2024

Summary:

EPRI SUPPLY CHAIN WORKSHOP III FOR STRUCTURAL COMPONENTS IN ADVANCED ENERGY SYSTEMS

Executive Summary

Unprecedented energy transformation is reshaping the energy system and placing new strain on an already pressed global supply chain.

This white paper outlines key industry themes and provides potential actions based on the third EPRI-organized Supply Chain Workshop for Advanced Energy Systems (AES), which focused on the cross-cutting themes of supplying structural components for future advanced nuclear technology, transformational thermal generation, concentrating solar power, and advanced power cycles.

The results of the first two Workshops were captured in publicly available EPRI reports: 3002025254 and 3002027773.

The transition to advanced energy systems (AES) is gaining momentum, driven by local, state, and federal policies that encourage early investments. These policies aim **for initial deployments between 2025 and 2030**. Successful deployment of AES requires increased collaboration between developers and supply chain entities, focusing on manufacturability and the qualification of new materials and practices. Recent industry reports emphasize the importance of reducing supply chain risks to enable the adoption of commercially available energy supply technologies. Electric utility planners seek certainty to plan their future resources, and **addressing these risks through innovations such as modularization, early coordination, and accelerated demonstration activities is crucial**. These steps are seen as essential for risk reduction and the successful deployment of future nuclear and other advanced energy systems.

However, there are significant challenges. **Component suppliers are hesitant to invest in new capabilities without clear market signals, and there is a shortage of skilled workers**, with current development not meeting demand. Many companies are no longer qualified to supply nuclear components and are not investing in qualification programs. Additionally, global supply chain disruptions pose a risk to obtaining necessary materials and components, further complicated by growing demands from other sectors like naval and aerospace.

Advanced manufacturing (AM) methods and **materials** could offer alternative supply chains, to augment traditional methods, but challenges such as Codes and Standards acceptance remain. While rapid progress is being seen across many different industries, the power industry lags behind. Existing industry roadmaps, near-term applications, and supply chain feedback are helping to prioritize **collaborative projects**. EPRI's global collaborative model engages various stakeholders across the energy supply landscape, providing independent perspectives on industry needs to support the future of energy applications.

Supply Chain Opportunities Based on Key Themes

EPRI's third workshop continued to explore specific topics from the seven key themes identified in EPRI's inaugural workshop in 2022:

1. **Joint industry qualification programs** should be pursued to accelerate **new materials** development into the existing supply chain.
2. Strategies to expand and support the future **skilled workforce** in the areas of **machining and welding** are needed.
3. Improved coordination, collaboration, and qualification are needed to maximize the value of the existing supply chain, develop new supply chain partners from other industries, and provide a **robust supply chain.**
4. It's essential to foster widespread involvement and progress in the methods used to **qualify advanced manufacturing techniques** for inclusion in ASME Codes and other Standards.
5. **Test loops, pilot facilities, and demonstration projects** provide a key opportunity to gain practical supply chain experience and accelerate acceptance and industry adoption of new materials and manufacturing methods; more are needed.
6. Despite recent investments in new forging capabilities and advanced manufacturing methods, **additional infrastructure investment** will likely be needed to meet future demands.
7. Improved **collaboration** is needed at an earlier stage in the development process between **AES developers** and prospective **supply chain partners**.

CONTENTS

SUMMARY OF WORKSHOP III ACTIVITIES

The workshop brought together **95 attendees from 56 organizations** representing key industry stakeholders throughout the entire AES supply chain landscape, which included:

- **AES equipment manufacturers and developers**
- **Piping, tubing, valve, pump, and reactor manufacturers**
- **Educational and training institutions**
- **Codes and Standards leaders**
- **Fabricators, field service providers, architectural engineering firms**
- **Decision makers from across industry**
- **Utilities and operators**

The workshop was highly interactive and included **41 short presentations** by participants combined with **facilitated panel discussions** in the following sessions:

- Review of actions from the two previous EPRI Supply Chain Workshops
- Voice of the customer – insight from AES developers regarding new builds
- How other industries address supply chain
- EPRI-NEI advanced reactor roadmap overview
- Materials qualification – deep dive
- Wire and powder manufacturing availability
- Large Directed Energy Deposition (DED) additive components and parts
    - In-situ and volumetric inspection
    - Manufacturing for inspectability
    - Qualification of materials
    - High temperature applications

EPRI would like to thank all the participants, speakers, panelists, and organizations who supported this workshop. The workshop was funded by a joint effort of EPRI's Nuclear and Generation Sectors through EPRI's Advanced Manufacturing Methods & Materials (AM3) strategic initiative.

SUMMARY OF WORKSHOP III FINDINGS – DAY 1

Summary of Collaboration and Key Findings

Voice of the Customer

The session focused on new AES developers engaged in demonstration projects for both fission and fusion. The presenter highlighted the value of these first-of-a-kind demos in expanding the supply chain and focused on opportunities for improvement. Collaboration among government, manufacturing, and utilities was identified as crucial for success. **Modernization and modularization** were seen as important enablers to allow developers to **engage a larger number of vendors and suppliers to build a more robust supply chain**. Advanced manufacturing is recognized as a potentially transformative opportunity, but due to aggressive demonstration schedules and the focus on the AES technology, traditional supply chain are the current focus.

Updates on Actions from Previous Workshops

This session emphasized advancements, partnerships, and initiatives stimulated by previous workshops, focusing on Fit for Nuclear (F4N), expanding supply chain opportunities, and Welding Workforce Development. It discussed **the EPRI sponsored F4N pilot program** to guide companies on initial steps and highlighted the need to modernize nuclear quality assurance by focusing on product quality and leveraging risk-informed programs.

Supply Chain Across Various Industries

The fabrication and construction of **thermal energy assets are lagging behind other industries in addressing supply chain issues**. This session aimed to share strategies, lessons learned, and insights from industries like oil and gas, academia, and large component fabrication. The goals were to understand how other industries face supply chain issues, explore current strategies and innovations to address these challenges, and gain perspectives on how the advanced energy fleet can apply these lessons.

EPRI-NEI Advanced Reactor Roadmap

The Advanced Reactor (AR) Roadmap comprises 13 strategic elements and 46 key actions to support future nuclear fleet deployment, focusing on supply chain and workforce development. This session reviewed action items related to component and structural materials supply chain, such as expanding module fabrication capability, establishing a sufficient supply of nuclear-grade components, increasing small forging facilities' capacity, and commercializing advanced manufacturing capabilities. **Industry leaders' involvement is crucial for multistakeholder collaboration and strategy execution**, leading to the establishment of a **Roadmap Implementation Board**. This board aims to ensure the successful large-scale deployment of advanced reactors, essential for Canada and the U.S. to achieve their national goals. The industry also plans to expand the roadmap globally.

Government/State Support and Opportunities

Various federal offices and regional supplier organizations, including the Clean Energy Supplier Alliance, US Department of Energy Nuclear Energy Office, National Reactor Innovation Center (NRIC), DOE Office of Manufacturing and Energy Supply Chains (MESC), and the Loan Program Office (LPO), provided overviews of their roles in supporting the clean energy transition. They highlighted numerous resources, initiatives, and opportunities available for the supply chain to leverage federal support. A key gap identified was the **lack of representation by the overall AES supply chain in some of these DOE offices** which are looking to industry to help inform their future research, development, and demonstration projects.

Materials Qualification and Deployment – Deep Dive

Advanced energy systems require materials that can withstand high temperatures and new environments, but **there are still technical gaps to address for widespread use**. Research on material behavior under various conditions is resource-intensive and challenging for any single organization. This session focused on identifying collaboration opportunities and showcasing successful material deployments. It also aimed to develop strategies for qualifying new materials and establishing a knowledgeable supply chain for advanced energy systems.

SUMMARY OF WORKSHOP III FINDINGS – DAY 2

Summary of Collaboration and Key Findings

Feedstock Supply Chain for Welding and Manufacturing

This session evaluated the current state of the feedstock supply chain for AES alloys in additive manufacturing and welding, focusing on wire and powder forms. It identified existing vulnerabilities and future risks and discussed strategic actions to ensure a stable supply for industrial applications. The supply chain status varies by material, with some nickel and stainless-steel alloys being special order only. While wire quality is not an issue for DED-AM, the required quantity could disrupt overall supply. Several nickel and stainless-steel alloys have fragile supply chains and scaling up production faces challenges like capacity and raw material quality. Low volume and custom materials also suffer from poor availability. Overall the **suppliers appear poised to expand to the needs** of the industry but the **'specialty' of the materials of need for AES will limit how fast such expansion can happen**.

AM Suppliers and Developers

This session focused on the market of large-area AM of metallic parts, with participants discussing their organizations and expertise. Topics included large-area AM technology trends, build size, production capacity, lead time limitations, and the maturity of AM materials relevant to advanced energy systems. The session highlighted opportunities for AES supply chain engagement and risks associated with AM applications. Large-area AM, especially DED, has reached commercial maturity and is used by other industries and DED print cell sizes have increased to handle large parts. Early supplier interaction and design flexibility are crucial for mitigating risks. Currently, only a few materials relevant to AES are routinely printed, with limiting factors including feedstock availability, development costs, and market maturity. **Codes and Standards approvals are needed** for consistency, and other adoption barriers include a lack of mechanical property data, customer awareness, and risk aversion.

Perspectives on AM for Energy Applications

This session discussed the perspectives on additive manufacturing for AES from a utility viewpoint, covering current ASME Codification objectives and progress, and highlighting where utilities plan to use AM in the near and long term. It described industry drivers pushing for AM in supply chains and areas where DED-AM is being considered. While only a few utilities are exploring AM seriously, other industries like aerospace and military are ahead in AM development. Current AM applications are mainly structural, but new standards are prompting interest in pressure-retaining parts like valves and pump housings. Specific applications mentioned include hydro runners and valve bodies. The domestic foundry industry's capacity and workforce challenges suggest **AM as a viable option for replacing large imported steel parts**, with existing alloy filler metals being considered for DED-AM builds due to their proven reliability.

Existing AM User Perspectives

This session focused on organizations outside the commercial power generation sector that are actively developing and deploying AM parts and technologies, with an emphasis on large-area additive manufacturing. Participants were provided with potential talking points and questions to aid in their presentations, such as describing their organization's AM journey, the value AM brings to their supply chain, qualification and deployment barriers faced and how they were addressed, industry actions to accelerate AM development and deployment, and examples of AM applications, lessons learned, and future plans. Many participants from the AES community were surprised to see that rapid progress had been made outside the energy industry and commented on the **need to re-assess their current timelines** for large area DED in particular for new and replacement applications.

Summary of Workshop III Sessions
Day 1

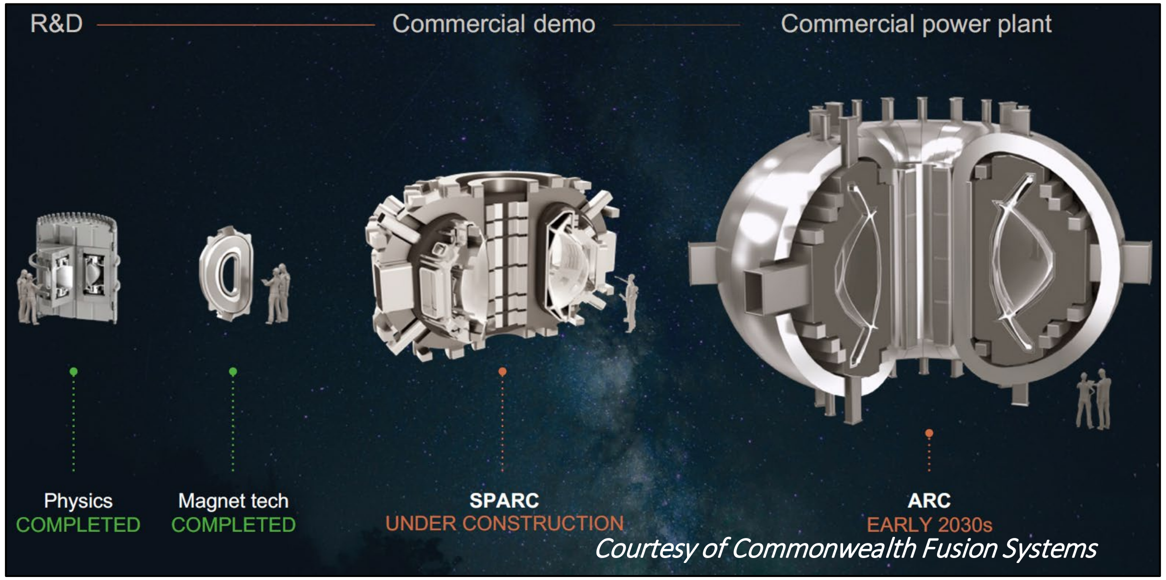
Voice of the Customer

Global supply chain disruptions have been identified as a significant risk to the timelines and schedules for obtaining pertinent materials and components. First-of-a-kind projects pose significant challenges but also many opportunities to advance the supply chain

Session Description & Specific Goals

Past workshops focused on end-user expectations for AESs and the need for such systems to enable the energy transformation. In this session, developers of new AESs which have near term demonstrations were asked to explore their specific global supply chain challenges and strategies. A key takeaway was the necessity of collaboration among government, manufacturing, and utilities. Three diverse technologies were explored:

- DOW Chemical: X-Energy XE-100 advanced gas-cooled nuclear technology for process heat & power generation
- Commonwealth Fusion Systems: SPARC/ARC fusion demo reactors
- TerraPower: Natrium™ advanced sodium nuclear



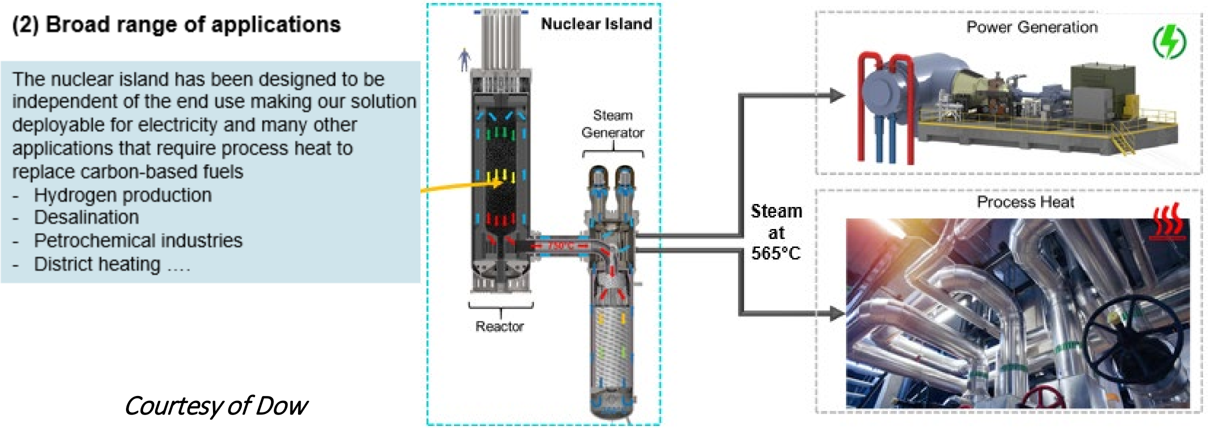
Courtesy of Commonwealth Fusion Systems

Current State of the Industry

The presentations and discussions emphasized that "first-of-a-kind" equipment and technologies pose significant challenges, including long lead times for certain components, with an aim to keep as much manufacturing as possible within the U.S. Other key challenges the industry faces include:

- For nuclear energy to become competitive in the U.S., the "first-of-a-kind" plant must be completed on budget and on schedule. Commodities (concrete, structural steel, etc.) are a large part of the cost and pricing has escalated in recent years putting strains on budgets.
- Due to the large scale of the equipment and the lengthy lead times needed for many components, testing, transportation, and installation are increasingly becoming obstacles to success
- Aligning goals is crucial, and with a rapidly expanding workforce and numerous partners and suppliers, continuous communication is essential to maintain this alignment

Voice of the Customer



Courtesy of Dow

Opportunities

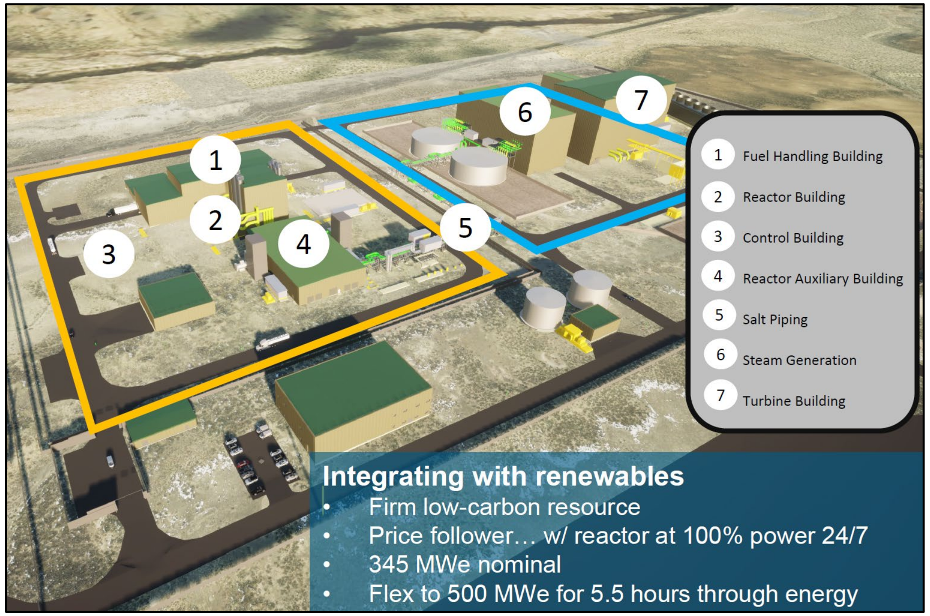
Large-scale demonstration of new technologies highlight opportunities for innovation which could positively impact the overall industry and AES supply chains:

- U.S. DOE Advanced Reactor Demonstration Program is helping to accelerate much needed demo's with commercialization plans (e.g. Dow & X-energy agreement to develop a 4 unit Xe-100 facility) focusing on how we address future supply chain needs now. More demonstration and commercial projects are needed now so we don't end up in a 'start-and-stop' situation
- Applying modularization by moving construction offsite and leveraging other U.S. facilities for manufacturing takes time now but can lead to acceleration later
- Minimizing the 'nuclear island' and modernizing nuclear regulation will expand the potential suppliers for a more robust supply chain
- Finding ways to utilize advanced manufacturing capabilities has not been a focus for demonstration projects due to aggressive project timelines but is recognized as a large opportunity which requires broader industry acceptance

Ongoing Activities: Demonstrations

While the general sentiment of the community is that more demonstration activities are needed in order to accelerate technology advancement, some key activities being undertaken now include:

- **Construction of a nuclear fusion energy SPARC Facility**: Collaborations with global forging vendors are in place to supply SPARC components in existing austenitic grades at approximately 20-tonne scale. Cryogenic testing infrastructure is being scaled up to quickly validate properties and performance. Future alloy design pathways are being identified based on the experience gained from SPARC deliveries.
- **TerraPower Natrium^{TM} Reactor:** Oct 2020, the Natrium team was one of two teams selected by DOE to receive cost-shared funding under the Advanced Reactor Demonstration Program (ARDP). The Natrium Demo will demonstrate the ability to design, license , construct, startup and operate the Natrium^{TM} sodium fast reactor.



Courtesy of TerraPower

Update on Actions from Previous Workshops

Past workshops on Supply Chain have concentrated on the workforce issues and the manufacturing and materials needed for advanced energy systems. The aim was to pinpoint deployment gaps and identify where industry should target future efforts and foster partnerships.

Session Description & Specific Goals

This session aimed to emphasize the advancements, partnerships, and initiatives that were stimulated by the conversations from the previous workshops. Areas highlighted include:

- Fit for Nuclear
- Expanding the supply chain opportunities and options
- Welding Workforce Development

Based on prior workshops, EPRI sponsored a F4N pilot program (based on the UK's AMRC F4N program) which was discussed to inform companies on the initial steps of the F4N process and program. There is a need to modernize nuclear quality assurance by focusing on the quality of the product (e.g., reliability and capability performance) and leveraging Risk-informed programs.

Current State of Industry

Strategies to expand and support the future skilled workforce in the areas of machining and welding are at the forefront of the workshop conversations and will continue to be one of the biggest concerns in the supply chain. Workforce issues will require coordination, both locally (near facilities) and globally, to tackle industry-wide problems through collective initiatives.

Supply Chain - Codes, Standards and Owners Requirements vary between jurisdictions and owners and need to be harmonized.

Update on Actions from Previous Workshops

Opportunities

Key opportunities noted during this session include:

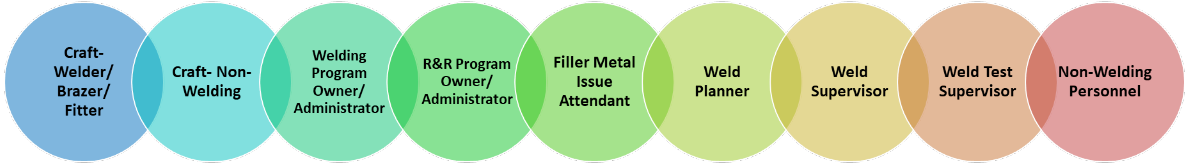
- Once again emphasis on workforce challenges - will need to be coordinated both locally (close to facilities), as well as globally, to address the industry wide issues
- Engagement with Technical Societies to take advantage of the resources available (e.g., scholarships, training, mentoring)
- Engagement with universities to understand curriculums that address future needs, capabilities (Collaborative Robots (COBOTs), data acquisition, monitoring, automation)
- Worldwide endorsement of Codes and Standards, coupled with commercial quality programs that cater to the requirements of advanced reactors, to bolster design, licensing, procurement, and construction processes
- F4N opportunities to collaborate between the UK, USA, and Canada to develop strategic capabilities, research and development projects of mutual benefit and to develop ability to share SMEs and manufacturers
- Pilot Program for developing long-term strategy for using ISO-9001, ISO-19443 or other commercial programs

Courtesy of NAMRC

Potential Actions

- Hold workforce specific Supply Chain Workshops with focus on collaborations, and industry efforts for workforce retention and growth
- Create forums for discussing best practices or lessons learned, mentoring and capturing knowledge for future workforce/to include all related industries
- Establish roadmap for advanced manufacturing techniques/processes to minimize impact on Supply Chain issues
- Harmonization of Codes and Standards – meet all jurisdictional and owner requirements and "Justification/Sharing" approach - based on establishing equivalence of Codes and Standards from different jurisdictions ("one fits all" in different jurisdictions)

Key Welding Roles in Nuclear Energy



Advanced Reactor Roadmap: North America

The purpose of this Advanced Reactor Roadmap is to outline the critical strategies and support actions necessary for the successful large-scale deployment of advanced reactors. This will be a living document that evolves and refocuses strategies and actions as the future unfolds.

Deep Dive on Supply Chain Action Items within the AR Roadmap

The Advanced Reactor (AR) Roadmap is made up of 13 strategic elements and 46 key actions necessary to support the deployment of a future nuclear fleet. Supply Chain and Workforce Development are two of those strategic elements made up of several action items developed from previous workshops. This workshop took a deep dive reviewing the action items (and sub actions) related to component and structural materials supply chain and their current status:

- Expand module fabrication capability
- Establish a sufficient supply of nuclear grade components
- Increase the capacity of small forging facilities
- Establish competent material supply chain with production capacity
- Commercialize advanced manufacturing capabilities

Each of the above action items include several sub actions focused on achieving the above goals to enable a sufficient supply chain for large scale deployment of advanced reactors to meet 2050 climate goals.

Visit the Roadmap website for additional details and action item statuses.

ARRoadmap.com

Advanced Reactor Roadmap: North America

Roadmap Implementation

The active involvement of industry leaders has been a key driver for multistakeholder collaboration in developing the roadmap. Continued industry leadership is essential to execute and drive the strategy, promote collaboration and coordination, and ensure that actions are being completed on the roadmap. For this reason, a Roadmap Implementation Board was established. This is aimed at the successful large-scale deployment of advanced reactors, which are crucial for Canada and the U.S. to achieve their national goals in energy, climate, environment, economy, and security.

The industry also has plans to expand the roadmap with other regional roadmaps across the globe.

Opportunities

Several actions are currently underway to develop the necessary supply chain to enable large scale deployment of advanced reactors. Many of the actions were developed via previous EPRI Supply Chain Workshops and are highlighted in the 2024 workshop session on "Updates on Actions from Previous Workshops." A few specifically discussed include:

- Fit for Nuclear F4N Pilot Study
- OCNI Ready4SMR Program
- NEI 22-04 "Utilization of ISO 9001 and Other Non-nuclear Suppliers for Safety-related Applications"
- LANE – Listing of Accepted Nuclear Equipment to Facilitate Procurement
- Welding Workforce Development

There are several opportunities, including the above initiatives, to get more engaged in implementing the AR Roadmap.

Government Opportunities and Industry Input

Supply Chains are often a lagging indicator driven by market demand rather than speculative deployment. Like EPRI's efforts, several federal, state, and regional offices are taking proactive approaches to develop the necessary supply chains for advanced energy systems.

Session Description & Specific Goals

Various federal offices and regional supplier organizations provided overviews of their objectives and roles in supporting the clean energy transition. Numerous resources, initiatives, and opportunities exist for the supply chain to utilize the federal resources. Participating organizations include:

- Clean Energy Supplier Alliance
- US Department of Energy Nuclear Energy Office
- Gateway for Accelerated Innovation in Nuclear (GAIN)
- National Reactor Innovation Center (NRIC)
- US Department of Energy Manufacturing and Energy Supply Chains (MESC)
- US Department of Energy Loan Programs Office (LPO)

Current State of Industry / Industry Feedback

Presenters from governmental and regional bodies invited input from workshop participants on the most critical needs from the supply chain's viewpoint, where assistance could significantly influence the deployment of advanced energy systems. This constructive dialogue centered on areas where government and regional entities could establish initiatives, aid programs, and explore potential future funding opportunities.

- Innovative funding options with the government organizations are desired to reduce owner risk

To help generate discussion and provide a glimpse into the challenges facing advanced nuclear procurement, EPRI also highlighted preliminary results from a recent industry questionnaire. The survey polled numerous international nuclear technology developers on their biggest challenges in nuclear component manufacturing and procurement both within North America and abroad. Key takeaways include:

- To meet the impending nuclear demand during new-build, more "nuclear qualified" fabrication capabilities/facilities are needed
- There is considerable concern over the drain on the supply chain that will come from the military and aerospace over the next couple of decades
- Early engagement from suppliers with developers is desired in design, manufacturing, fabrication, and construction
- There is a perceived lack of domestic capabilities or experience around steam generators, heat exchangers, high temperature alloys, and heavy forging manufacturing for nuclear applications from government agencies which don't fully appreciate the differences in domestic and global supply chains

Government Opportunities and Industry Input

Opportunities

Each government office or regional organization provides unique capabilities and opportunities to support supply chain development.

- Clean Energy Supplier Alliance – four major focuses include:
    - Nuclear Quality Management Center of Excellence
    - Process evaluation and development of business systems to prepare suppliers for nuclear business
    - Workforce training
    - Supply chain innovation to accelerate and economize Nth-of-a-kind nuclear deployments. One of the major innovations includes planning for development of a large scale (> 4 meters diameter) powder metallurgy hot isostatic pressing (PM-HIP) facility
- National Reactor Innovation Center (NRIC) – major focus is to enable nuclear reactor tests and demonstrations by assisting developers to go from concept to commercial production and building foundations for testing and addressing costs and markets.
- US Department of Energy Manufacturing and Energy Supply Chains (MESC) – the office focus is on the “how” of the energy transition with the goal of securing and strengthening critical manufacturing and energy supply chains. The office’s core functions include manufacturing and workforce investing and manufacturing analytics.
- US Department of Energy Nuclear Energy Office announced plans for a potential future funding opportunity announcement related to supply chain coming later in 2024.

Courtesy of NRIC. Examples of companies NRIC works to support.

Potential Actions

From DOE perspective:

- Production capacity is adequate, but the bottleneck lies in Non-Destructive Testing (NDT). DOE is asking companies to share their experiences and lessons learned from NDT to expedite production.
- There is a lack of representation by the overall AES supply chain in some of these DOE offices which are looking to industry to help inform their future research, development, and demonstration projects

AES Companies perspective:

- Lack of experience working with DOE to get funding. Looking at it from a Funding Opportunity Announcement (FOA) standpoint, there’s a need for more direction to effectively maneuver through the entire process.

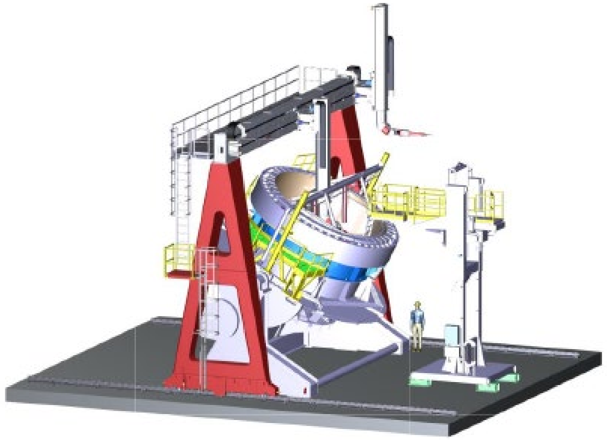
Supply Chain Across Various Industries

Manufacturing for advanced energy systems can learn from other industries that are currently addressing supply chain issues through adoption of technology, additional materials, and differing approaches.

Session Description & Specific Goals

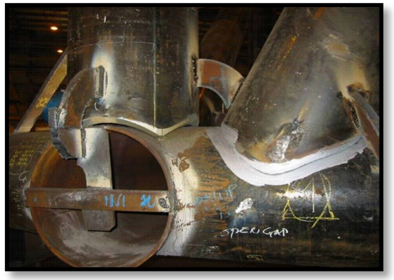
Fabrication and construction of thermal energy assets are in many ways lagging behind other industries already addressing supply chain issues. Lessons learned from how other industries have addressed supply chain challenges can be important for adopting the same or similar strategies for AES. This session was intended to communicate some strategies, lessons learned, and insights into how other industries such as oil and gas, academia, and large component fabrication are addressing supply chain issues. Some specific goals for the session were:

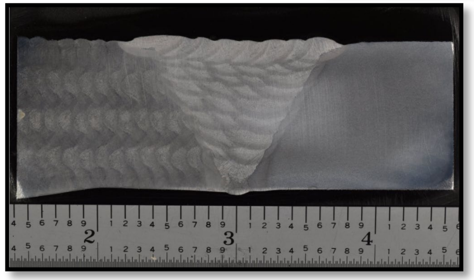
- Understand why other industries are having supply chain issue(s)
- What strategies, innovations, or other techniques are being used to address supply chain issues now
- Perspective on how advanced energy fleet can use lessons learned from other industries



Courtesy of Famatome

Courtesy of The Ohio State University College of Engineering





Courtesy of Stress Engineering Services INC

Current State of Industry

Large component fabricators and the supply chain as a whole are challenged with preparing and having capability to meet future demand for new AES construction. However, using prospective future demand without actual orders challenges many privately owned companies to make large investments. Additional observations follow:

- Additive manufacturing is being used more frequently for fabrication of components, but challenges remain regarding Codes and Standards adoption, qualification, and in some instances material availability
- The adoption of non-metallic materials seems to have slower adoption for existing nuclear and future AES
- Some organizations are working with university partners to research approaches to address supply chain issues

Supply Chain Across Various Industries

Opportunities: Use Lessons Learned From Other Industries

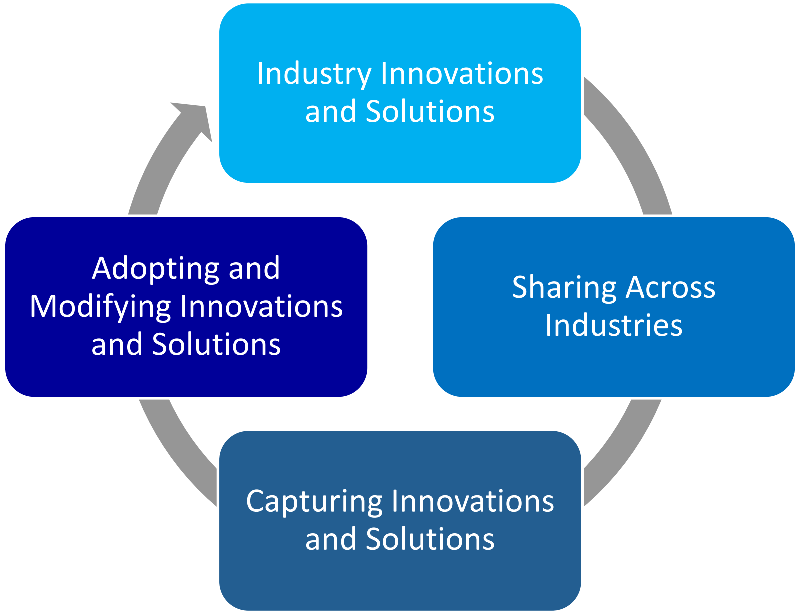
Other industries are addressing supply chain through several approaches such as increased use of academia, advanced manufacturing, use of non-metallic materials, increased capital expenditures on large manufacturing capabilities, and using innovative quality management systems. These are detailed below:

- Engagement with universities offers unique benefits such as researching potential innovation strategies on a smaller scale, potential workforce hiring through engagement with students, and greater understanding of industry challenges and issues. Universities can leverage government and other research dollars to help address specific industry challenges
- Advanced and additive manufacturing is being used in many areas such as oil & gas, defense, energy, etc. Many of these industries have worked through the qualification of advanced/additively manufactured components. Some of the qualification approaches may translate directly to advanced energy systems and corresponding Codes
- Some strains on the supply chain for metallic piping could be relieved through greater adoption of non-metallics such as high density polyethene (HDPE) piping. Non-metallic materials might offer the benefits of reallocating skilled labor (i.e., welders) for joining metallics, faster installation, and in some applications offer superior corrosion resistance compared to traditional metallic materials
- Some organizations are increasing and expanding capabilities such as welding and machining gantry systems and positioners for large fabrication of heavy components for new advanced energy systems but also replacements. Capital expenditures for this equipment is now intended to increase production for replacement components while achieving capacity for new AES in the future
- Flexible quality management systems (QMS) can be adopted that facilitate competing in many simultaneous industries. However, organizations that successfully implement flexible QMS have developed a culture where quality is ingrained in its people. This approach can help with keeping a diverse manufacturing portfolio while advanced energy system demand begins to be realized

Potential Actions

Much can be learned from other industries and their approaches to solving some of the supply chain issues. In many instances, a solution used by one industry will create a hardship to another (e.g., competing for certain materials or manufacturing) and understanding this dynamic and working together to prevent this is important. The following are vital for increased collaboration:

- Continued forums for presenting and sharing ideas, innovations, and lessons learned
- Increased engagement at cross-industry workshops and conferences to continue sharing ideas and solutions for supply chain
- Living document to detail innovative solutions across multiple industries regarding materials, manufacturing, workforce, and quality systems



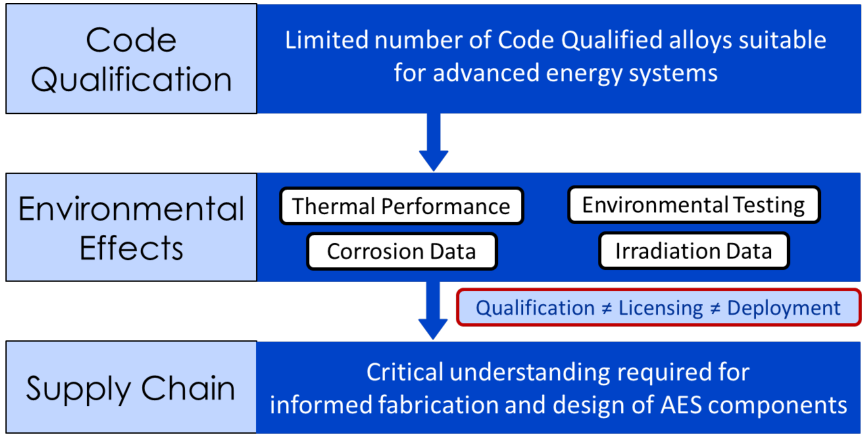
Materials Qualification and Deployment – Deep Dive

New materials for AES must be qualified in Codes & Standards, but also need to be demonstrated in prototypic environments and have an established supply chain. Collaborative approaches are needed as the scope is too large for any one organization to take on.

Session Description & Specific Goals

Advanced energy systems will rely on materials expected to operate at high temperatures and in new environments where there is limited operating experience. While exploratory and developmental work has been conducted across many candidate materials, a number of technical gaps must be overcome to support widespread deployment of these materials in advanced reactors, fusion plants, sCO2 power cycles, and concentrating solar power. Moreover, the research needed to understand material behavior in time-dependent temperature ranges, under irradiation, and in various coolant environments can be too resource intensive for any one organization to address.

This session took a deep dive into the material needs for developers and designers of advanced energy systems. The goal of the session was to identify areas for collaboration and provide examples of previous successes in deployment of new materials. This session also developed potential actions and approaches to not only qualify new materials, but also establish an available and knowledgeable supply chain necessary to enable deployment of advanced energy systems. This is underscored by the **ARRoadmap.com** action items on material data and associated supply chain.



Current State of Industry

Few materials with both a sufficient supply chain and material data exist for deploying novel advanced energy systems. For example, only 6 materials are qualified in ASME Section III Division 5 for high temperature advanced reactors. As shown by the most recent qualification efforts, it can take up to a decade of material testing and $10-20 million dollars to qualify a material, particularly for nuclear applications. However, qualification is only one piece of the deployment. Various developers are working tirelessly to perform testing and capture material performance in prototypic advanced energy system environments. Additionally, the workshop included a large discussion on the need for a coordinated effort from the material and manufacturing supply chain to have confidence in deployment of new materials in new environments that will perform safely and reliably.

Some of the ongoing efforts across industry include:

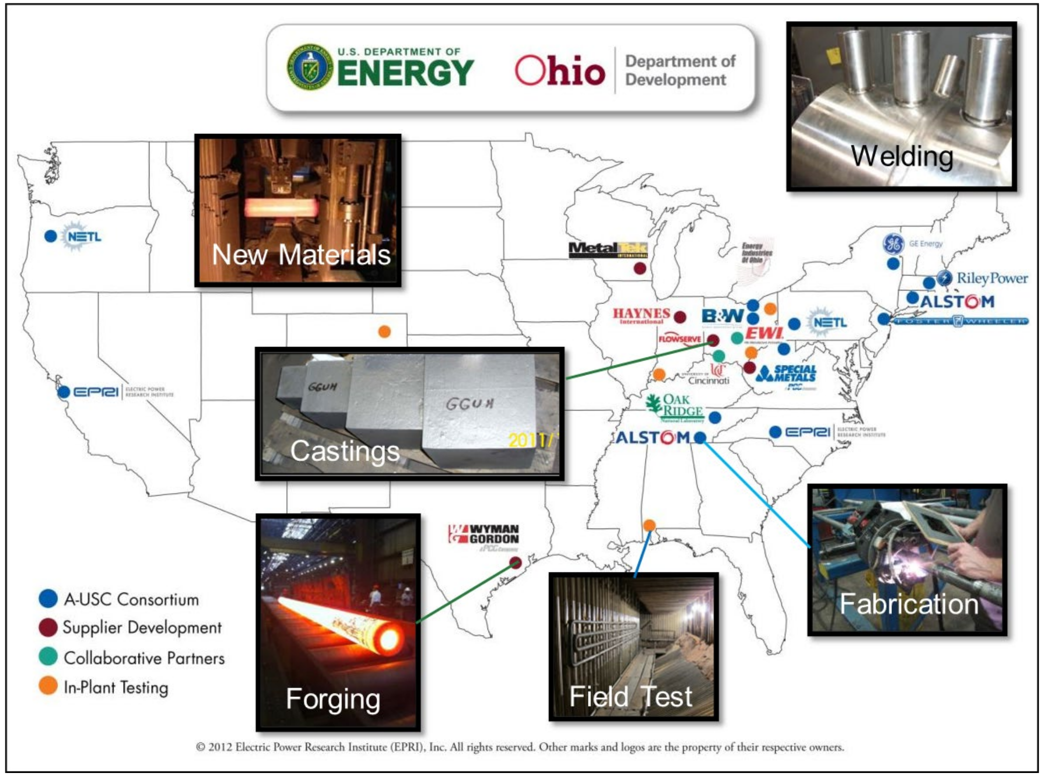
- ASME Section III Division 5 volunteer committees working to address gaps in material data needed for deployment of advanced reactors. The challenge being that most of these efforts are incumbent by individual technology developers or led by publicly funded efforts.
- The US Department of Energy has ongoing workscopes to qualify Alloy 709 in ASME Section III Division 5, which includes some engagement with material suppliers for plate product form. Additional work is needed to develop a supply chain and qualify additional product forms such as heavy wall piping.
- Various studies are being conducted to understand material behavior under prototypic environments across industry including developers, national labs, academia, and other research organizations. These efforts are sometimes quite disparate with limited supply chain engagement.

Materials Qualification and Deployment – Deep Dive

Opportunities: Examples of Previous Successes in Materials Deployment for Energy Applications

The transition to advanced energy systems to meet greenhouse gas emission goals is not the first thrust for new materials in the energy sector. Numerous examples exist as the energy industry sought to increase efficiency by pushing operating limits, deploy new technologies, or demonstrate advanced power cycles. In most instances, significant collaboration and partnerships were required to enable a coordinated approach to not only the material development, but also the establishment of a suitable supply chain ready and able to manufacture the necessary product forms.

One success story presented during the workshop was the *U.S. Department of Energy (US DOE) / Ohio Coal Development Office (OCDO) A-USC Steam Materials Consortia*. The project set out with the goal of developing the materials and manufacturing technology to build and operate an advanced ultra supercritical CO_2 (A-USC) steam boiler & turbine with steam conditions up to 760°C and 35MPa. This federal, state, national laboratory, non-profit, and for-profit cost sharing consortium brought together the entire supply chain from material suppliers to fabricators and end users. The overwhelming success was attributed to the direct engagement by all stakeholders in performing activities necessary to not only qualify nickel super alloys (740H and 282) in Codes and Standards, but also establish a qualified supply chain for A-USC applications.



Potential Actions

Attendees broadly agreed on the need of coordinated approaches to new material development, including a strong interest from material suppliers and fabricators to be engaged early in the process. Following the approach of the successful A-USC consortia, EPRI is launching the *Advanced Reactor Materials Initiative (ARMI)* – A global collaborative focused on developing and deploying new and existing materials for advanced non-light water reactors. ARMI directly addresses several critical focus areas associated with de-risking the use of materials in new advanced reactors:

- Establishing a technical advisory committee to direct and coordinate ARMI priorities.
- Extend operating envelope (temperature and lifetime) for materials already qualified
- Develop required data to add new materials to Codes and Standards (ASME, RCC-M, etc.)
- Generate, compile, and curate environmental data to support reactor design, licensing, and reduce project risk and ensure long-term operation.
- Develop accelerated qualification approaches to de-risk reactor licensing
- Conduct manufacturing and fabrication demos to establish a qualified supply chain

Additional discussion during the workshop included available metrics for quantitative assessments of the existing supply chain. As part of the **ARRoadmap.com**, EPRI is conducting three supply chain assessments to identify challenges for AR deployments

Summary of Workshop III Sessions Day 2

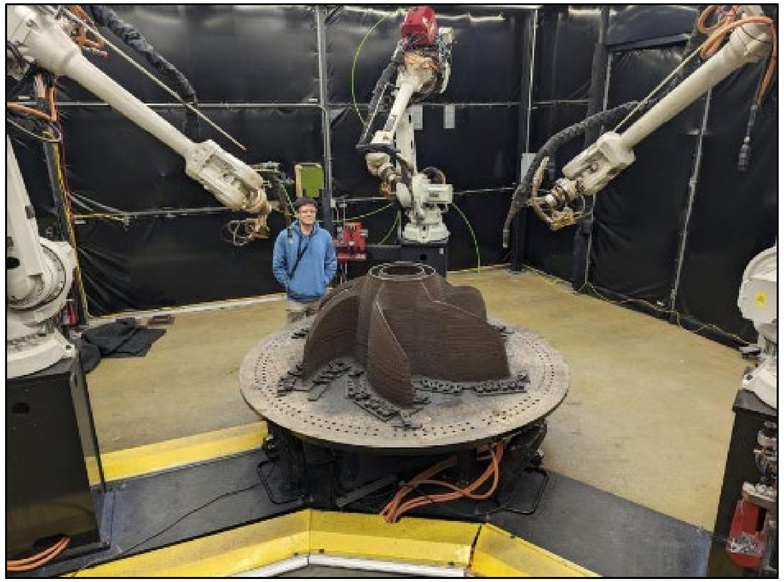
Perspectives on AM for Energy Applications

Although still in its initial stages of adoption, AM is poised to provide a fresh avenue for the production of structural and pressure-retaining components for AES applications. In the foreseeable future, it could potentially enhance or even substitute current manufacturing techniques like forging and casting.

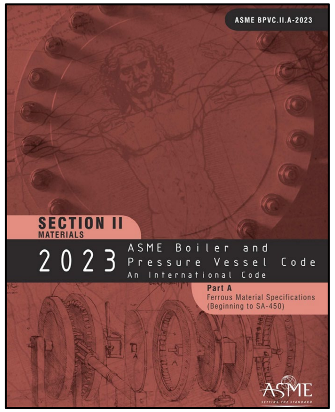
Session Description & Specific Goals

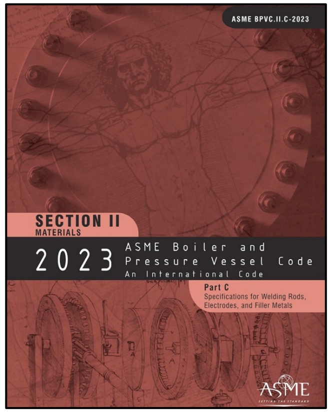
This session aimed to discuss perspectives on AM for use in AES applications from a utility point of view. Discussion specifics included:

- To describe current ASME Codification objectives and progress
- Highlight where utilities/others are looking to utilize AM in both near and long-term
- Describe some of the industry drivers that are forcing utilities/industry to look toward alternative manufacturing approaches such as AM in the supply chain
- Highlight areas where DED-AM is being considered for industry applications



Courtesy of The US Department of Energy and Oak Ridge National Laboratory





Current State of Industry

Only a handful of utilities are beginning to explore AM seriously for energy applications. Other industries such as aerospace and military appear to be slightly ahead of the energy industry in terms of PBF-AM and DED-AM development/applications.

- Only a few multiple robotic applications have been demonstrated to date.

Specific AM applications to date have been relegated to structural applications, but as new Code Cases/Standards are put into place utilities appear to be interested in pressure retaining applications such as: valves, pump housings, nozzles, flanges, etc.

- A few specific applications cited during the presentations in this session include hydro runners, tees/elbows, and valve bodies.

The domestic foundry industry lacks high-tonnage capacity and workforce. AM may offer a viable option to produce large parts that are currently imported in steel product forms.

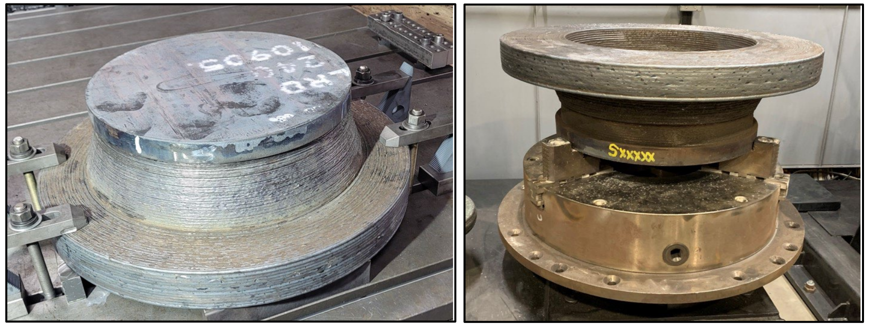
Existing alloy filler metals currently accepted under ASME Section II are being considered for DED-AM build applications due to the excellent experience with these alloys over multiple decades.

Perspectives on AM for Energy Applications

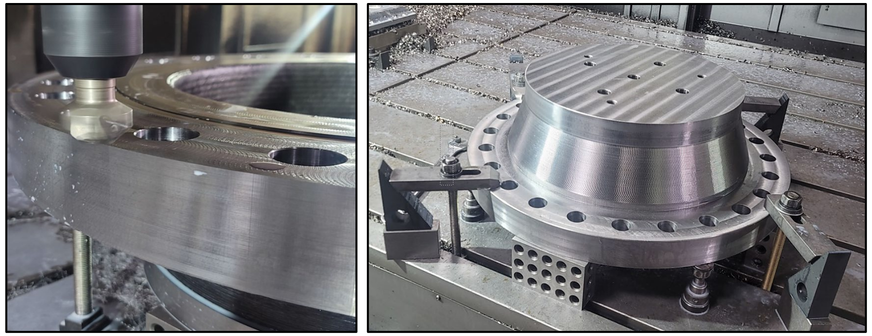
Opportunities

Key opportunities noted during this session include:

- Large scale DED (e.g., Wire Arc Additive Manufacturing (WAAM)) and hybrid DED-AM processes will be used to develop robust domestic supply chains for critical large energy production components
- Key targets of DED-AM in energy applications include:
    - 50% reduction in lead time,
    - 100% domestic production,
    - Reduction in component cost, and
    - Improved performance (e.g., improved flow, thinner wall thickness, etc.)
- Early medium-to-large part applications for the energy industry include hydro runners, tees/elbows, valve bodies, flanges, pump housings, nozzles, etc.
- In-situ inspection methods should be explored in greater detail.
    - Volumetric inspection methods used today require the entire outer surface of a component build to be machined or ground for dye-penetrant (PT) or ultrasonic (UT) examination.
    - Machining and grinding will add considerable expense to the component build and may render DED-AM too costly when compared with forgings or castings.
    - Development and demonstration of in-situ inspection methods could provide an alternative method for volumetric inspection of DED-AM parts/components.
- Coupling of multiple robots together to improve build time and component scale is one avenue that requires additional attention.



Near net shape geometry supplied by the additive manufacturer



Final machining of NPS

Example of DED AM flange construction courtesy of Syncrude Research and presented by GBR Consulting

Potential Actions/Ongoing Activities

- EPRI has kicked off an in-situ inspection project with University of Tennessee, Knoxville (UTK) and Oak Ridge National Laboratory Manufacturing Demonstration Facility (ORNL MDF) to begin exploring alternative inspection practices for DED-AM builds.
- Two Code Cases, one for DED-AM and one for PBF-AM, are currently being addressed within Section III of ASME BPVC. These two Code Cases appear to be paving the way for introduction of AM for pressure retaining components.
- A DOE Advanced Materials & Manufacturing Technologies Office (AMMTO) project has been initiated to build large near-net shaped hydro runners using a multiple robot approach.
- Hybrid build/machine methods are being jointly explored by ORNL MDF and EPRI.

Existing AM User Perspectives

Four organizations from outside the advanced energy system community shared their experiences with additive manufacturing and described how their respective industries are leveraging advanced manufacturing technologies.

Session Description & Specific Goals

This session specifically focused on hearing from organizations that are not from the commercial power generation sector and are actively developing and/or deploying additive parts and technologies. A particular emphasis was placed on large-area additive manufacturing. Potential talking points and questions were provided to session participants to assist with creating presentation materials. Example talking points and questions included:

- Describe the "additive journey" at your organization and what value does additive bring to your supply chain
- Describe qualification and deployment barriers you have experienced and what can industry do to accelerate the development and deployment of additive manufacturing
- Provide application examples, lessons learned, and future plans for additive manufacturing

Current State of Industry

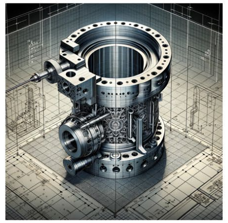
- Large-area additive technologies, particularly DED, have reached commercial maturity and are ready for deployment
    - Steel, stainless steel, and nickel-alloy parts of ~200-8,000kg (500-20,000lbs) are now being printed for many different applications
    - Many participants from the AES community were surprised to see that rapid progress had been made outside the energy industry and commented on the need to re-assess their current timelines for large area DED for new and replacement applications.
- Additive is a complementary technology to casting and forging, not a replacement for conventional methods of manufacturing
- Value drivers for additive compared to casting and forging include lead time reduction, improved quality and performance, design flexibility, and reduced reliance on tooling
- Challenges:
    - Use cases for additive manufacturing include reactive part replacement and proactive development of new parts and materials
    - First applications can be costly, time consuming, and involve an element of iteration – need to build, test, and qualify parts
    - The additive feedstock supply chain is fragile for emergent jobs requiring specialty materials
    - The supplier base for additive parts is fragile as multiple industries are competing for a relatively limited set of capable suppliers

Courtesy of Bechtel Plant Machinery, Inc.

Courtesy of Chevron

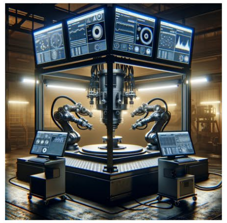
Existing AM User Perspectives

Design



Print

Monitor



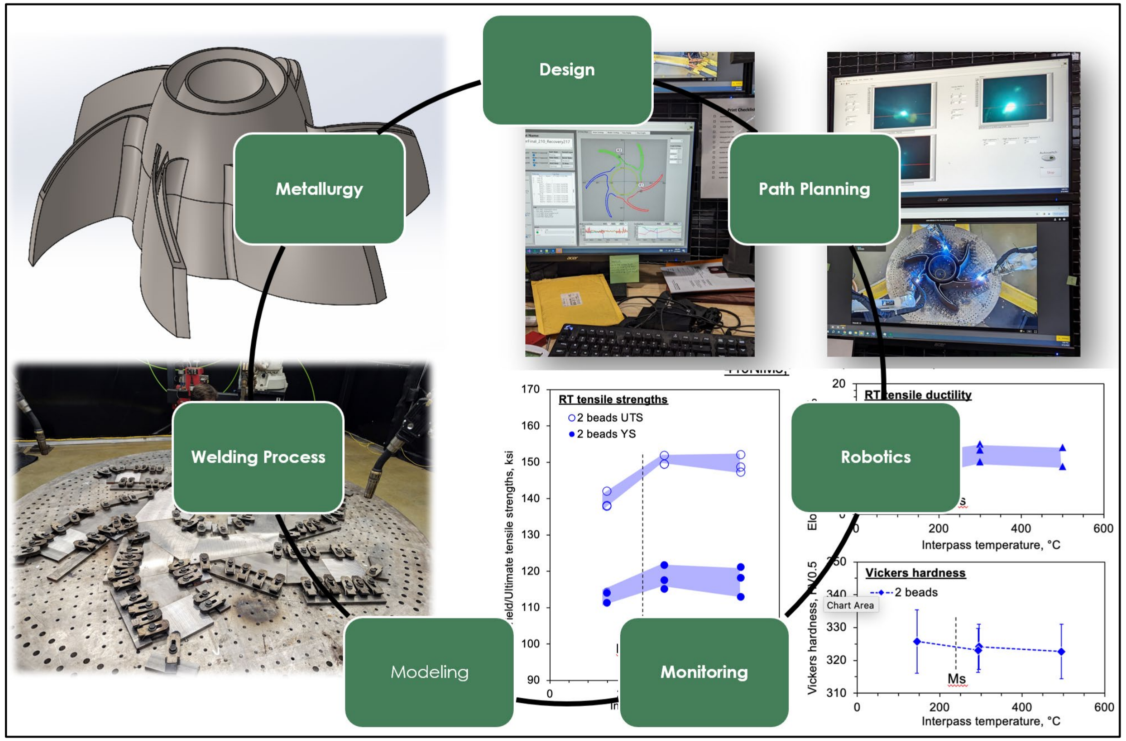
Test

Certify

Courtesy of Oak Ridge National Laboratory

Potential Actions

- Develop and demonstrate in-situ monitoring approaches for large area AM to replace ex-situ nondestructive evaluation and extensive testing
- Identify and coordinate joint industry projects to engage all aspects of the AM supply chain, develop AM material data, and document lessons learned and best practices
- Work with Codes and Standards committees to mature consistent frameworks for AM applications and enable AM supply chain growth



Courtesy of Oak Ridge National Laboratory

Opportunities

- When possible, develop AM capabilities on "low consequence of failure" parts/components to build familiarity and confidence in processes and materials
- Codes and Standards already exist or are under development for AM across multiple industries; additional work is needed within the Codes and Standards space to further develop and improve these frameworks and enable more than one-off applications
- AM users should consider inspection requirements as a portion of the part design process; designs should minimize machining while still being inspectable (i.e., design for inspection)
- Nondestructive evaluation and extensive mechanical testing can be burdensome for AM part qualification and certification; developing in-situ monitoring approaches for defect detection could alleviate some of the burden
- Guidance should be developed to describe when and where AM makes sense compared to conventional manufacturing approaches
- Strategic partnerships amongst end users, researchers, feedstock manufacturers, AM suppliers, and current OEMs are seen as key to mature AM technologies and build an AM supply base

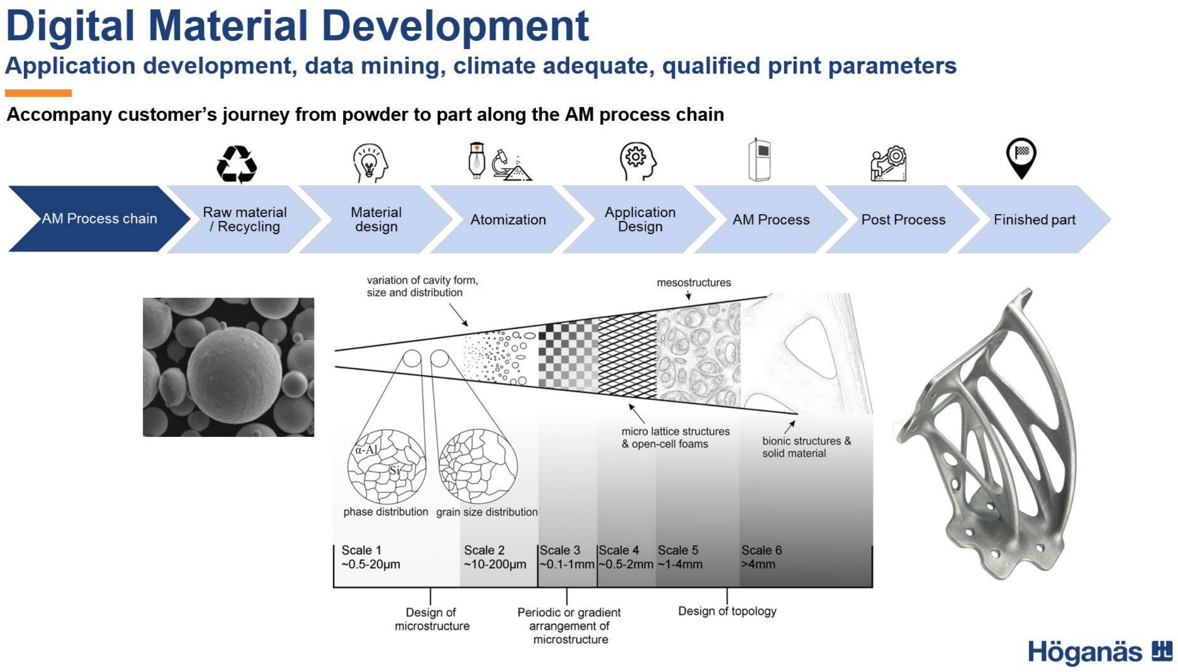
Feedstock Supply Chain for Welding & Manufacturing

Advanced Manufacturing offers an alternative source for AES components. However, the availability of feedstock is crucial not only for these advanced manufacturing processes but also for traditional welding used in plant components.

Session Description & Specific Goals

When describing the current feedstock supply for AES alloys relevant to additive manufacturing or welding, it's important to consider both wire and powder forms. This session specifically focused an evaluation of the supply chain's current state, identifying any existing vulnerabilities and potential future risks. Additionally, the discussion focused on ways to develop strategic actions to mitigate these risks, ensuring a stable and reliable supply of AES alloys for industrial applications in both AM and traditional welding.

Courtesy of ESAB Welding and Cutting



Current State of Industry

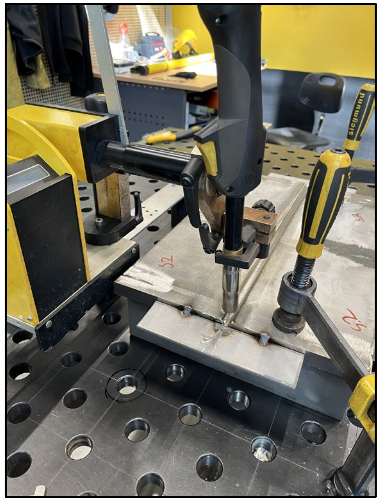
- The status of the supply chain varies significantly depending on the material. Some nickel and stainless-steel alloys applicable to AES are not kept in stock, and are special order only
- Wire quality is not an issue for DED-AM, but the quantity required could be disruptive to the overall wire supply considering how much wire goes into a large component
- Several nickel and stainless-steel alloys were identified as feedstocks with the most fragile supply chain
- Scaling up production for future increased demand is also material specific, and potential challenges would be production capacity, raw material supply quality and quantity
- Low volume and custom materials are a weak point with poor availability regardless of material type

Feedstock Supply Chain for Welding & Manufacturing

Opportunities

There is still not enough demand to generate interest in strengthening the feedstock supply chain. A single supplier can not drive the change needed, collaborative groups and government involvement will be necessary. Ways to accomplish this include:

- Securing a steady feedstock supply will necessitate cooperation between AES developers and the entire supply chain
- Considering what moves the supply chain towards being flexible, agile and reliable instead of driving towards the lowest cost
- Promoting collaboration from material suppliers all the way through to end users, at every step of the supply chain to ensure all stakeholders have input



Courtesy of ESAB Welding and Cutting

Courtesy of MTC Powder Solutions

Potential Actions

- Promote industry groups and government programs to strengthen feedstock supply chain
- Encourage clear and early communication with suppliers to understand the AES needs
- Some suppliers are looking at increasing production capacity to meet increasing demand
- Work more closely with OEMs and the customers in order to create better transparency in working relationships which will ultimately support industry growth.
- Material qualifications are key to expanding the AM market

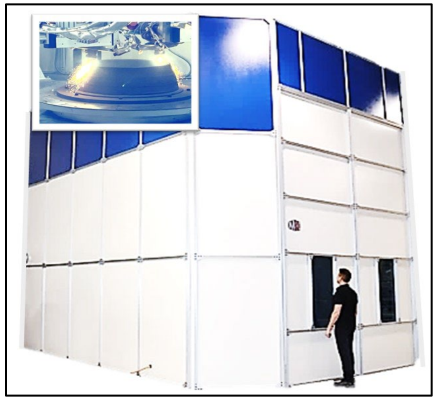
AM Suppliers and Developers

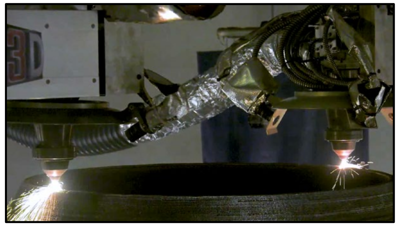
Seven organizations that provide contract AM services and develop systems for AM applications discussed the status of the AM industry and highlighted areas where advanced energy system stakeholders could leverage the benefits of AM technologies.

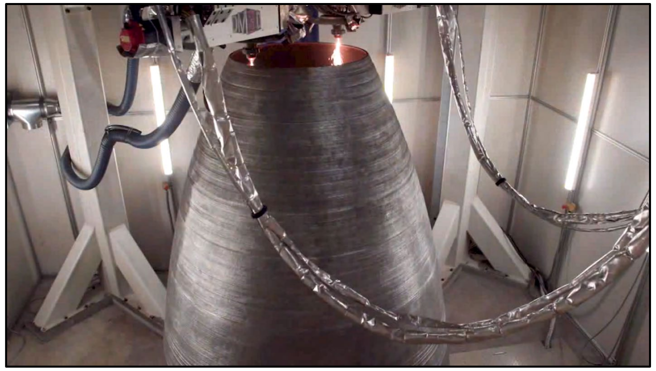
Session Description & Specific Goals

The session specifically addressed the market of large-area AM of metallic parts. Session participants were asked to briefly introduce their organization and discuss the following topics as they relate to their market segment and areas of expertise:

- Large-area AM technology descriptions and trends in the industry
- Build size, production capacity, and lead time limitations
- Maturity of AM materials that are relevant to advanced energy systems
- Opportunities for AES supply chain engagement
- Risks and risk mitigation for AM applications







Courtesy of DM3D Technology

Courtesy of AML3D

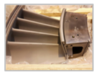
Current State of Industry

- Large-area AM (particularly DED) has reached commercial maturity and is actively being developed and used by other industries
- DED print cell sizes have increased considerably to accommodate individual parts that are on the order of 1000s of pounds with working dimensions of 5-10 feet
- Lead times for printed AM parts can range from same day builds to 10s of weeks depending on feedstock supply, machine availability, and part size/complexity
- Early supplier interaction and design flexibility is essential to work through project requirements and mitigate risks
- Today, only a few materials that are relevant to AES applications are routinely printed commercially
- Limiting factors for new alloys include feedstock availability, development and qualification costs, and maturity of the market
- Codes and Standards approvals are needed for suppliers to understand what will be accepted and drive consistency across industry
- Other factors currently hampering AM adoption include the lack of available mechanical property data of printed materials, general customer awareness, and risk averseness

AM Suppliers and Developers

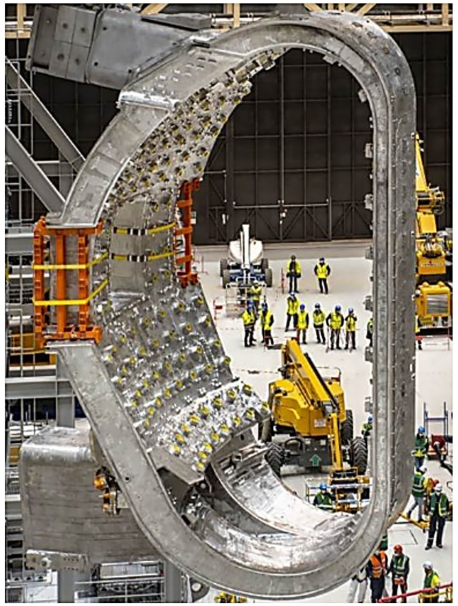
Opportunities

- Joint industry development, qualification, and demonstration efforts should initially focus on high value and/or low risk applications for relevant materials and parts
- Modeling and simulation can be used to decrease the reliance on iterative AM part development. Thermal, residual stress, and distortion modeling tools should be matured and leveraged to assist with scaling for large and/or complex parts
- Advancements in process controls and in-situ process monitoring approaches are needed to manage heat input and quickly identify print abnormalities or defects
- High quality mechanical property data sets for AM materials are often incomplete or not accessible, especially at elevated temperatures. AM mechanical property data sets are needed to assist with material and process selection, part design, and the development of AM Codes and Standards
- Engaging and educating the AES supply chain and designer communities on the capabilities, benefits, and nuances of AM compared to conventional methods of manufacturing is critical for the adoption of AM technologies

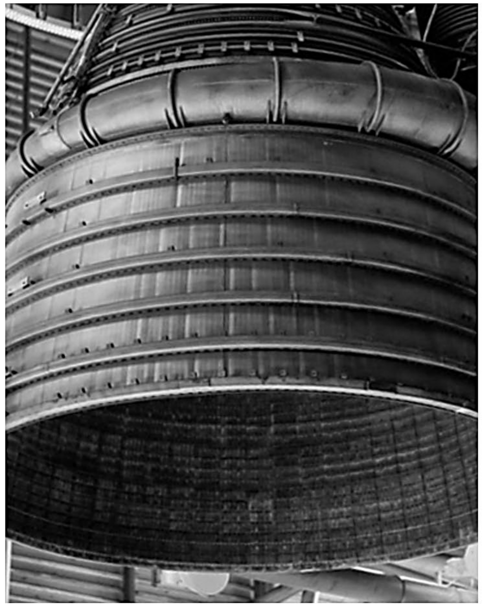
Value Lever	Reduce Lead Time	Reduce Material Waste	Reduce Tooling / Fabric. Cost	Simplify Joining	Enhance Performance
Use Case	Large & imported castings Repair parts Functional prototypes	High chip removal Low yield components Unneeded material massing	Large or complex tools Complex casting molds & cores	Tubular connections Multiple joints or weldments Modularized, in-the-field joining	Light-weighted components Shape modifications Material switch
Example					

Opportunities matching more than one use case are an exceptional fit for WAAM

Courtesy of Lincoln Electric Additive Solutions



Nuclear fusion vacuum vessel of ITER tokamak



Regenerative cooling in Saturn V rocket nozzle - Complex arrangement of cooling channels

Courtesy of Fortius Metals Inc.

Potential Actions

- Develop AM training resources (e.g., industry whitepapers, handbooks, best practices documents) for advanced energy system stakeholders
- Identify high value applications and coordinate joint industry projects to enable model development/validation and generate mechanical property for data AM parts
- Create an AM material property database and support Codes and Standards development for AM technologies

Additional Information

Collaboration Discussion

Overview & Key Points

Over the course of the two-day workshop, Slido was used to facilitate group poll discussions on various supply chain topics. Here are some of the key points highlighted during these discussions:

- The most significant gaps in the U.S. nuclear supply chain appear to be in the fabrication stage
- Several factors have been identified that could potentially be preventing orders from going to U.S. suppliers, including:
    - Capability
    - Quality
    - Cost
    - Schedule/throughput
- Capability gaps that have been noted include:
    - Size limitations
    - Weight and handling
    - Procedural gaps
    - Qualifications
- There do not seem to be enough ASME N-Stamp holders in the domestic U.S. to address fabrication needs and foster competitive pricing. Some of the barriers for companies trying to obtain the appropriate ASME N-Stamp include cost, demand, and commitment of orders placed.

Future Workshop Topics

- Castings and forgings
- Governmental programs/projects
- Heat exchangers
- Expand to included Carbon Capture & Storage (CCS), geothermal, and other current industries working on the same supply chain challenges
- Status of test loops and pilot demonstrations

Collaboration Discussion: Word-Clouds New Nuclear

Safety-Related Program Barriers

Demand/Business Case

QA Program Expertise

Commitment

Workforce Resources

Cost

Culture

Code Knowledge

Requirements

Key Items Holding Back U.S. Deployment of New Nuclear

Design Consolidation

Inconsistent Govt. Budget

Workforce Resources

Commitment/Orders

Cost

Public Perception & Overall Confidence in the Technology

NRC Design Approval

Collaboration Discussion: Word-Clouds U.S Suppliers

Hardest to Source Parts/Components

Steam Generators

Nickel-Based Parts/Components

Castings

Tubing

Heavy Sections/Components

Large Pressure Envelopes

Fabrication Demonstrations to Establish Confidence

Round Robin Demos

Convergent Manufacturing

High Temperature Materials

Complete PB Scope

Inspection Demos

Full Scale Demos

Demos Under QA

Rapid EB Welding & Robot Welding

NRC Design Approval

Collaboration Discussion: Company Engagement and Future Readiness

- Besides a large number of orders and the initial commitment, what else is needed for companies to stay engaged and be ready for the future?

Engagement in Design

Customer Engagement

Long Term Commitments & Continuing Investments

Honest Timelines & Realistic Forecasts

Code Cases

Money/Funding

Collaboration and Consistent Communication

Large Scale Demonstrations

Practical Business Cases

Insurance on Investment

Funded Studies

SUPPLY CHAIN REPRESENTATION AT WORKSHOP

- 3D Systems
- 6k Additive, LLC
- AML3D USA, Inc.
- ANSER
- Bechtel Plant Machinery Incorporated
- Chevron USA, Inc.
- Clean Energy Supplier Alliance
- Commonwealth Fusion Systems
- DM3D Technology
- Dominion Engineering, Inc.
- DuBose National Energy Services, Inc.
- ESAB Welding & Cutting Products
- Flowserve Corp.
- Fortius Metals, Inc.
- Framatome SAS
- Framatome, Inc.
- GBR Consulting
- GE Hitachi Nuclear Energy Americas, LLC
- General Public Access
- Haynes International, Inc.
- Hayward Tyler, Inc.
- IHI Americas Inc.
- Kiewit Engineering Group Inc.
- Lehigh Heavy Forge Corporation
- Lewis Reliability Resources
- Lincoln Electric Co.
- MELD Manufacturing
- MPR Associates, Inc.
- MTC POWDER SOLUTIONS
- New Brunswick Power Corp.
- Newport News Shipbuilding
- Niagara Energy Products, Inc.
- North American Forgemasters Company
- North American Hoganas, Inc.
- Nuclear Energy Institute
- NuSource, LLC
- Oak Ridge National Laboratory
- Ohio State University
- Organization of Canadian Nuclear Industries
- Precision Custom Components
- Quintus Technologies
- Riley Power Group, LLC
- R-V Industries, Inc.
- Scot Forge Co.
- Shell Global Solutions (US) Inc.
- Southern Company
- Southern Company Services, Inc.
- Special Metals Corporation
- Stress Engineering Services, Inc.
- Tennessee Valley Authority (TVA)
- TerraPower
- The Dow Chemical Company
- Turner Industries Group, LLC
- University of Tennessee
- Velan, Inc.
- Zap Energy Inc.

Acknowledgements

This product was developed by EPRI.

Principal Investigators

N. Harless

J. Shingledecker

D. Gandy

M. Albert

B. Sutton

N. Mohr

S. Tate

This workshop summary document would not have been possible without the robust participation of key stakeholders across the industry. EPRI is indebted to those organizations that took their time to attend the workshop. In particular EPRI acknowledges the key contributions from all the presenting organizations, which set the stage for robust discussion sessions. Special thanks to Robin Bedilion for their review and helpful comments on the report.

This report describes research sponsored by EPRI. This publication is a corporate document that should be cited in the literature in the following manner:

EPRI Supply Chain Workshop III for Structural Components in Advanced Energy Systems. EPRI, Palo Alto, CA: 2024. 3002029870.

Disclaimer of Warranties and Limitation of Liabilities

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

EPRI PREPARED THIS REPORT.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA

800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com