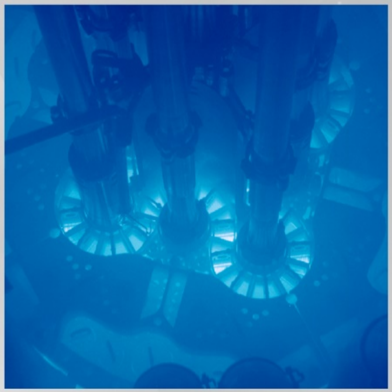
U.S. DEPARTMENT OF
ENERGY

Office of ENERGY EFFICIENCY
& RENEWABLE ENERGY

Materials for Harsh Environments



2020 Virtual Workshop Summary Report

October 27-30, 2020

Disclaimer

Foreword

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's (EERE's) Advanced Manufacturing Office (AMO) partners with industry, small businesses, universities, and other stakeholders to catalyze research, development, and adoption of energy-related advanced manufacturing technologies and practices to drive U.S. economic competitiveness and energy productivity.

The DOE Office of Fossil Energy's (FE's) mission is to discover and develop advanced fossil energy technologies to ensure American energy dominance, create American jobs, support a resilient infrastructure, maintain environmental stewardship, and enhance America's economy. FE ensures America's access to and use of safe, secure, reliable, and affordable fossil energy resources and strategic reserves.

The DOE Office of Nuclear Energy (NE) has a mission to advance nuclear power to meet the nation's energy, environmental, and national security needs. Within NE, the Advanced Methods of Manufacturing program goal is to accelerate innovations to reduce cost and schedule for new nuclear plant construction and to make fabrication of nuclear power plant components faster, less expensive, and more reliable.

Authors

This document was prepared as a collaborative effort between DOE AMO, DOE FE, DOE NE, and Idaho National Laboratory (INL). This report was authored by Robert Fox (INL), J. Nick Lalena (AMO), and Seth W. Snyder (INL).

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List of Acronyms

ºC	Celsius (degrees)
AI	Artificial Intelligence
AM	Additive Manufacturing
AMO	Advanced Manufacturing Office
AUSC	Advanced Ultra-Supercritical
Btu	British Thermal Unit(s)
C2P	Coal-to-Product
CMC	Ceramic Matrix Composites
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSP	Concentrated Solar Power
DOE	U.S. Department of Energy
EBC	Environmental Barrier Coating
EERE	Office of Energy Efficiency and Renewable Energy
EPRI	Electric Power Research Institute
FE	Office of Fossil Energy
Fe	Iron
GWe	Gigawatt(s) Electric
H_2	Hydrogen
ICME	Integrated Computational Materials Engineering
M4HSC	Materials for Harsh Service Conditions
ModSim	Modeling and Simulation
NACE	National Association of Corrosion Engineers
NE	Office of Nuclear Energy
Ni	Nickel
R&D	Research and Development
SBIR	Small Business Innovation Research
sCO_2	Super-Critical Carbon Dioxide

SiC	Silicon Carbide
STTR	Small Business Technology Transfer
TBC	Thermal Barrier Coating
TBtu	Trillion British Thermal Unit(s)
TRL	Technology Readiness Level

Executive Summary

This report identifies seven high-priority, crosscutting research directions for energy-producing and energy-intensive industries in which harsh service environments are experienced. Electrical power-generating technologies that could benefit include nuclear, renewable (e.g., wind, solar thermal, geothermal, and hydro), and combustion processes (e.g., hydrogen, natural gas, biomass, and coal). Investment in these research areas could drive deployment of new materials and manufacturing innovations that would, in turn, enable widespread implementation of advanced materials into the energy production and manufacturing sectors, leading to step-changes in materials systems' performance and manufacturing efficiency. Those technological step-change advancements would stimulate and reinvigorate domestic manufacturing, improve U.S. manufacturing competitiveness, markedly improve energy efficiency in targeted energy-intensive manufacturing processes, and enable practice of technologies that reduce the carbon footprint across a broad swath of manufacturing and electricity production supply chains.

The 2020 Materials for Harsh Service Conditions (M4HSC) Workshop was coordinated by three different U.S. Department of Energy (DOE) Offices: the Advanced Manufacturing Office (AMO), the Office of Fossil Energy (FE), and the Office of Nuclear Energy (NE). The event was held virtually October 27–30, 2020. The workshop brought together stakeholders from academia, industry, national laboratories, and DOE offices to identify the opportunities (paths for obtaining desirable goals), challenges (actionable tasks taken up along these paths), barriers (obstacles impeding advancement along the paths), and research and development (R&D) needs for enabling development of technology readiness level (TRL) 3–6 materials and materials systems, as well as their advancement into widespread commercial application. The purpose of the workshop was to identify data gaps, R&D needs, technology challenges, and fabrication

- **More Data:** Data-driven materials/system testing approaches that lead to more accurate prediction of materials behavior and materials properties under harsh service conditions at relevant timescales
- **Accelerated Testing and Qualification:** Reduced time to market for improved materials systems through accelerated testing and qualification
- **Improved Manufacturing Methods:** Methods and capabilities that are advanced, adaptable, agile, smart, and more efficient
- **Greater Understanding:** Improved understanding of advanced manufacturing process fundamentals, control parameters, and subsequent effects on materials properties
- **Smart:** Improved in situ process monitoring technologies, including sensors, modules, and packaging that can be embedded inside furnaces, downhole wells, reactors, and other extreme environments to provide valuable real-time data for utilization in process monitoring and control
- **Access:** Access to capabilities through publicly available facilities
- **Improved Materials:** Improvements in material performance for essentially every harsh service condition in which either power generation or energy-intensive processes are employed

Figure ES-1. Priority research directions in M4HSC methodologies for practical commercial deployment into harsh service environments in energy-producing or energy-intensive industries. The higher-level objectives of the workshop were to identify high-value, crosscutting research opportunities of interest to DOE stakeholders, and to determine intersecting R&D needs that constitute the highest-potential R&D portfolio investment opportunities. The virtual conferencing platform used was versatile and allowed both plenary session speakers and technical breakout session participants—including academic leaders in the field and high-level representatives from industry and the national laboratories—to engage in discussion, brainstorming, and networking.

On October 27 and 28, a series of plenary presentations provided workshop attendees with an overview of M4HSC needs relevant to the interests of DOE AMO, FE, and NE as those interests relate to harsh service conditions experienced in either energy production technologies or energy-intensive commercial industrial manufacturing processes. Topics covered during the plenary sessions included challenges faced while generating electrical power from combustion (e.g., hydrogen, natural gas, coal, and biomass), nuclear, or renewables (e.g., solar thermal, geothermal, wind, and hydro), and materials needs for various turbines to improve efficiency by going to higher operating temperatures, and when transitioning from one fuel form to another. Carbon management and utilization of carbon derived from combustion was discussed, and innovative routes for carbon capture and utilization to form graphite and advanced thermally tolerant materials for harsh service conditions were presented. Materials needs for nuclear microreactors and harsh service conditions experienced during electrical power generation from nuclear plants was highlighted, as was the need for advanced materials in space nuclear propulsion systems and advanced next-generation nuclear reactor designs. DOE program management staff from the Office of Energy Efficiency and Renewable Energy (EERE) informed workshop attendees about materials challenges and barriers involved in power generation from concentrated solar thermal plants, wind energy resources, geothermal resources, and hydrogen fuel cells. Speakers from DOE AMO and U.S. industry brought the plenary session to completion through discussion of the potential impacts brought about by step-change technological improvements, as well as discussion of the materials R&D needs for energy-intensive, harsh-environment applications found in the steelmaking, chemical manufacturing, high-performance materials, and power generation industries. Some of the more significant impacts are given below.

Potential Impacts of Step-Change Improvements in Materials for Harsh Service Conditions

- **Development of High-Performance Carbon-Base Products:** Developing new manufacturing technologies that give rise to potentially attractive sources for high-performance, value-added materials used in advanced materials having wide applicability across energy-generation and energy-intensive processes
- **Higher-Efficiency Turbines for Electric Power Generation:** Achieving higher plant efficiency in the combustion power generation sector

- **Advancement of Hydrogen and Low-Carbon Fuel Turbines:** Enabling and widely deploying next-generation, low-carbon combustion fuel sources for efficient power generation
- **Improved Materials Having Multiple Materials Property Requirements:** Realizing higher reliability factors, longer service life, and lower component/system lifecycle costs
- **More Efficient and Safer Nuclear Power Plants:** Enabling nuclear microreactors, improving safe operation, providing higher reliability factors, lowering plant costs, and yielding longer service lifecycles
- **Improved Corrosion Resistance:** Reducing the number of accidents and the costs of accidents/injuries resulting from corrosion-induced failure in critical infrastructure such as gas pipelines
- **More Efficient Process Heating:** Reducing heat loss, improving efficiency, and reducing costs of system maintenance and repair.
- **Advanced Sensors and Better Process Diagnostics:** Improving process diagnostics, developing improved modeling and simulation (ModSim) tools, and enabling sustained/reliable operation of materials and systems under harsh service conditions
- **More Resilient Systems Capable of Withstanding Shocks and High Load:** Reducing abrasive or contact friction and wear losses, reducing maintenance/repair costs to make processes more efficient and less costly, and increasing time online
- **Enabling Renewable Energy Resources:** Enabling a greater degree of sustainability and efficiency for wind, solar, geothermal, hydroelectric, and other low-carbon renewable energy sources
- **Materials Testing and Qualification:** Reducing material time to market, reducing verification/validation testing time, reducing material deployment costs, and bringing about more rapid deployment of step-changes in technology
- **Improved Advanced Manufacturing Methods:** Enabling the fabrication of components for less cost, or in forms or geometries, and having materials properties that would be very difficult or impossible to achieve with traditional manufacturing methods

This document provides an overview of the motivation for convening the 2020 M4HSC Workshop, the impact that improved materials and advanced manufacturing methods can have on U.S. industry competitiveness, the recurring high-impact R&D needs coming out of the workshop, an overview of workshop logistics, and a summary of data arising from comments/discussions that occurred during dialog and brainstorming in the technical breakout sessions held October 29 and 30. Of specific note are the highlighted topics identified during the workshop as high-impact, priority, crosscutting research needs.

Information, data, and feedback generated at this workshop is expected to provide DOE sponsoring offices with guidance for upcoming R&D investment opportunities in the M4HSC area and direction for future M4HSC programmatic decisions. The R&D investments could prove critical to maintaining robust, resilient, low-carbon domestic manufacturing.

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1 Motivation

Nuclear reactors and other advanced electrical energy-generating technologies require materials for harsh service conditions (M4HSC). Operation under harsh service conditions includes extremes, rapid fluctuations in extremes, and often exposure to combinations of extreme temperatures, pressures, mechanical wear/stress/strain/shock, chemicals and corrosive media (liquids and gases, including hydrogen), particulate loads, or radiation. Materials for such environments must be able to maintain structural integrity and functional performance under extreme conditions in which duty cycles are high, time online can extend from thousands of hours to 100,000+ hours, and the need for safe and economic operation demands that materials and systems have a high reliability factor.

Developing and manufacturing M4HSC is a grand challenge in which incremental improvements in material performance and/or fabrication efficiency can provide a unique competitive advantage to U.S. industry, while step-changes in technology can result in achieving massive increases in performance and function such that the impacts are far-reaching, technologically transformative, and market-disruptive. Although advanced materials can be used in conventional manufacturing processes to achieve incremental advances, advanced manufacturing processes are being developed and employed that not only achieve more efficient operation, but also give rise to materials properties that are unachievable using conventional manufacturing methods. The U.S. Administration launched the Harsh Environment Material Initiative in 2020 to address these competitive opportunities and to invest in step-changing technologies through development of both advanced materials and advanced manufacturing methods.

October 27–30, 2020, the Department of Energy’s (DOE’s) Advanced Manufacturing Office (AMO), Office of Fossil Energy (FE), and Office of Nuclear Energy (NE) held a virtual workshop focused on M4HSC to gather input from stakeholders concerning:

1) The general vision of future research opportunities, and the technical challenges and barriers associated with deployment and scale-up of advanced materials and manufacturing processes

2) Identifying the high-impact, crosscutting research and development (R&D) needs that can achieve step-change improvements in system performance for a) thermoelectrical energy production systems and b) energy-intensive manufacturing technologies where harsh service conditions exist

3) Identifying where synergies exist and where R&D needs overlap between the three DOE program offices in order to make informed R&D investment decisions that advance materials and manufacturing capabilities resulting in step-change improvements in materials and technologies benefiting thermoelectric power production and energy-intensive manufacturing processes needing M4HSC.

The motivation for conducting the 2020 M4HSC Workshop was to identify and define critical crosscutting challenges whose solutions represent near- to mid-term (~3–5 years) commercially viable paths for obtaining step-change improvements in materials and manufacturing capabilities. Those step-change improvements in technology will result in improved materials systems that, when deployed under harsh service conditions, will result in improved system performance that is significantly above the state of the art.

In August 2020 (prior to the 2020 M4HSC workshop), AMO published a request for information that garnered responses from 46 organizations. This feedback was used to inform the M4HSC workshop plenary and breakout session topic selections, culminating in descriptions of a broad array of M4HSC conditions and materials challenges spanning AMO, FE, NE, and EERE technology areas related to power production and energy-intensive manufacturing processes. In the final stage of the workshop, six technical breakout sessions were convened to identify high-value, crosscutting areas in which a concerted effort in R&D investment could help overcome major material and processing technology challenges impeding step-change advancement.

2 Potential Impacts of Improved Materials for Harsh Service Conditions

It is widely recognized that many energy-producing and energy-intensive technologies involve exposure of process equipment to harsh conditions of some type (and often multiple types simultaneously) while in operation. Examples include combustion chambers, gas turbines, steam turbines, wind turbines, furnaces, heat recovery systems, nuclear reactors, transportation, mining, and oil and gas drilling equipment (on-shore and off-shore), as well as agricultural, steel production, primary metals, pulp and paper, and chemical/refining processes. Harsh environments, as previously defined, can impede device operation and shorten a material component's useful lifetime. These aggressive environments—and the associated materials durability challenges—are common across multiple applications and sectors. New materials and materials manufacturing solutions are needed to meet stringent application demands for future products that will provide energy savings, reduce carbon emissions, and increase the competitive advantage of U.S. industries.

During the workshop, plenary speakers illustrated the impacts that advancing selected technologies can have on various energy production and energy-intensive applications. Some of these presenters were invited to the workshop to expand on their earlier responses to AMO's request for information. These plenary topics are listed in Figure 2 and summarized below.

- **High-performance carbon-based products.** Potentially attractive sources for high-performance, value-added carbon-based materials (e.g., graphite, carbon fiber, etc.) with unique high-temperature mechanical properties including CO_2-precursor (captured CO_2) pathways (Quance and Smith 2020), upcycling waste plastics (DOE 2021), and coal-to-product (C2P) carbonization and graphitization technologies (Atkins 2020). Coal may also be used as a source of syngas ($CO + H_2$), hydrogen (after separation from syngas), chemicals (e.g., methanol), rare earth elements, and critical minerals, all of which have energy-related uses. DOE recently announced the intent to fund establishment of several coal product innovation centers that will research and incubate environmentally sustainable coal processing paths to such products (DOE 2020).

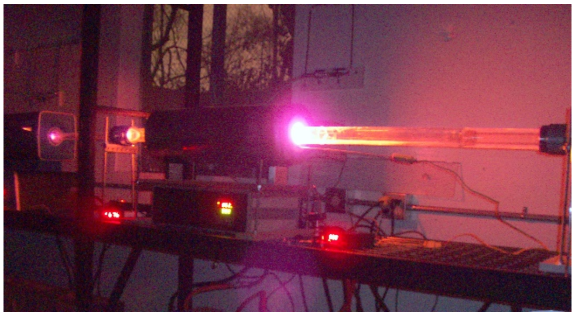

Figure 1. Graphitic materials from CO_2

Photo courtesy of Seerstone Development LLC

- **Higher-efficiency turbines for electric power generation**. U.S. retail electricity sales (net imports minus exports) to end-use customers totaled about 3,750 billion kWh—or 3.7 trillion kWh—in 2019 (U.S. Energy Information Administration 2020), equating to a value of hundreds of trillions of dollars. Gas, steam, and combined-cycle turbine power

- **Development of High-Performance Carbon-Base Products:** Developing new manufacturing technologies that give rise to potentially attractive sources for high-performance, value-added materials used in advanced materials having wide applicability across energy-generation and energy-intensive processes
- **Higher-Efficiency Turbines for Electric Power Generation:** Achieving higher plant efficiency in the combustion power generation sector
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- **More Resilient Systems Capable of Withstanding Shocks and High Load:** Reducing abrasive or contact friction and wear losses, reducing maintenance/repair costs to make processes more efficient and less costly, and increasing time online
- **Enabling Renewable Energy Resources:** Enabling a greater degree of sustainability and efficiency for wind, solar, geothermal, hydroelectric, and other low-carbon renewable energy sources
- **Materials Testing and Qualification:** Reducing material time to market, reducing verification/validation testing time, reducing material deployment costs, and bringing about more rapid deployment of step-changes in technology
- **Improved Advanced Manufacturing Methods:** Enabling the fabrication of components for less cost, or in forms or geometries, and having materials properties that would be very difficult or impossible to achieve with traditional manufacturing methods

Figure 2. Potential impacts of step-change improvements in M4HSC

plants in the U.S. electric power sector collectively generate about 1,800 billion kWh of electricity annually, comprising about 46% of the country's total electricity production (DOE 2015). Natural gas and steam turbine power plants could achieve higher efficiencies if they operated at higher turbine inlet temperatures. Current advanced stationary gas turbine inlet temperatures are in the 1300°C–1500°C range (~50% to ~55% combined-cycle plant efficiency), with the primary limitations arising from the mechanical properties of Ni-superalloy substrate materials at temperatures above 1400°C. Further increases in natural gas turbine inlet temperature beyond 1400°C, into the 1700°C–1800°C range where combined-cycle plant efficiency of >65% could be achieved, will require turbine materials with superior mechanical properties (e.g., creep resistance and fatigue strength), high-temperature oxidation and corrosion resistance, and higher melting points. Such requirements limit further advancements in the operating temperatures and efficiencies of gas turbines using metallic turbine materials. For this reason, ceramic matrix composites (CMCs) for this application have been under development over a number of years. With fuel costs accounting for up to four-fifths of total running costs for gas turbines, even a small increase in efficiency amounts to a large cost savings. Achieving a 1% increase in combined-cycle plant efficiency for a single gas turbine is expected to produce a fuel savings of $50 million over ten years (Forbes 2018).

- **Hydrogen and low-carbon fuel turbines**. Hydrogen is the low-carbon fuel of the future. For instance, using a 5% blend of hydrogen in the natural gas supply to a General Electric F-type gas turbine reduces its annual CO_2 emissions by nearly 19,000 metric tons. A 50% blend saves 281,000 tons, while a 95% blend cuts CO_2 emissions by more than one million metric tons (Noon 2019). It is expected that gas turbines will eventually evolve to be powered by 100% hydrogen and other green/low-carbon fuels. Many of the materials used in natural gas turbine engines are applicable for syngas and hydrogen-powered turbines. Nonetheless, the need to develop materials and barrier coatings with maximal durability in the environments of these combustion system technologies will require continued R&D investment, as will the materials requirements of other low-carbon energy technologies.
- **Improved materials having multiple materials property requirements.** In addition to adequate creep strength, resistance to weld failures (stress relief, stress relaxation, and strain age cracking), low thermal expansion, and high thermal conductivity, materials used in gas, steam, and super-critical carbon dioxide (sCO_2) turbine systems must also have excellent oxidation and chemical corrosion resistance in their respective service environments. The impacts of improved materials having multiple materials property requirements equate to higher reliability factors, longer service lives, and lower component/system lifecycle costs.
- **Improved materials for electricity generation using nuclear power.** In the nuclear power industry, a similar paradigm of multiple (often contradictory) material property requirements exists. For advanced reactors, these include adequate strength, ductility, and toughness; excellent dimensional stability (resistance to void swelling and creep); and resistance to corrosion, stress corrosion, and embrittlement. Various advanced reactor designs (including nuclear microreactors under development by industry, molten salt reactors, gas-cooled reactors, and fast-neutron reactors) require component materials resistant to corrosion from specialized coolants and/or fuels (Gandy 2020). One family of material of crosscutting interest in fossil and nuclear programs is SiC, including SiC-SiC

composites. These can be engineered to have irradiation resistance, oxidation resistance, hermeticity, high-temperature strength and toughness, as well as tailorable thermal properties (Jacobsen 2020). With microreactors, there is a recognized need for higher-quality joints at interfaces and improved joining methods (brazing) for dissimilar materials such as ceramic–ceramic and ceramic–metal systems (Filippone 2020). Developing improved materials for nuclear power applications will result in improved safe operation of nuclear plants, higher reliability factors, lower plant costs, and longer service lifecycles.

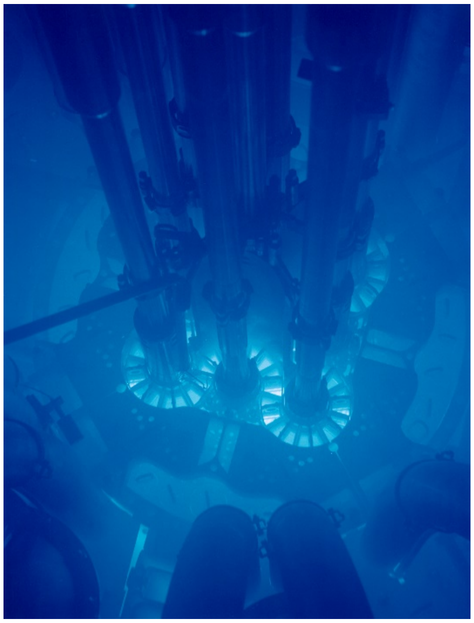

Figure 3. Advanced Test Reactor at Idaho National Laboratory, powered up

Photo courtesy of Idaho National Laboratory

- **Corrosion resistance in energy-related applications.** A study conducted by the National Association of Corrosion Engineers (NACE International) in 2013 estimated that the economic impact of corrosion on the United States is greater than $450 billion annually, which is approximately 2.7% of the U.S. gross domestic product (NACE International 2016). In many industries (steel, chemical, petrochemical, refractories, etc.), component failures due to corrosion cause process disruptions that necessitate startup/shutdown cycles, resulting in productivity loss and energy loss, especially in high-temperature production processes. One type of corrosion is known as metal dusting, which occurs in high-temperature hydrocarbon or other strongly carburizing environments (such as steam reforming to produce hydrogen). Metal dusting results in the disintegration of bulk metals into particulate matter. This type of corrosion can occur in oil refining, ammonia and methanol production, coal gasification, and direct iron reduction plants. Reliable and cost-effective solutions to eliminate metal dusting corrosion and suppression of coking would enable higher-efficiency processes and equipment (Christie 2020). In many instances, there are also significant safety- and environment-related issues. Corrosion of iron and steel pipelines, for example, can cause natural gas leakage, leading to wasted energy, explosion hazards, and methane emissions. Pipeline corrosion has accounted for over 1,000 significant incidents over the past 20 years, directly resulting in 23 fatalities and over $822 million in property damage (DOE 2015).

Figure 4. Metal dusting

Photo courtesy of Linde

- **Improved process heating materials.** Process heating consumes more than 7 quads of manufacturing energy annually (70% of all process energy use), with approximately 36%

of that energy lost as waste heat, accounting for over 2,500 TBtu annually across the U.S. manufacturing sector (Advanced Manufacturing Office 2016). Thus, there are significant opportunities to recover waste heat from industrial process heating operations, but many sources of industrial waste heat are unrecoverable because existing heat exchanger alloys and power conversion materials are incompatible with corrosive, high-flow-rate, and/or high-temperature flue gases (DOE 2015). Moreover, heat exchangers and thermal management devices with complex designs can be difficult and costly to fabricate, particularly with traditional manufacturing methods.

- **Advanced sensors for harsh environments.** Data and automation can accelerate processing, increase real-time feedback, and optimize energy use at every manufacturing systems level, with the potential to save millions of dollars per year in various sectors (DOE 2015). For many energy-intensive industries, such as steel production, advanced embedded sensors capable of withstanding high temperatures, corrosive environments, and abrasive particulates (e.g., in blast furnaces, basic oxygen furnaces, and electric arc furnaces) could validate ModSim data and improve energy efficiency of these operations (Sortwell 2020). Additionally, information is needed on materials and manufacturing of sensors and other components suitable for sustained and reliable operation under conditions of high static and dynamic pressure, for example, in mineral extraction, well drilling, hot or cold isostatic processing, or other heavy-duty industrial processes.
- **High mechanical loads, wear, and friction.** As with energy-production technologies, some energy-intensive industrial processes involve high mechanical loading and/or friction. For example, the global estimate for abrasive or contact friction and wear losses (as a percentage of the total energy consumed) for the industrial sector (including mining, agriculture, primary metals processing, chemical/refining, and pulp and paper) has been estimated at around 20% (Holmberg and Erdemir 2017). Paths are needed to reduce friction and wear losses in such energy-intensive and high-mechanical-load applications. Aluminum and other lightweight structural metal alloys, for example, could significantly reduce the weight of vehicles for better fuel economy and lower emissions: a 10% reduction in vehicle mass can yield a 6% increase in fuel economy. However, the use of lightweight metals in automobiles is limited by joining and repair challenges and the metals' corrosion resistance and durability in high-friction environments (DOE 2015).
- **Improved renewable energy materials for power generation.** The renewable energy sector is not immune from harsh service conditions and their adverse effects. Third-generation concentrated solar power (CSP) systems under development have challenges related to corrosion management of materials exposed to molten salts (at temperatures as high as 1000ºC), which function as heat transfer fluids and thermal energy storage media. Wind turbines experience transient operations (variable wind loads), particulate loads (dust/debris), and severe tribological conditions that require reliable low-torque drivetrain designs and enabling innovations (Ghobrial 2020). Geothermal energy systems involve

high temperature and pressure. Geothermal drilling requires very hard and tough drill bits, as well as sensors and bearings that can endure extreme temperatures and pressures and corrosive geothermal fluids (McKittrick 2020). While geothermal power generation currently constitutes less than 1% of total U.S. electricity generation, the U.S. Geological Survey estimates that there are nine GWe of identified geothermal resources and an additional 30 GWe of undiscovered geothermal resources. In geothermal energy development, two areas are identified as major technological challenges: 1) developing the subsurface engineering technologies and practices necessary for economic deployment of enhanced geothermal system technologies, and 2) reducing the cost and risk associated with accessing the subsurface through characterization technologies that can improve drilling success rates and/or developing technologies to directly reduce drilling costs (DOE 2015).

Figure 5. Tricone bits used for geothermal shaft drilling.

Photo courtesy of Geothermal Technologies Office

- **Material testing and qualification**. All new materials under development must undergo stringent testing to be qualified/certified for use in their given end-use commercial applications, with qualification times being up to 10 years in length. Typically, microstructural and phase stability, a slew of time-dependent mechanical properties, and the effects on these properties of environmental conditions (temperature, corrosivity, irradiation, etc.) must be investigated. The following will be beneficial: high-throughput and accelerated testing methods, openness to and platforms for collaboration/data-sharing, in-service inspection, incorporation of uncertainty in published ModSim data, more standardization, and a better understanding of multiscale degradation mechanisms.
- **Advanced manufacturing methods.** Advanced methods often enable the fabrication of components for less cost, or in forms or geometries, and having materials properties that would be very difficult or impossible to achieve with traditional methods. However, not all advanced manufacturing methods (for example, additive manufacturing [AM], powder metallurgy–hot isostatic pressing, and electron beam welding of large-size components with relatively simple geometries) have been amply demonstrated at scale for the most demanding applications, such as nuclear power production. Research is needed to expand the AM capability to the production of a much larger number of metals, ceramic parts, and composites. Better understanding of phenomena occurring during advanced manufacturing is required to concisely control material properties across the angstrom, nanometer, and micron length scales.

3 High-Impact, Priority, Crosscutting Research Needs Identified from the 2020 M4HSC Workshop

Sets of high-impact, crosscutting, priority R&D topics emerged from the 2020 M4HSC Workshop plenary speaker sessions and technical breakout session discussions. Summaries of the breakout group discussions, answers to the questions above, and priority topics for R&D are outlined below.

In addition to opportunities for advancing selected technologies, workshop participants identified the associated challenges (actionable items/tasks) and barriers (obstacles) specific to the topic areas for each of six breakout sessions, all of which contribute toward the vision of rapidly deploying cost-effective, innovative new materials—often manufactured using advanced techniques—capable of delivering step-change superior performance and/or longer service life during operation in harsh service environments.

Several common, or interconnected, enabling technology innovation challenges emerged:

- **Data-driven materials/system testing approaches that lead to more accurate prediction of materials behavior and materials properties under harsh service conditions at relevant timescales.** Qualification costs and risks associated with failure of emerging materials/systems under harsh service conditions deter industry from developing and deploying new materials needed to advance technologies—despite the potential step-change in performance and resulting energy and cost savings. Accurate and more complete materials property data sets are needed for a larger number of materials and material systems across an array of harsh service conditions. Data are needed using standardized test conditions, test assemblies, and analysis methods at relevant timescales. Filling data gaps with quality data will enable more accurate modeling, prediction, and simulation of materials properties and behavior under harsh environments. Materials and materials systems tested as a function of manufacturing method (including joining method) will reveal processing–microstructure–properties relationships and changes in those relationships as a function of conditions/time. Collaborative efforts for component demonstrations and open, multi-party assessments can result in the compilation of reliable published databases for industry-wide use.
- **Accelerated testing and qualification methods to reduce time to market for materials and systems.** Acquisition of large quantities of high-quality materials behavior data at relevant timescales under an array of harsh service conditions is time-consuming and expensive. Qualifying materials for nuclear power applications is one example, as it requires extensive stress corrosion, thermal performance, and irradiation impact experimental data (Gandy 2020), taking more than a decade at a cost of tens of millions of dollars. When iterative irradiation cycles are necessary to develop a sufficient understanding of an alloy’s in-reactor performance, costs and delays are cumulative and

enormous. Data-driven experimental approaches to accelerate materials testing, qualification, and validation would be of vast benefit. There is a need for data-driven materials/systems tests that employ accelerated aging, stress, exposure, etc. to reduce materials/systems time to market. Test development would take place with the goal in mind of providing sufficient data and evidence to ensure that the accelerated test methodology accurately characterizes materials behavior for kinetically slow changes, phenomena, and/or failure modes that would manifest only under extended service periods. High-throughput materials testing and characterization methods are needed. The data provided by these advancements will enable ModSim tools' employment for accurate prediction of materials performance at extended service conditions. For example, a key enabler would be the combination of microstructurally informed ModSim tools that include irradiation and other experimental data, which could significantly reduce the time/cost for the qualification/validation of new materials for nuclear applications (Jacobsen 2020). New capabilities developed should be accessible to industry stakeholders who may lack the capital to build testing facilities. Speed of access and flexibility of facilities to address industry challenges are critical.

1) **More Data:** Data-driven materials/system testing approaches that lead to more accurate prediction of materials behavior and materials properties under harsh service conditions at relevant timescales
2) **Accelerated Testing and Qualification:** Reduced time to market for improved materials systems through accelerated testing and qualification
3) **Improved Manufacturing Methods:** Improved manufacturing methods and capabilities that are advanced, adaptable, agile, smart, and more efficient
4) **Greater Understanding:** Improved understanding of advanced manufacturing process fundamentals, control parameters, and subsequent effects on materials properties
5) **Smart:** Improved in situ process monitoring technologies, including sensors, modules, and packaging that can be embedded inside furnaces, downhole wells, reactors, and other extreme environments to provide valuable real-time data for utilization in process monitoring and control
6) **Access:** Access to capabilities through publicly available facilities
7) **Improved Materials**: Improvements in material performance for essentially every harsh service condition in which power generation or energy-intensive processes are employed

Figure 6. High-value, crosscutting R&D needs.

- **Improved manufacturing methods and capabilities that are advanced, adaptable, agile, smart, and more efficient.** An increased use of systems that integrate manufacturing intelligence in real time and the convergence of artificial intelligence, robotics, automation, advanced sensors, non-destructive analysis, and other smart manufacturing innovations and diagnostics and analytics could transform and introduce step-changes along the entire manufacturing value chain, benefiting a wide range of projects, materials systems, technology areas, and industry partners.

- **Continued improvements to better understand advanced manufacturing process fundamentals, control parameters, and subsequent effects on materials properties.** These improvements are necessary to fabricate robust or resilient materials of high quality for harsh service conditions at lower cost and lower energy consumption. Today, components produced by these routes often do not possess the properties of those produced by more traditional manufacturing methods. There is a finite amount of materials properties data available, as well as a limited number of alloys and feedstocks developed for use in new manufacturing methods. When compared to traditional routes, there is also a less mature understanding of AM process fundamentals and process control parameters that could enable production of components with the desired optimal properties; understanding is even less advanced in terms of producing materials and systems with superior properties imparted through the AM process. In addition to high capital investment, AM processes also face many scaling barriers, such as slow production speeds, limited materials development (unavailability of suitable materials), materials property inconsistencies/quality assurance issues (repeatability, part-to-part variation), software and hardware weaknesses, and lack of industry-wide standards. In addition, there are education and workforce development deficiencies (managers, engineers, and technicians not possessing the required training and skill sets) that often result in inefficient attempts to force-fit AM to a component build rather than designing materials/components specifically for AM.
- **Smart manufacturing innovations.** Advanced metrology equipment for in situ harsh process monitoring can be costly and, in some cases, commercially unavailable. An investment in advanced in situ process monitoring technologies could have benefits for a wide range of projects and industry partners. Such technologies include sensors, modules, and packaging that can be embedded inside furnaces, downhole wells, reactors, and other extreme environments to provide valuable real-time data for utilization in process monitoring and control. Other potentially beneficial smart/digital manufacturing facets include the need for digital twins, improved process modeling and simulation tools, and early-stage consideration of design-for-manufacturability and concurrent engineering.

Figure 7. Glass furnace.

Photo courtesy of AMO

- **Access to facilities.** Access to highly specialized fabrication, analysis, and testing capabilities is limited by the high costs to own and maintain such equipment and capabilities. This has restricted deployment of new materials. Industry requires access to capabilities on a cost-recovery basis without making large, high-risk investments.

- **Improved materials.** Nearly every plenary session speaker and technical breakout session discussion provided numerous calls for improved materials and materials systems when asked about top R&D needs, challenges, and barriers. Participants called for improved alloys for turbine blades with higher-temperature capability, longer-term stability, and lower defect rates. Materials having wide applicability across various power generation platforms were ranked in the top responses. Improved materials designed specifically for rapid solidification and use in efficient AM processes were called for, as well as advanced coatings, materials and coatings that are more resilient (tribological conditions) for improved reliability and increased power density, thermally tolerant materials, and materials more resistant to hydrogen embrittlement. The list goes on to essentially cover every harsh service condition in which either power generation or energy-intensive processes are employed.

4 M4HSC Workshop Structure and Overview

DOE held the M4HSC Workshop on October 27–30, 2020. The videoconferencing/web-conferencing software platform ZOOM (ZOOM Video Communications, San Jose, California) was used to facilitate the virtual workshop. Use of the ZOOM platform license was provided as a conferencing service through The Building People® (Leesburg, Virginia). Gravis Tech (Gravis Technologies, Wallace, Idaho) set up the official workshop webpage: https://inl.gov/m4hsc-virtual-workshop/. The webpage was used to post the workshop purpose and objectives, announcements, the workshop agenda, and the read-ahead document, as well as to register workshop participants and provide weblinks to various workshop sessions.

Representatives from government, industry, academia, DOE national laboratories, and non-governmental organizations gathered to hear plenary speakers on October 27 and 28 and to participate in workshop breakout sessions held on October 29 and 30. The workshop featured 25 plenary speakers comprising 12 speakers representing DOE and national laboratories and 13 speakers from industry. Of the 12 government-aligned plenary session speakers, 3 were high-profile federal employees representing EERE, AMO, FE, and NE who underscored the national importance of advanced materials and manufacturing capabilities. The balance of the speakers (9 government representatives and 13 industry representatives) provided technical content and insight into the materials challenges and research needs relevant to their respective programs and business areas. Each plenary session speaker and the title for that speaker's presentation are given below.

- Angelos Kokkinos, Associate Deputy Assistant Secretary, Clean Coal and Carbon Management, FE, "Welcome from the FE Office"
- Robert Schrecengost, Program Manager, FE, "FE Office Overview: Materials for Harsh Environments"
- Sean Bradshaw, Turbine Technology Manager, Pratt & Whitney representing the Gas Turbine Association, "Energy in Transition – High-Performance Materials and Systems for Tomorrow's Energy Sector"
- Neva Espinoza, Vice President, Energy Supply and Low-Carbon Resources, Electric Power Research Institute (EPRI), "Accelerating the Clean Energy Transition Reliably and Affordably"
- Jack deBarbadillo, Special Metals, "Metallic Structural Materials for Advanced Energy Systems"
- Charles Atkins, Director of R&D, Ramaco, "Coal to Advanced Materials and Manufacturing from and for Harsh Service Conditions (C2AMM 4HSC)"
- Isabella Van Rooyen, Distinguished Staff Scientist, Idaho National Laboratory, "NE Office Materials for Harsh Service Conditions R&D Needs"

- Gay Wyn Quance and Randall Smith, Solid Carbon Products/Seerstone Development, “Critical Materials: Graphitic Materials from CO_2 – Synthetic Graphite and Carbonite®”
- Dave Gandy, EPRI, “Materials & Manufacturing Needs for Advanced Nuclear Applications”
- Doug Burns, Space Nuclear Power and Isotope Systems, Idaho National Laboratory, “Space Nuclear Propulsion (SNP) Fuel Development”
- George Jacobsen, Lead Scientist, General Atomics, “Advanced Core Materials for Current and Next-Generation Nuclear Reactors”
- Claudio Filippone, Chief Executive Officer, HolosGen, “Distributable Modular Nuclear Reactor Materials/Manufacturing Challenges”
- Alex Fitzsimmons, Deputy Assistant Secretary for Energy Efficiency, EERE, “Welcome from EERE”
- Avi Shultz, Solar Energy Technologies Office, EERE, “Concentrating Solar-Thermal Power (CSP) Research and Development”
- Lillie Ghobrial, Wind Energy Technologies Office, EERE, “Wind Energy Materials”
- Alexis McKittrick, Geothermal Technologies Office, EERE, “Overview of Harsh Conditions in Geothermal Development”
- Ned Stetson, Hydrogen and Fuel Cell Technologies Office, EERE, “Materials Compatibility in Hydrogen Service”
- Valri Lightner, Deputy Director, AMO, “Advanced Manufacturing and Materials for Harsh Service Conditions”
- Leo Christodoulou, Idaho National Laboratory, “Manufacturing Materials and Structures for Extreme Environments”
- Michael Sortwell, Senior Director, Technology, American Iron and Steel Institute, “Steel Industry Challenges for Producing Steel in Harsh Environments”
- Mark Thompson, Principal Scientist, GE Research, “Materials and Processing Challenges for Power Generation”
- Jason Sebastian, President, QuesTek Innovations, “Materials Challenges and ICME [Integrated Computational Materials Engineering] for Advanced Alloys for Harsh Environment Applications”
- Max Christie, R&D Director – Ceramic Membranes, Linde, “Materials for Harsh Service Environments: Linde Priorities”

- Adam Stevenson, Saint-Gobain, “Challenges for Materials in Harsh Service Environments”

In addition to 25 plenary session speakers, the workshop included six different technical breakout sessions. Breakout session discussion topics focused on opportunities, challenges, barriers, and R&D needs for development of advanced materials and manufacturing methods for a number of harsh operating environments found in energy production and energy-intensive industrial processes.

Technical breakout session titles (depicted in Figure 8) and session facilitators are listed below.

- Materials for Thermal Management, Extreme Temperatures, and Energy Conversion – Session Leads: Jeff Hawk (National Energy Technology Laboratory), Kashif Nawaz (Oak Ridge National Laboratory)
- Wear, Oxidation, and Corrosion-Resistant Alloys, Components, and Coatings for Static and Rotary Applications – Session Leads: Bruce Pint (Oak Ridge National Laboratory), Brian Gleeson (University of Pittsburgh)
- Ceramics, Composites, and Functionally Graded Materials for Harsh Environments – Session Leads: Edgar Lara-Curzio (Oak Ridge National Laboratory), Elizabeth Opila (University of Virginia)
- Enabling Materials through Advanced Manufacturing Technologies – Session Leads: Gary Rozak (HC Starck), Isabella Van Rooyen (Idaho National Laboratory)
- Accelerating Qualification of Advanced Materials & Experimental Validation of ModSim Methodology for Materials, Manufacturing, and Performance During Service – Session Leads: David Alman (National Energy Technology Laboratory), Michael McMurtrey (Idaho National Laboratory)
- Mechanisms for Collaborative Demonstration of Processes at Industrially Relevant Scale – Session Leads: Briggs White (National Energy Technology Laboratory), Rob O’Brien (Idaho National Laboratory)

Registered workshop attendees numbered 468 total, broken down as follows: 238 (50.9%) attendees from government agencies/labs, 169 (36.1%) attendees from industry, 56 (12.0%) attendees from academia, and 5 (1.1%) unaffiliated (see Figure 9). Approximately 56.6% (265) of the M4HSC workshop registrants attended the plenary sessions, and 203 (43.4%) registrants attended one or more of the technical breakout sessions. Of the government/lab registrants, 127 of 238 (53.3%) attended the plenary sessions, with 22 of 238 (9.2%) of the government/lab registered attendees being workshop support staff. Discounting support staff, the actual number of government/lab attendees participating in the breakout sessions was closer to approximately 89 (43.8% of breakout session attendees). An equal number (89, 43.8%) of technical breakout

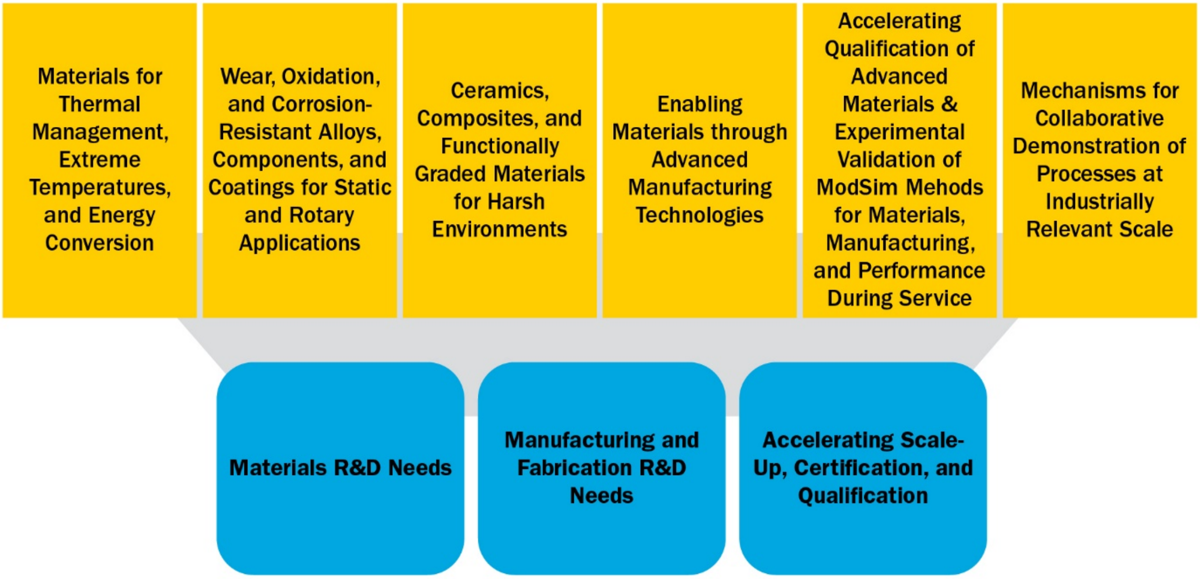

Figure 8. Breakout session titles and crosscutting themes

session registrants were affiliated with industry, along with 25 (12.3%) breakout session participants from academia. Breakout session participants averaged 45 per session. Figure 10 depicts the breakout session attendee breakdown by affiliation.

In this workshop, AMO, FE, and NE (hereafter referred to collectively as DOE) sought to gather input from stakeholders on the vision of future opportunities and technical challenges facing development and scale-up of materials science, process, and equipment that can make step-change improvements in material performance under harsh service conditions. DOE also sought individual input on challenging performance metrics and identification of key problem sets to be addressed. At this workshop, participants identified mid-technology readiness level (mid-TRL) R&D needs, market challenges, metrics and impacts, and other considerations for M4HSC. The intent was to define critical crosscutting problems/barriers that, if successfully addressed, represent a step-change beyond the current state of the art.

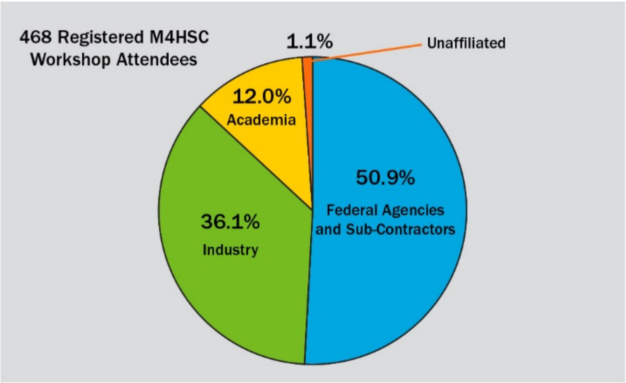

Figure 9. Registered workshop attendee affiliation

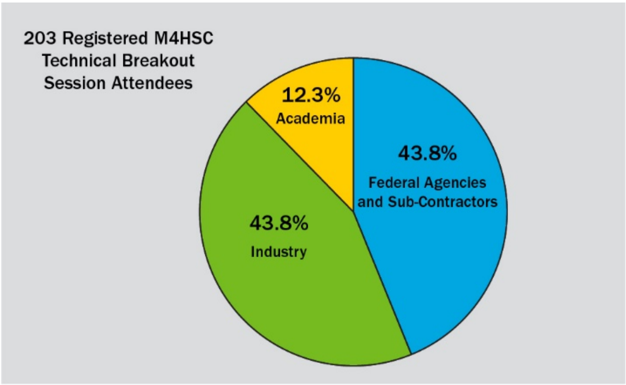

Figure 10. Registered breakout session attendee affiliation

The following objectives were established for the joint workshop.

- Identify high-value, crosscutting research opportunities of interest to DOE related to materials challenges. Determine the research needed to overcome those challenges that prevent transition of the material into achieving improvements in energy efficiency or extension of service life of process componentry employed under harsh service conditions.
- Identify high-value crosscutting research opportunities of interest to DOE related to fabrication of operable parts/coatings.
- Identify needed advanced manufacturing research and methodology that leads to reduced embodied energy in functional parts and coatings, improves material performance, increases operational service life, and reduces energy needed to operate the process under harsh service conditions.
- Identify materials science data gaps and research needs that can lead to scalable manufacturing techniques that give rise to parts and/or coatings whose physical properties and cost/value outperform conventionally produced parts.
- Identify opportunities, data gaps, and technical limitations preventing development of rapid qualification methodologies that reduce material/part certification time and cost.
- Identify data gaps and research needs that enable modeling and simulation methodology improvements for materials during fabrication and during operation under harsh service conditions at relevant spatial and temporal scales.
- Identify data gaps and research needs in fabrication process monitoring, control, and feedback that allow more efficient machine learning that translates to reduction in fabrication time, intensification of fabrication processes, and overall improvements in fabrication process efficiency.

To facilitate breakout session discussion and to elucidate high-value crosscutting research needs, workshop participants were asked to respond to a set of questions. To capture breakout session participant responses, organizers used GroupMap™ (GroupMap Technology Pty Ltd, East Victoria Park, Western Australia, Australia), a real-time, online brainstorming tool for workshops, meetings, conferences, classrooms, and events. In some cases, responses were ranked during the session; in other cases, responses were grouped into categories, and the number of “like” responses per category were assessed and evaluated to obtain ranking.

5 Summary of M4HSC Technical Breakout Session Input

5.1 Breakout Session 1: Materials for Thermal Management, Extreme Temperatures, and Energy Conversion

Breakout Session 1, conducted on October 29, focused on four key topic areas as related to the use of materials in thermal management, extreme temperatures, and energy conversion applications. The key topics are given below:

- Topic 1: High-impact opportunities (paths) for advancing the technology area(s)
- Topic 2: Key performance and operational metrics and the targeted advancement
- Topic 3: Key challenges (actionable items to be taken in working with the opportunities) and barriers (obstacles/hurdles) that impede advancement
- Topic 4: R&D needs

For each topic area, individual participants' views and responses were captured via GroupMap. There were 31 separate responses to **Topic 1**. Responses were categorized as related to materials (8 responses), manufacturing (19 responses), or market applications (4 responses). Participants were asked to score each response on a scale of 1 to 10, with 10 being considered the highest importance. Table 1 provides the top 4 responses in each category for Topic 1, according to their ranking. Note there is some overlap between Session 1 responses with Sessions 3 and 4 data.

For **Topic 2,** priority operation/performance metric targets were elucidated. There were 3 responses. Table 2 shows all three responses provided in order of their ranking.

For **Topic 3**, participants identified key challenges and barriers related to materials for thermal management, extreme temperatures, and energy conversion applications, providing 30 responses. Those were divided into categories of Key Challenges (12 responses) and Key Barriers/Obstacles (18 responses). Table 3 provides the top 4 responses in each category, according to session participant ranking.

For **Topic 4**, the top R&D needs for end-use applications and manufacturing processes were identified for materials systems used in harsh thermal environments. Session participants gave 11 responses, ranked them, and divided them into Materials R&D needs (5 responses) and Manufacturing R&D needs (6 responses). Table 4 shows the top four responses in each category, along with their ranking.

Analysis of data given in Tables 1–4 indicates Breakout Session 1 participants stated that—for materials for thermal management, extreme temperatures, and energy conversion applications—the highest-impact areas are related to energy-producing technologies, e.g., materials for

Table 1. Topic 1, Breakout Session 1: Opportunities for Materials, Manufacturing, and Market Applications

Materials Technologies	Manufacturing Processes	Market Applications	Rank
Improved alloys having higher-temperature capability for turbine blades, with longer-term stability and lower defect rates	Improved ability to manufacture components such as tubes, shells, plates, heat exchangers, turbine blades, and compressor wheels using >1200 °C materials	Advanced turbine systems	1
Low to zero Co Ni-based alloy for sCO2, AUSC, cyclic ultra-supercritical, or gas turbine applications	Near-net-shape hot isostatic pressing manufacturing for a lower-cost alternative to forging, then machining	Materials of wide applicability across power generation platforms	2
New alloys designed specifically for rapid solidification and efficient AM processes	Improved traditional manufacturing processes such as casting, forging, and joining for high-temperature alloys	sCO2 power generation systems	3
Bimetallic (cladded) tubes/ piping for fluid transfer in high-temperature corrosive environments (steam, AUSC)	Cost-competitive advanced manufacturing methods for fabrication of compact heat exchangers at scale	Cryogenic systems	4

advanced turbine systems, materials having wide applicability across power generation platforms, and materials for sCO_2 power generation systems. The breadth of materials and applications for this category is large. Nonetheless, some specific metric targets were identified, and key overarching/crosscutting opportunities were outlined in a number of areas:

- **New materials.** There is a need to develop 1) new materials designed specifically for efficient AM, bimetallic (cladded); 2) tubing for high-temperature fluid transfer in steam system and advanced ultra-supercritical (AUSC) piping; 3) high-entropy alloys for gas turbines; 4) engineered functionally graded materials for control of thermal properties (see Section 5.3 data); and 5) lightweight aluminum alloys for harsh environments.

Figure 11. Extruded Alloy 740H AUSC CO_2 steam header pipe. AUSC boilers facilitate collection and sequestration of carbon-base emissions.

Photo courtesy of Special Metals Corporation

- **Material performance.** R&D needs include targeting 50% reduction in the cost of Ni-based alloys for AUSC and sCO_2 power generation system piping; achieving 67% combined efficiency in gas turbines; and additively manufacturing Ni-based super alloys with creep resistance comparable to wrought/cast alloys.
- **Manufacturing yield.** Focus should increase on manufacturing defect reduction and yield improvements.
- **Manufacturability.** There is a need to improve the ability to fabricate topologically/geometrically complex parts, such as heat exchangers, and to advance the ability to join/weld parts (including dissimilar materials) beyond the state of the art.

Table 2. Topic 2, Breakout Session 1: Operational and Performance Metric Targets

Description	Rank
50% reduction in cost of Ni-based alloys for AUSC/sCO_2 power generation system piping	1
67% combined efficiency in gas turbines	2
AM of Ni-based superalloys with creep resistance comparable to wrought/cast	3

Table 3. Topic 3, Breakout Session 1: Key Challenges and Barriers

Challenge	Barrier	Rank
Joining of multiple materials (see Session 4 data)	**Long lead time for demonstration components**	**1**
Attaining more process control/less material variability	**Limited U.S. capacity**	**2**
Overcoming potential disruptions in critical materials supply chains	**Sluggish industry acceptance**	**3**
Lowering the cost of CMCs (see Session 3 data)	**Long time for TRL advancement**	**4**

Table 4. Topic 4, Breakout Session 1: Top R&D Needs Identified

Materials R&D Needs	Manufacturing R&D Needs	Rank
Conducting component demonstrations and open assessments by multiple parties	Ability to produce ceramic components via AM with properties equivalent to or better than traditional routes	1
Quantifying the required performance improvement and analyzing cost–performance ratio (cost–benefit)	Use of legacy systems for new materials and designs	2
Working with industry to collect non-proprietary information on properties of alloys for use in data science and modeling	Manufacture with reproducible properties in various product forms	3
Defining a single metric that accounts for combined effects	Ability to produce large parts by AM	4

5.2 Breakout Session 2: Wear, Oxidation, and Corrosion-Resistant Alloys, Components, and Coatings for Static and Rotary Applications

This technical breakout session, known as Breakout Session 2, was run concurrent to Breakout Session 1 (described in Section 5.1 above). Session 2 was also focused on the four key topic areas identified earlier. This session is distinct in that attendees did not attend other sessions on October 29. This session focused on wear, oxidation, and corrosion-resistant alloys, components, and coatings for static and rotary applications.

For each topic area, individual participants' views and responses were captured via a brainstorming process using GroupMap, the collaborative brainstorming software platform. Highlights of participant responses are given below in tables and summarized in a bulleted format.

For **Topic 1,** Breakout Session 2, 44 responses were provided and ranked by session attendees. Responses were then categorized as having either materials applications (33 responses) or manufacturing applications (13 responses). Participants scored responses during the session. Rankings for the top six responses in each category appear in Table 5.

For **Topic 2,** Breakout Session 2, some operation/performance metric targets were elucidated. Participants provided and ranked 7 responses. The top 4 responses are shown in Table 6.

For **Topic 3**, Breakout Session 2, challenges and obstacles were identified for various types of systems and materials related to wear, oxidation, and corrosion-resistant alloys, components, and coatings for static and rotary applications. Participants provided and ranked 57 responses. Responses were divided into six different technology areas, and challenges and barriers were

Table 5. Topic 1, Breakout Session 2: Opportunities for Materials and Manufacturing

Materials	Manufacturing	
Description	Description	Rank
Advanced coatings (including thermal and environmental barrier coatings [TBCs and EBCs]) that enable use of lower-cost base materials	AM of functional composition gradient surface architecture	1
Materials for nuclear power above 750ºC	Scalable, conformal coating fabrication processes	2
High-temperature alloys for gas turbines at temperatures of 1300ºC and above	AM for corrosion-resistant Ni alloys for higher fire temperature	3
More resilient materials and coatings (tribological conditions) for improved reliability, and increased power density for drivetrain components (vehicles, wind turbines, etc.)	Solid-state joining of high-temperature alloys	4
High-temperature coating (2000ºF) for impact wear and fretting wear	Machine learning for microstructure control and performance in digital manufacturing	5
Extended-life, resilient materials and coatings for applications requiring high durability (e.g., offshore wind turbines)	Dissimilar material joining	6

Table 6. Topic 2, Breakout Session 2: Operational and Performance Metric Targets

Description	Rank
Materials that can withstand molten salts at 750°C	1
Low-cost materials compatible with sCO_2 at 720°C to achieve above 50% efficiency	2
Improved materials for heat exchangers	3
Hydrogen-resistant materials	4

identified for each technology class. Table 7 displays responses, technology categories, and the top ranked responses for each category. Technology categories are also arranged in the table in their order of ranking. In some instances, only a single response was provided for a given category.

For **Topic 4**, Breakout Session 2, top R&D needs for the end-use applications and manufacturing processes were identified. Participants offered 15 responses, which were then ranked. The top 4 responses are shown in Table 8.

Table 7. Topic 3, Breakout Session 2: Key Challenges and Barriers

Molten Salts	Challenges	Barriers	Rank
	Need standard, commercially available, molten salt compatible sensors	Supply chain for chloride salts (high demand for high-purity salt in Asia will account for >50% of global trade by 2028)	1
		High cost of materials	2
		Poor understanding of degradation mechanisms	3
		Poor understanding of effect of impurities on wear, corrosion, etc.	4
Hydrogen-Resistant Materials	Challenges	Barriers	Rank
	Industry needs to be agile (adapt/react quickly to changes)	Uncertainties in markets/supply chains	1
	Need ability to use high-strength steel in pipelines for transporting hydrogen	Incomplete understanding of hydrogen combustion in gas turbines	2
	Need to optimize pressure for hydrogen storage and transportation	High investment cost due to large specific volumes (low-pressure compressed gas storage); advanced materials for high-pressure compressed gas storage; energy-intensive liquification of liquid hydrogen storage	3
	As the industry matures, the challenges will become clearer	Hydrogen embrittlement	4
Extending the Life and Capability of Fossil Fuel Power Plant Components	Challenges	Barriers	Rank
	Need advanced durable high-temperature TBCs	Natural gas for new connections banned in some states	1
	Need in situ coating repair methods	Supply chain issues for advanced coal-fired burners	2
	Need process innovations	High cost	3
	Need faster repair strategies	Reliability	4

Table 7. Topic 3, Breakout Session 2: Key Challenges and Barriers (cont.)

sCO$_2$-Resistant Materials	Challenges	Barriers	Rank
	Need predictive methods for long-term degradation of thin metal sections for compact heat exchangers (understanding and quantifying effects of carburization)	High CO$_2$ solubility of low-cost Fe-based alloys compared to Ni-based alloys	1
		Polymer degradation	2
		Seal degradation	3
		Uncertainties in supply chain	4
Extending the Life of Offshore Wind Turbines	Challenges	Barriers	Rank
	Finding bearing materials with high contact stress capacity and low wear rate, which contributes greatly to reducing the cost of energy but entails great replacement cost	Manufacturability (fabrication and coatings) of large turbine main bearings and pitch bearings	1
	Reducing component costs	Reduced life of bearing materials due to stresses as wind turbine structures become larger and more flexible	2
	Need accelerated testing of materials and coatings	High cost of components	3
	Need corrosion modeling and lifetime prediction	Long time for fatigue testing of large turbine components	4
Improved Materials for Heat Exchangers	Challenges	Barriers	Rank
	Need scalable coatings processes that allow effective homogenous deposition of protective layers on components with complex geometries that may have non-line-of-sight areas	Clogging and condensation issues	1
	Need low-cost and high-reliability heat exchangers	Thermal cycling issues	2
	Need manufacturing methods for complex geometries	Cracking of additively manufactured high-strength alloy heat exchangers	3
	Need corrosion-resistant alloys that can be fabricated by AM	Aqueous corrosion issues	4

In reviewing Breakout Session 2 attendee response data provided in Tables 5–8, it can be seen that, similar to Breakout Session 1, the breadth of materials and manufacturing issues related to the breakout session topic is very large and diverse, encompassing several different energy generation platforms and harsh service conditions. Nonetheless, some specific metric targets were identified, and some overarching crosscutting opportunities were outlined in key areas, as shown below.

- **New materials.** Participants identified needs for the following:
    - Advanced coatings, including TBCs and EBCs, which can enable use of lower-cost base materials
    - Hydrogen-compatible materials
    - sCO2-compatible materials
    - Materials for nuclear power generation
    - High-temperature alloys for gas turbines
    - More resilient drivetrain components and coatings (vehicles, wind turbines, etc.)
    - Strong, ductile, and hard coatings (this would have a very wide cross-cut)
    - High-temperature coatings for impact wear and fretting wear
    - High-strength materials (nickel-based alloys and steels) for use in hydrogen environments
    - Strong, lightweight corrosion-resistant materials
    - Regenerating (self-healing) materials for in situ repair
    - Sensors and control materials for harsh environments
    - Lightweight wear-resistant materials for bearings
    - Low-cost, high-contract-stress materials for rolling element bearings (high-load-density bearings).
- **Material performance metrics.** Various kinds of material metrics should be targeted, including materials that:
    - can withstand molten salts at 750°C
    - are low-cost and compatible with sCO_2 at 720°C to achieve above 50% efficiency
    - are compatible with carbon-based fuels in metal-supported solid oxide fuel cells
    - are compatible with high volumetric fractions of hydrogen (up to 100%)
    - are of improved efficiency to 65%–70% for combined cycle, 45%–50% for coal-fired, and >50% for sCO_2
    - can extend the life of offshore wind turbines beyond 30 years.
- **Accelerated testing.** Methodologies are needed to accelerate wear tests for materials in very harsh conditions, such as 720ºC salt, and to accelerate corrosion testing.
- **Manufacturability.** New or improved methods of scalable, high-throughput manufacturing are needed for conformal coatings, functionally graded materials, solid-state joining of high-temperature alloys, microstructure control and performance, dissimilar material joining, and corrosion-resistant Ni alloys for higher fire temperature.

Table 8. Topic 4, Breakout Session 2: Top R&D Needs Identified

Description	Rank
Accelerated corrosion testing	1
Accelerated high-throughput experiments and testing (simulating field experience)	2
An integrated computational model for life prediction of alloys with multiple failure modes (chemical, mechanical) and microstructure considerations	3
Accelerated coating material development, such as machine learning	4

5.3 Breakout Session 3: Ceramics, Composites, and Functionally Graded Materials for Harsh Environments

Breakout Session 3 also focused on the four key topic areas previously identified. The participant results were more numerous than in the other sessions. To save time, the GroupMap ranking tool was not used for ranking but was instead maintained in its function of logging participant responses while dialogue was ongoing. Logged participant responses were analyzed after the session by dividing responses into categories and ranking categories according to the number of similar responses in that category.

For Breakout Session 3, **Topic 1**, 91 participant responses were logged in GroupMap. These were then analyzed and divided into 11 sub-categories. Table 9 shows the top 5 sub-categories (representing 69% of the Topic 1 responses) and the number of responses per sub-category.

Table 9. Topic 1, Breakout Session 3: Opportunities Identified

Category	Number of Responses
Improved Manufacturing of Materials/Systems	18
Improving Materials/Manufacturing Costs	12
Specific Materials/Systems	12
Improvements in Size/Throughput/Scaling	11
Specific Topic Areas	10

- **Improved manufacturing of materials/systems.** Where attendees were asked to offer their input on R&D opportunities, manufacturing with advanced materials to achieve superior performing materials/systems received the largest number of responses (18 of 91 = 19.8%). Applications wherein advanced manufacturing methods are developed for use with advanced materials for fabrication of functioning parts/components, such as for ceramic heat exchangers, refractory ceramics, composites, and functionally graded materials comprised 55% of the responses in this sub-category (10 of 18). Defect-free manufacturing, hybrid ceramic/CMC system manufacturing, and improved sintering of refractory ceramics were noted, as were continuous-fiber manufacturing and digital twin production. Of the responses in that sub-category, 44% were related to promoting opportunities to develop advanced manufacturing methodology specifically to enable a material effect not achievable through conventional manufacturing.

- **Opportunities to improve material/manufacturing costs.** Opportunities to improve costs, and similarly grouped "materials cost" or "manufacturing cost" responses targeting specific material and manufacturing opportunities, received an equal number of responses each (12 of 91 = 13.2%) in this sub-category. Lower-cost manufacturing of fibers, composites, and compact heat exchangers at scale were identified as opportunities, with lower fiber costs receiving 33% of the responses. Lower-cost SiC and carbon fiber, composite, and carbon foam systems were shown to be of particular interest, as were lower-cost coatings for fiber materials used in harsh service conditions. Approximately 12% of the session attendee responses dealt with opportunities to improve scaling and throughput of ceramic materials, and production of larger-format components/coatings from ceramics and ceramic composite materials as means to reduce costs.
- **Specific materials/systems.** Of significant interest in this sub-category were SiC fibers, CMCs, CMC coatings, fiber coatings, improved EBCs, and improved material systems for heat exchangers, nuclear applications, and rotating blades/turbines.
- **Improvements in size/throughput and scaling.** In this sub-category, uniform feedstocks for scale-up reproducibility, development of high-throughput ceramic AM methods, and manufacture of large (e.g., >6" x 6" x 6" ceramic heat exchanger parts or >2' x 2' turbine parts) were provided as examples where improved methods for scale-up and throughput would provide crosscutting, high-impact advances.
- **Specific topic areas.** Challenges related to specific topic areas drew 10 of 91 responses (10.9%) for Topic #1. Recurring responses in this sub-category included the need for improvements in matrix densification, development of alternative heating technologies, understanding of combined environment effects (e.g., combined heat/radiation) on materials/systems, and improved ability to control grain properties during fabrication of materials/systems.

For Breakout Session 3, **Topic 2**, some operation/performance metric targets were elucidated. Session attendee responses were evaluated and then placed into various sub-categories. The sub-categories are ranked by the number of responses per sub-category. Table 10 shows the top 3 sub-categories, which cover 85% of participant responses for Topic 2.

The greatest number of responses for Topic 2 (Table 10) were provided in the first two sub-categories of Manufacturing to Improve Materials Properties to a Stated Metric, and Improvements in Manufacturing Methods to Achieve Efficiency, Lower Error Rates, Lower Cost, and Higher Throughput. Nearly 73% of Session 3 attendee Topic 2 responses (45 of 62

Table 10. Topic 2, Breakout Session 3: Operational and Performance Metric Categories

Operational/Metric Sub-Category	Number of Responses
Manufacturing to improve materials properties to a stated metric	23
Improvements in manufacturing methods to achieve efficiency, lower error rates, lower cost, higher throughput	22
Manufacturing to specific size/scale metrics	8

total) addressed use of advanced manufacturing either to improve the performance of a TRL 3–6 material used for fabricating superior-functioning parts/components for harsh service conditions or to achieve improvements in specific manufacturing metrics such as lower error/defect rate, lower cost, and higher throughput. The latter equates to a more efficient bottom line in terms of materials/resource/time consumption. Key metrics included in responses were improved operating temperatures, improved radiation resistance, reduced creep/elongation, improved material densification, and improved part durability for longer on-line operating time.

For Breakout Session #3, **Topic 3**, challenges and barriers were identified for various types of systems/applications. Attendees offered 99 different responses, which were analyzed and placed into 12 different sub-categories based on the content in the response. Table 11 shows the top 5 categories, representing 72% of the 99 responses.

Table 11. Topic 3, Breakout Session 3: Challenges and Barriers

Challenge or Barrier Category	Number of Responses
Supply chain, technology to market, and market challenges	24
Specifically identified material/manufacturing challenges	21
Scaling/throughput	11
Cost	8
Improvements in ModSim, data gap barriers	7

For Breakout Session #3, **Topic 4**, the top R&D needs for the end-use applications and manufacturing processes were identified. Attendees supplied 50 responses, which were divided into 5 different sub-categories. All 5 sub-categories are given in Table 12.

Analysis of responses for Topic 4, R&D Needs sub-categories, indicates that government-sponsored test facilities, collaborations, guidance, working groups, and Small Business Innovation Research (SBIR)/ Small Business Technology Transfer (STTR) activities garnered 17 of 50 (34%) total responses; improved advanced manufacturing techniques garnered 10 of 50 (20%) of the responses; improvements in testing, sensing, analysis, and ModSim obtained 9 of

50 (18%) responses; and the last two sub-categories of cost improvements and manufacture of improved materials logged 7 responses each for a combined 28% (7 + 7 of 50) of the total R&D Needs responses. Of specific note were the number of responses indicating the value placed on national laboratories and their roles in developing advanced materials and manufacturing technologies. National laboratories were seen to be ideal locations for testbed activities where expensive-to-maintain equipment and standardized test loops could be housed as user facilities. Also of importance were comments pointing to national laboratories playing important roles in establishing common test criteria, providing input to standardization, and participating in materials/manufacturing R&D consortia.

Table 12. Topic 4, Breakout Session 3: R&D Needs Categories and Number of Responses Per Category

R&D Categories	Number of Responses
Government-sponsored labs, testing facilities, collaborations, guidance, working groups, and SBIR/STTR	**17**
Improved advanced manufacturing techniques	**10**
Improvements in testing, sensing, analysis, and ModSim	**9**
Improved costs	**7**
Manufacture of improved materials	**7**

5.4 Breakout Session 4: Enabling Materials through Advanced Manufacturing Technologies

Breakout Session 4 discussed the four key topic areas as they relate to enabling materials through advanced manufacturing technologies.

For each topic area, individual participants' views and responses were captured via GroupMap. For Breakout Session 4, **Topic 1**, opportunity responses were placed into various sub-categories, as shown in Table 13.

For Breakout Session 4, **Topic 2**, some operation/performance metric targets were elucidated. The top 4 are provided in Table 14.

For Breakout Session #4, **Topic 3**, participants provided 62 responses. The top 7 responses in each of the Challenges and Barriers categories are arranged according to rank in Table 15.

In Table 15, about 56% of the identified manufacturing challenges are associated with the advanced manufacturing methods, including but not limited to AM, powder metallurgy, and materials joining. Improvements are still needed with these methods for fabricating robust or resilient materials of high quality for harsh service conditions. Materials and components produced by these routes—even after post-process annealing—often do not possess the same

Table 13. Topic 1, Breakout Session 4: Opportunities for Manufacturing Methods

Category	Rank	Number of Responses
Joining/welding	1	4
Powder metallurgy	2	3
Surface/coatings	3	5
Smart manufacturing	4	21
ModSim	5	5
Repair/re-use	6	2
Scale-up	7	6
Additive manufacturing	8	18

microstructures/textures or physical attributes (e.g., density/porosity) and mechanical properties (e.g., toughness–resistance to cracking, internal/residual stresses) as those materials/components produced by more traditional methods. There is also a limited number of properties data available, as well as a limited number of alloys and feedstocks developed for use by AM. As compared to traditional routes, there is a less mature understanding of AM process fundamentals and process control parameters that could enable production of components with the desired optimal properties. Additionally, AM processes face many scaling challenges, such as slow production speeds, limited materials development (availability of suitable materials), material property inconsistencies and quality assurance issues (repeatability, part-to-part variation), lack of industry-wide standards, and education and workforce development needs (managers, engineers, and technicians possessing the required training and skill sets) to enable the designing of materials/components specifically for AM.

Table 14. Operational and Performance Metric Targets Identified

Description	Rank
Materials for T >1500°C	1
Materials for T >1600°C	2
Improvements to all advanced manufacturing method feedstock powder production efficiencies/yields and powder quality (>30%)	3
AM deposition rate >50 kg/hr	4

Table 15. Breakout Session 4: Challenges and Barriers

Challenges	Barriers	Rank
Design materials specifically for AM processes	Testing the properties of materials under extreme conditions	1
Working with new materials for T >1500°C	No properties database	2
Developing non-line-of-sight coatings process	Inadequate understanding of AM process fundamentals and process control (e.g., AM non-equilibrium solidification)	3
Materials qualification	Inadequate number of alloy feedstocks for AM	4
Need digital twins and machine learning	Low AM repeatability at speed	5
Need more alloys for AM materials development	Lack of availability of pilot-scale equipment for refractory AM materials	6
Metallic material compatibility with AM materials with 1000°C+ capability	Potential for oxide impurities from traditional ceramic crucible melting/atomization	7

About 11% of the challenges are associated with smart/digital manufacturing, including a widely recognized need for in situ sensors for harsh environments and needs for increased use of robotics and automation, process data analytics, and data-based approaches such as artificial intelligence/machine learning for speedier materials discovery and process development improvements. Another 11% of the challenges identified are associated with needed improvements to traditional manufacturing technologies.

The balance of the identified challenges, 22%, is apportioned between various items: field demonstration, supply chain, coating process, high-temperature materials fabrication, prototyping, and materials discovery challenges.

Technical barriers associated with AM account for 34% of the identified manufacturing barriers. A 12% apportionment is associated with each of the flowing: lack of data/basic (fundamental) understanding, field demonstration, and traditional manufacturing methods. The balance of the identified manufacturing barriers (30%) is allocated between standardization, protection of intellectual property, excessive regulation/restrictions, education and workforce development, and materials testing barriers.

For Breakout Session 4, **Topic 4**, top R&D needs of the end-use applications and manufacturing processes were identified. Participants provided 9 responses, the top 6 of which are shown in Table 16, according to rank. Table 16 shows that the identified manufacturing R&D needs closely mirror the challenges discussed above, namely, the needs for 1) a properties database; 2) increased understanding of AM process fundamentals and control to enable design for AM; 3) digital twins; 4) demonstration projects; 5) in situ process monitoring; and 6) accelerated process qualification for advanced manufacturing methods.

Table 16. Breakout Session 4, Topic 4: R&D Needs Identified

R&D Need	Rank
Need materials properties database	1
Materials qualification	2
Increase understanding of AM process fundamentals and process control to enable Design for AM	3
Develop digital twins	4
Demonstration projects with pre- and post- materials/manufacturing evaluations	5
In situ process monitoring technologies	6

5.5 Breakout Session 5: Accelerating Qualification of Advanced Materials and Experimental Validation of ModSim Methodology for Materials, Manufacturing, and Performance During Service

Breakout Session 5 focused on accelerating qualification of advanced materials and experimental validation of ModSim methodology for materials, manufacturing, and performance during service. The following four topic areas were discussed during the discussion:

- Topic 1: High-impact opportunities for advancing the technology area(s)
- Topic 2: Key performance and operational metrics and targeted advancement
- Topic 3: Key challenges (actionable items to be taken in working with the opportunities) and barriers (obstacles/hurdles) that impede advancement
- Topic 4: R&D needs

For each topic area, individual participants' views and responses were captured via GroupMap. For Topic 1, 43 responses were obtained and ranked during the session. The top 6 responses are found in Table 17 according to their ranking.

Table 17. Breakout Session 5, Topic 1: High-Impact Opportunities for Advancing Technology Areas

Response	Rank
High temperature testing capabilities	1
Utilizing WBG power electronics devices in harsh environment and understanding their reliability	2
Developing reliable models to translate the behavior/response from an accelerated test to service life	3
Development of high throughput testing techniques for critical properties and mix-mode failures	4
Defining and deploying the necessary tools, sensors, software, and interfaces to enable a future digital manufacturing economy	5
Uncertainty quantification of experimental and computational data	6

The top-ranked response, “High-temperature testing capabilities,” obtained a score of 9.5 out of 10 possible; however, further analysis of the 43 responses show that 24 responses (55.8%) could be sub-categorized under a single topic heading titled “Machine Learning, Artificial Intelligence, Lifetime/Failure Prediction, and ModSim Improvements.” The top-ranked response “High-temperature testing capabilities” was one of three responses obtained under the sub-category titled “Improved Testing Capabilities.” When the responses are grouped (with less focus on their numerical ranking), the data decidedly show that modeling issues were of significant interest to participants where acceleration of qualification is desired. High-temperature testing capabilities certainly are important, but the majority of the “discussion” for Topic 1 in Breakout Session 5 was centered on ModSim and development of prediction tools for accelerating qualification. Table 18 demonstrates the disparity between responses received related to prediction tools and the rest of the comment sub-categories.

The 20 responses obtained during Breakout Session 5, Topic 2, Operational and Performance Metric Targets, are given in Table 19 according to their ranking. Of the top 10 ranked responses, 4 responses are related to modeling and predictive tools, with no other “sub-category” being so heavily represented in the top 10.

Analysis of the complete Topic 3 data set shows 9 of 27 (33.3%) responses related to ModSim needs and predictive tools, 5 of 27 (18.5%) responses related to testing and test conditions, and 4 of 27 (14.8%) responses related to standards and standardization methodology where accelerated qualification was of concern.

There were 27 responses generated during discussion of Topic 3, Challenges and Barriers, Breakout Session #5. The top 4 responses are found in Table 20, according to their ranking.

Table 18. Breakout Session 5, Topic 1: Grouping of Responses

Response Sub-Category	Number of Responses
Machine learning, artificial intelligence, lifetime/failure prediction, and ModSim Improvements	24
Improvements in sensors	6
Improved testing capabilities	3
Calls for consortia	3
Improvements in diffusion bonding	2
Utilizing wide-bandgap power electronics devices in harsh environments and understanding their reliability	1
A compact heat exchanger, cross-cutting NE, FE, Solar	1
Design and development of new refractory alloy-containing functionally graded materials	1
Coatings and code qualifications for such for use in harsh environments	1
Using non-crystalline solids (e.g., glasses) in AM	1

Table 19. Breakout Session 5, Topic 2: Operational and Performance Metric Targets

Response	Rank
Incorporating multiple failure modes into an integrated model to increase design capability and improve part life predictions	1
Conventional Si-based vs. wide-bandgap power electronics for high-temperature operation	2
Acceleration of the quantification of uncertainty in the performance of structure induced by initial micro-structure and with varying operating conditions	3
Standardize how committed resources are tracked	4

The top-ranked responses were evenly spread between developing standards, developing improved models, and obtaining quantitative/empirical data under standardized conditions to better understand model performance for qualification efforts.

Breakout Session #5, Topic 4, R&D Needs, garnered 15 responses. The top 4 responses are found in Table 21. Analysis of Topic 4, R&D Needs, data indicates the top-ranked responses related to modeling, accelerated testing, and quantitative testing for model validation.

Table 20. Breakout Session 5, Topic 3: Challenges and Barriers

Response	Rank
Development and testing of standards for utilizing accelerated aging tests for model validation	1
Reliable models to predict intrinsic ductility of alloys, ductile-to-brittle transition, oxidation resistance, and corrosion resistance	2
Minimized test duration while still obtaining relevant information that accurately reflects long-term tests at service conditions (time, temperature, environment)	3
Bridging bench-scale testing and full-scale dyno testing and actual operation	4

Table 21. Breakout Session 5, Topic 4: R&D Needs

Response	Rank
Cross-validating modeling with accelerated testing for electronic devices and materials for harsh applications	1
In situ sensing, which is critical for both process development and field operation	2
Development of a methodology to benchmark power electronic devices for their application in harsh conditions; collection of data to develop a degradation model; and development of a platform to perform in situ failure analysis to facilitate advanced manufacturing of power electronic devices for hash application	3
R&D to bridge bench-scale testing and full-scale dyno testing and actual operation	4

Breakout Session #5 attendees were also asked to list their top 3 challenges and then to rank each challenge listed. The attendees provided 17 #1 challenge responses, 11 #2 ranked challenges, and 9 #3 challenges. The top four responses are provided and ranked in Table 22, Table 23, and Table 24. Of particular note was the mention of “lack of data” or “data scarcity” for modeling, which points to a need to obtain more empirical data under standardized test conditions for given material systems.

Table 22. Listing of First Choice R&D Challenges Offered by Participants during Breakout Session 5

#1 R&D Challenge	Rank
Data scarcity – from both test data and field experience as well as high-quality thermodynamic and kinetic databases for complex alloys in different/harsh environments	1
Development of high-throughput, accelerated (short-term) testing methods that sample key mechanisms for long-term degradation	2
Rapid evaluation of properties of multi-component materials, especially at high temperature and in severe environments, via experiments and computation	3
Sparse data for artificial intelligence/machine learning models	4

Table 23. Listing of Second Choice R&D Challenges Offered by Participants during Breakout Session 5

#2 R&D Challenge	Rank
Integrated life-prediction methodology for multiple failure modes	1
Formulating standardized methods for summarizing (statistically) and distributing characterized material microstructures	2
Uncertainty evaluation of data and models at high temperatures and harsh environments	3
Multiple competing damage mechanisms	4

Table 24. Listing of Third Choice R&D Challenges Offered by Participants during Breakout Session 5

Response Category	Rank
Testing methodology to replicate (and validate) field experience	1
Integration of experimental and low-length-scale physics modeling into a machine learning framework to make predictions for long-term properties in a way that respects our knowledge of the physical system	2
Building trust in qualification methodologies and tools, either experimental or computational	3
Reduced material development cycle	4

5.6 Breakout Session 6: Mechanisms for Collaborative Demonstration of Processes at Industrially Relevant Scale

Breakout Session 6 focused on five key topic areas related to Mechanisms for Collaborative Demonstration of Processes at Industrially Relevant Scale.

- Topic 1: Key challenges (actionable items to be taken in working with the opportunities) and barriers (obstacles/hurdles) that impede advancement
- Topic 2: High-impact opportunities for collaboration
- Topic 3: Best practices and structures of existing consortia and national lab models
- Topic 4: Practices that do not work that should be avoided
- Topic 5: How to handle intellectual property and rapid format agreements

For each discussion topic area, individual participants' views and responses were captured via GroupMap. Highlights of discussions on each topic area are given below. Topic 1 elicited 31 responses, which were evaluated and subdivided into 8 different groupings. The top 5 groups, representing 87% of the responses, are shown in Table 25 according to their ranking.

Discussion Topic 2, high-impact opportunities for collaboration, obtained 14 responses. Opportunities offered were of a general nature, and in only two instances did attendees offer specific collaboration examples. Those provided were the Solar Energy Technology Office's example of providing DOE funding for the construction, maintenance, and operation of a test loop at Oak Ridge National Laboratory, and supercritical CO_2 bearing/seal testing facilities at GE. National lab user testing facilities were generally cited, as were the contract vehicles (e.g., Strategic Partnership Projects, Cooperative Research and Development Agreements, SBIR/STTR) for conducting business at the national labs.

Topic 3, best practices and structures of existing consortia and national lab models, obtained 29 responses from 11 different authors. Several of the more notable comments could be categorized into what would be referred to as "Customer Service": the ability to provide a customer service and to have the affiliated attitude of customer service. Excellence in customer service and having an agile, functional contractual ability to interact with academic, government, and private industry customers has many standard best practices. It is not difficult to point out those best practices when one receives an excellent service. The contrary is also true. For national labs and other organizations desiring to engage in a collaborative effort, it is more challenging to initiate said excellence and service, and then maintain that excellence and service over time.

Discussion of Topic 4, what does not work and should be avoided, elicited 4 different responses from 4 participants. The 4 responses can be viewed as practices that are lacking in a "service attitude" or practices that do not have a "customer-focused attitude" or do not engender the desire to provide excellence in customer service.

Table 25. Breakout Session 6, Topic 1: Key Challenges and Barriers

Response Category	Rank
Qualification, and testing for qualification	1
Transitioning technology from labs to industry	2
Supply chain stability	3
Risk associated with introducing new materials/technologies to industry	4
Advanced manufacturing scaling, iterative problem-solving	5

Topic 5, how to handle intellectual property and rapid format agreements, resulted in 6 responses, 3 of which related to problematic issues involving the relationships between government national laboratories and industry, and the expectations which each party has going into the relationship. Of the remaining responses, 2 dealt with establishing longer-term intellectual property strategies, or a master intellectual property strategy framework over the organization.

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Appendix A: Agenda

Materials for Harsh Service Conditions Virtual Workshop
October 27 – 30, 2020
AGENDA

Energy in Transition – Understanding the Characteristics and Production Barriers for High Performance Materials for Tomorrow's Energy Systems

Day 1 – Oct 27

- 9:00 – 9:10 am Mountain Time: Workshop Administrative Team - Attendee instructions and expectations (**Moderator**)
- 9:10 – 9:20 am Mountain Time: Welcome from the AMO Office (**Valri Lightner**)
- 9:20 – 9:30 am Mountain Time: Workshop Background and Purpose (**Nick Lalena**)

Fossil Energy Office:

- 9:30 – 9:35 am Mountain Time: Welcome from the FE Office, **Angelos Kokkinos**, Associate Deputy Assistant Secretary, Clean Coal and Carbon Management, Office of Fossil Energy
- 9:35 – 9:55 am Mountain Time: FE Office **Robert Schrecengost**, Program Manager, Office of Fossil Energy, "FE Office Overview: Materials for Harsh Environments".
- 9:55 – 10:15 am Mountain Time: **Sean Bradshaw**, Turbine Technology Manager, Pratt & Whitney representing the Gas Turbine Association, "Energy in Transition – High Performance Materials and Systems for Tomorrow's Energy Sector".
- 10:15 – 10:35 am Mountain Time: **Neva Espinoza**, Vice President Energy Supply and Low Carbon Resources, Electric Power Research Institute (EPRI), "Accelerating the Clean Energy Transition Reliably and Affordably".
- 10:35 – 10:55 am Mountain Time: **Jack deBarbadillo**, Special Metals, "Metallic Structural Materials for Advanced Energy Systems".
- 10:55 – 11:15 am Mountain Time: **Charles Atkins,** Ramaco, "Coal to Advanced Materials and Manufacturing from and for Harsh Service Conditions (C2AMM 4HSC)".

BREAK 11:15 am – 11:30 am Mountain Time

Day 1 – Oct 27
NE Office:

- 11:30 – 11:50 am Mountain Time: **Isabella Van Rooyen**, National Technical Director, Advanced Methods for Manufacturing Program for DOE-NEET, "NE Office: Materials for Harsh Service Conditions R&D and Advanced Manufacturing Needs".
- 11:50 – 12:10 pm Mountain Time: **Gay Wyn Quance/Randall Smith**, Solid Carbon Products/Seerstone Development, "Critical Materials: Graphitic Materials from CO_2 - Synthetic Graphite and Carbonite®".
- 12:10 – 12:30 pm Mountain Time: **Dave Gandy**, EPRI, "Materials & Manufacturing Needs for Advanced Nuclear Applications".

- 12:30 – 12:50 pm Mountain Time: **Doug Burns**, Space Nuclear Power and Isotope Systems, Idaho National Laboratory, "Space Nuclear Propulsion (SNP) Fuel Development".
- 12:50 – 1:10 pm Mountain Time: **George Jacobsen**, Lead Scientist, General Atomics**,** **"**Advanced Core Materials for Current and Next Generation Nuclear Reactors."
- 1:10 – 1:30 pm Mountain Time: **Claudio Filippone**, CEO HolosGen, "Distributable Modular Nuclear Reactor Materials/Manufacturing Challenges".

Day 2 – Oct 28

- 9:00 – 9:10 am Mountain Time: Workshop Administrative Team - Attendee instructions and expectations (**Moderator**)

EERE Office up 3rd:

- 9:10 – 9:20 am Mountain Time: **Alex Fitzsimmons**, Deputy Assistant Secretary for Energy Efficiency, Office of Energy Efficiency and Renewable Energy (EERE).
- 9:20 – 9:40 am Mountain Time: **Avi Shultz**, EERE Solar Energy Technologies Office, "Concentrating Solar-Thermal Power (CSP) Research and Development".
- 9:40 – 10:00 am Mountain Time: **Lillie Ghobrial**, EERE Wind Energy Technologies Office, "Wind Energy Materials".
- 10:00 – 10:20 am Mountain Time: **Alexis McKittrick**, EERE Geothermal Technologies Office, "Overview of Harsh Conditions in Geothermal Development".
- 10:20 – 10:40 am Mountain Time: **Ned Stetson**, Hydrogen and Fuel Cell Technologies Office, "Materials Compatibility in Hydrogen Service".

BREAK 10:40 – 11:00 am Mountain Time

Day 2 – Oct 28
AMO Office 4th:

- 11:00 – 11:20 am Mountain Time: **Valri Lightner**, Deputy Director, Advanced Manufacturing Office, "Advanced Manufacturing and Materials for Harsh Service Conditions".
- 11:20 – 11:40 am Mountain Time: **Leo Christodoulou**, "Manufacturing Materials (& Structures) For Extreme Environments".
- 11:40 – 12:00 pm Mountain Time: **Michael Sortwell**, Senior Director, Technology, American Iron and Steel Institute. "Steel Industry Challenges for Producing Steel in Harsh Environments".
- 12:00 – 12:20 pm Mountain Time: **Mark Thompson**, Principal Scientist, GE Research, "Materials and Processing Challenges for Power Generation."
- 12:20 – 12:40 pm Mountain Time: **Jason Sebastian**, President, QuesTek Innovations, "Materials Challenges and ICME for Advanced Alloys for Harsh Environment Applications".
- 12:40 – 1:00 pm Mountain Time: **Max Christie**, R&D Director-Ceramic Membranes, Linde, "Materials for Harsh Service Environments: Linde Priorities".
- 1:00 – 1:20 pm Mountain Time: **Adam Stevenson**, Saint-Gobain, "Challenges for Materials in Harsh Service Environments".

Day 3 October 29, 2020 BREAKOUT SESSION #1: Materials for Thermal Management, Extreme Temperatures, and Energy Conversion.
9:00 am – 1:00 pm Mountain
Session Leads (Jeff Hawk (NETL), Kashif Nawaz, (ORNL))

Day 3 October 29, 2020 BREAKOUT SESSION #2: Wear, Oxidation, and Corrosion-Resistant Alloys, Components, and Coatings for Static and Rotary Applications.
9:00 am – 1:00 pm Mountain
Session Leads (Bruce Pint (ORNL), Brian Gleeson (University of Pittsburgh))

Day 3 October 29, 2020 BREAKOUT SESSION #3: Ceramics, Composites, and Functionally Graded Materials for Harsh Environments.
9:00 am – 1:00 pm Mountain
Session Leads (Edgar Lara-Curzio (ORNL), Elizabeth Opila (University of Virginia))

Day 4 October 30, 2020 BREAKOUT SESSION #4: Enabling Materials through Advanced Manufacturing Technologies.
9:00 am – 1:00 pm Mountain
Session Leads (Gary Rozak (HC Starck), Isabella Van Rooyen (INL))

Day 4 October 30, 2020 BREAKOUT SESSION #5: Accelerating Qualification of Advanced Materials & Experimental Validation of ModSim Methodology for Materials, Manufacturing, and Performance During Service.
9:00 am – 1:00 pm Mountain
Session Leads (David Alman (NETL), Michael McMurtrey (INL))

Day 4 October 30, 2020 BREAKOUT SESSION #6 ROUND TABLE: Mechanisms for collaborative demonstration of processes at industrially relevant scale.
9:00 am – 1:00 pm Mountain
Session Leads (Briggs White (NETL), Rob O’Brien (INL))

Appendix B: Participants

Larry Aagesen, Idaho National Laboratory

Michaela Abbs, Idaho National Laboratory

Mohammed Hussain Abdul Jabbar, Nissan-USA

Aamir Abid, Retech Systems, LLC

Dylan Addison, Nuscale Power

Trevor Aguirre, Oak Ridge National Laboratory

Moinuddin Ahmed, Argonne National Laboratory

Oyelayo Ajayi, Argonne National Laboratory

Erik Albenze, National Energy Technology Laboratory

David Alman, National Energy Technology Laboratory

Tyler Alvarado, Continuous Composites

Caleb Amy, Department of Energy

Iver Anderson, Ames Laboratory

Phani Angara, Tenaris

Christina Arendt, Pacific Northwest National Laboratory

Beth Armstrong, Oak Ridge National Laboratory

Clint Armstrong, Westinghouse

Saravanan Arunachalam, Spirit AeroSystems

Charles Atkins, Ramaco Carbon

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