, Oak Ridge National Laboratory

Attendees

Steven Aumeier, Idaho National Laboratory
Sudarsanam Babu, University of Tennessee / Oak Ridge National Laboratory
Heng Ban, University of Pittsburgh
Rita Baranwal, Idaho National Laboratory
Benjamin Betzler, Oak Ridge National Laboratory
Jeffrey Binder, Argonne National Laboratory
Craig Blue, Oak Ridge National Laboratory
Nicolae Bobolea, Framatome, Inc.
Jeremy Busby, Oak Ridge National Laboratory
Lei (Raymond) Cao, The Ohio State University
Jorge Carvajal, Westinghouse Electric Co.
Michael Case, US Nuclear Regulatory Commission
Jonathan Cirtain, BWX Technologies, Inc.
Jamie Coble, University of Tennessee
Douglas Crawford, Idaho National Laboratory
Ryan Dehoff, Oak Ridge National Laboratory
Marc Olivier Delchini, Oak Ridge National Laboratory
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Thomas Downar, Univ of Michigan
Kevin Field, Oak Ridge National Laboratory
Nidia Gallego, Oak Ridge National Laboratory
David Gandy, Electric Power Research Institute
Katherine Gaul, Oak Ridge National Laboratory
Jess Gehin, Idaho National Laboratory
Scott Greenwood, Oak Ridge National Laboratory
Askin Guler Yigitoglu, Oak Ridge National Laboratory
Micah Hackett, Kairos Power, LLC
Michelle Harstine, US Department of Energy
Robert Hathaway, Oshkosh Corporation
Alan Icenhour, Oak Ridge National Laboratory
Gabriel Ilevbare, Idaho National Laboratory
Robert Ivester, US Department of Energy
Shane Johnson, US Department of Energy
Dave Kennedy, Mazak Corp.
Hussein Khalil, Argonne National Laboratory
David Kropaczek, North Carolina State University
Venkat Krovi, Clemson University
John Kutsch, Terrestrial Energy USA
Bruce Landrey, US Department of Energy
Lonnie Love, Oak Ridge National Laboratory
Rick Lucas, The ExOne Company
Stuart Maloy, Los Alamos National Laboratory
Robert Martin, BWX Technologies, Inc.
Bill Matisiak, US DOE Oak Ridge Site Office
Tom Matthews, Lincoln Electric
Joseph Miller, BWX Technologies, Inc.
Padhraic Mulligan, Oak Ridge National Laboratory
Badri Narayanan, Lincoln Electric

William Peter, Oak Ridge National Laboratory
Christian Petrie, Oak Ridge National Laboratory
Dave Pointer, Oak Ridge National Laboratory
Alexandra Popova, Oklo Inc.
Conner Prochaska, ARPA-E
Lou Qualls, Oak Ridge National Laboratory
Cristian Rabiti, BEA, LLC / Idaho National Laboratory
Kevin Robb, Oak Ridge National Laboratory
Christopher Saldana, Georgia Institute of Technology
Sam Sham, Argonne National Laboratory
Rachel Slaybaugh, ARPA-E
Kevin Scott Smith, University of North Carolina, Charlotte
Andrew Sowder, Electric Power Research Institute
Daniel Stout, Tennessee Valley Authority
Kurt Terrani, Oak Ridge National Laboratory
Paul Tobin, Rolls-Royce
Ken Tobin, Oak Ridge National Laboratory
Jason Tokey, DOE Office of Nuclear Energy
Billy Valderrama, DOE Office of Nuclear Energy
Martin van Staden, Aerotherm Computational Dynamics USA, LLC
John Vetrano, DOE Office of Nuclear Energy
Richard Vilim, Argonne National Laboratory
Art Wharton, Studsvik
James White, Oak Ridge National Laboratory
Jeffrey Whitt, Framatome, Inc.
Paul Wilson, Univ of Wisconsin-Madison
Thomas Zacharia, Oak Ridge National Laboratory
Steve Zinkle, University of Tennessee / Oak Ridge National Laboratory

APPENDIX B. WORKSHOP AGENDA

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MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Technologies to Reactors: Enabling Accelerated Deployment of Nuclear Energy Systems Workshop July 25–26, 2018

Agenda as of 07/19/2018

Event contact	Ken Tobin, 865-574-5267 (office); 865-300-7024 (mobile); tobinkwjr@ornl.gov			
Time	Event/Activity	Lead	Attendees	Place
Wednesday, July 25, 2018				
7:30–8:00 am	Registration		All	5200, Rms. 202 A, B & C
8:00–8:15 am	Welcome/Workshop Kickoff	Thomas Zacharia	All	5200, Rms. 202 A, B & C
8:15–8:45 am	Overview of the Workshop Approach and Charge	Alan Icenhour	All	5200, Rms. 202 A, B & C
8:45–10:00 am	Panel Session – Industry Perspectives	Moderator: Shane Johnson, NE-5 Dan Stout, TVA Jonathan Cirtain, BWXT Andrew Sowder, EPRI	All	5200, Rms. 202 A, B & C
10:00–10:15 am	Review Charge	Ken Tobin	All	5200, Rms. 202 A, B & C
10:15–10:30 am	Break		All	
10:30–11:45 am	Stage Setting Talks (20 minutes each)	Panel A – Kevin Field, ORNL Panel B – Suresh Babu, UT-K Panel C – Rick Vilim, ANL Panel D – Jess Gehin, INL	All	5200, Rms. 202 A, B & C
11:45 am–3:00 pm	Working lunch – Panel Breakouts Panel A: Accelerated Development and Qualification of Materials and Fuels	Co-chairs: Jeremy Busby, ORNL/Micah Hackett, Kairos	Doug Crawford, INL Ryan Dehoff, ORNL Kevin Field, ORNL Stuart Maloy, LANL Sam Sham, ANL Steve Zinkle, UT-K	5200, Rm. 212

Event contact	Ken Tobin, 865-574-5267 (office); 865-300-7024 (mobile); tobinkwjr@ornl.gov			
Time	Event/Activity	Lead	Attendees	Place
	Panel B: Advanced Manufacturing Technologies to Enable New Designs	Co-chairs: Lonnie Love, ORNL/Suresh Babu, UT-K Note Taker – Katherine Gaul, ORNL	Dave Gandy, EPRI Bob Hathaway, Oshkosh Dave Kennedy, Mazak Rick Lucas, ExOne Tom Matthews, Lincoln Electric Joe Miller, BWXT Badri Narayanan, Lincoln Electric Chris Saldana, GA Tech Scott Smith, UNCC Kurt Terrani, ORNL	5200, Rm. 214
	Panel C: Sensors and Control Systems for Autonomous Operations	Co-chair: Ken Tobin, ORNL/ Raymond Cao, OSU Note Takers – Pat Mulligan and Scott Greenwood, ORNL	Heng Ban, Pitt Jorge Carvajal, Westinghouse Nam Dinh, NCSU Brenden Heidrich, INL Venkat Krovi, Clemson Paul Tobin, Rolls Royce Rick Vilim, ANL Jamie Coble, UT-K	5200, Rm. 219
	Panel D: High Fidelity Modeling and Simulation and Data Analytics for Design, Manufacturing, Licensing and Operations	Co-chair: Dave Pointer, ORNL/ Art Wharton, Studsvik Note Takers – Askin Guler Yigitoglu and Marco Delchini	Nick Bobolea, Framatome Tom Downar, UM Hussein Khalil, ANL Dave Kropaczek, NCSU John Kutsch, Terrestrial Energy Bob Martin, BXWT Cristian Rabiti, INL Martin van Staden, X-energy Jeff Whitt, Framatome Paul Wilson, UW-M	5200, Rms. 202 A, B & C
3:00–3:15 pm	Break		All	
3:15–4:30 pm	Continue Panel Breakout Sessions		Panels	5200, Rms. 202 A, B & C; 212; 214; 219
4:30–5:30 pm	End of Day 1 – Report out by Panel Co-chairs	Panel Leads	All	5200, Rms. 202 A, B & C
5:30–5:45 pm	Break		All	

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Event contact	Ken Tobin, 865-574-5267 (office); 865-300-7024 (mobile); tobinkwjr@ornl.gov			
Time	Event/Activity	Lead	Attendees	Place
5:45–7:00 pm	Working Dinner-Continue End of Day 1 – Prepare Summaries for Day 2 Recap	Panel Leads	All	5200, Rms. 202 A, B & C

Time	Event/Activity	Lead	Attendees	Place
Thursday, July 26, 2018				
8:00–8:10 am	Recap of Day 1	Alan Icenhour	All	5200, Rms. 202 A, B & C
8:10–8:30 am	DOE Perspective on Advanced Manufacturing	Rob Ivester, Director, Advanced Manufacturing Office, DOE-EERE	All	5200, Rms. 202 A, B & C
8:30–8:50 am	Keynote: Policy and Regulatory Approaches	Mike Case, Director, Division of Safety Analysis, Office of Nuclear Regulatory Research, NRC	All	5200, Rms. 202 A, B & C
8:50–10:00 am	Breakout into Panel Groups		Panels	5200, Rms. 202 A, B & C; 212; 214; 219
10:00–10:15 am	Break		All	
10:15–11:15 am	Continue Breakout into Panel Groups		All	5200, Rms. 202 A, B & C; 212; 214; 219
11:15 am–12:30 pm	Working Lunch – Panel Report Out		All	5200, Rms. 202 A, B & C

Time	Event/Activity	Time	Event/Activity
	Co-chairs and Selected Panelists	Tour Attendees	Tour Guides - Brian Post and Ryan Dehoff
12:30	Adjourn Workshop (Co-chairs and selected panelists remain)	12:30–1:00 pm	Travel to Manufacturing Demonstration Facility (MDF) via ORNL Bus

MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Time	Event/Activity	Time	Event/Activity
12:30–1:45 pm	Co-chairs, notetakers, and selected panelists will remain for the afternoon to prepare initial report	1:00–2:00 pm	Tour MDF
1:45–2:00 pm	Break	2:00–2:30 pm	Travel to ORNL
2:00–6:30 pm	Continue Preparing Report	2:30 pm	Depart ORNL
6:30 pm	Co-chairs and Selected Panelists Adjourn		