Materials for Harsh Service Conditions Workshop, November 19 – 20, 2015
Westin Convention Center Hotel, Pittsburgh, PA

Overall Purpose

- To gather input from stakeholders on the vision of future opportunities and technical challenges facing development and scale-up of materials, process, and equipment that can make step-change improvements of system performance in harsh service conditions. The Advanced Manufacturing Office (AMO) of DOE also seeks individual input on challenging performance metrics and identification of key problem sets to be addressed. The intent is to define critical crosscutting problems/barriers that if successfully addressed represent a step change beyond current state of the art.

Session Purposes

- To identify high value opportunities and manufacturing challenges to improve energy efficiency, reduce emissions, and extend useful life where harsh service conditions exist
- To increase natural gas turbine and rotary machinery temperature operation for improved system operational efficiency
- To develop material science and innovative technology for high temperature industrial, transportation, and clean energy systems and components
- To scale-up promising materials and manufacturing systems (grams to kilograms)
- To identify opportunities to reduce corrosion (oxidation/chemical/electrochemical/galvanic/other)
- To identify opportunities to reduce mechanical wear
- To introduce manufacturing communities that support materials and systems development for harsh service conditions to the U.S. DOE Advanced Manufacturing Office (AMO) and EERE offices
- To strategize how best to leverage R&D among the U.S. DOE and other Federal agencies
- To encourage discussion and networking among leaders in the field

Non-Purpose

- To reach 100% consensus or identify the solutions to problems that are identified
- To discuss specific budget formulation activities, procurement-sensitive or proprietary activities
- To reorganize EERE or the Advanced Manufacturing Goals, or discuss other non-germane issues

Facilitation Ground Rules

- No Speeches
- Listen to Each Other
- Suspend Judgment
- Spin/Churn Thoughts into Rich Ideas
- Merge Ideas to Create Strength
- Narrow to a Manageable Few
- Focus on Unique Factors
- Challenge Ideas, not People

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Description of the Opportunity:

The physical limitations of materials in demanding environments have long constrained engineers in the design of innovative new products and technologies. Aggressive service environments can involve high temperatures, high pressures, corrosive chemicals, mechanical wear, neutron irradiation, and hydrogen attack. These aggressive environments—and the associated materials durability challenges—are common across multiple applications and sectors, and new materials solutions are needed to meet stringent application demands for future products that will provide energy savings, emissions reductions, and other benefits. As a few examples:

- Gas and steam turbine power plants could achieve higher efficiencies if they operated at higher inlet temperatures, but operating temperatures are constrained by the thermal stability of existing turbine alloys at high temperatures and pressures. Gas, steam, and combined cycle turbine power plants in the U.S. electric power sector collectively generate about 1,800 million megawatt hours (6 Quads) of electricity annually,[1] comprising about 46% of the country's total electricity production.[2]
- Process heating across the manufacturing sector alone consumes over 7 Quads of energy.[3] 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.
- Waste heat recovery can provide major efficiency gains at manufacturing sites, but many sources of industrial waste heat are currently unrecoverable because recuperator alloys are incompatible with corrosive, high-temperature flue gases. Process heating across the manufacturing sector alone consumes over 7 Quads of energy.[4]
- Conventional nuclear fuel cladding materials are unstable at very high temperatures and can contribute to nuclear core meltdowns in loss-of-coolant accidents.[5] Safer, irradiation-resistant and phase-stable nuclear fuel cladding materials could mitigate Fukushima-like disasters at nuclear facilities.

Research Needs:

Durable materials have a strong impact on national infrastructure. While private entities are key stakeholders in these technologies, they lack the resources for infrastructural overhauls. Private companies may also have limited access to the analysis tools and equipment needed to develop new materials or adapt a new material to their needs. Uncertainties associated with emerging technologies also deter private industry from developing the new materials needed to advance technologies such as waste heat recovery in harsh environments, damage-resistant nuclear fuel cladding, and ultra-supercritical steam turbines—despite the potential energy and cost savings.

Because durable materials technologies are inherently interdisciplinary, major opportunities exist for national initiatives that tie together research and development efforts across fields. Resource sharing is one key element of additionality for such efforts.

Focus/Topics of Potential Efforts:

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[1] Total generation for steam, gas, and combined cycle turbines was calculated by assuming that these prime movers contribute 72% of all coal, oil, and natural gas electricity generation. The 72% ratio was calculated from the breakdown of capacities by prime mover as reported in 2012 EIA-860 survey data (http://www.eia.gov/electricity/data/eia860/). Total electricity production by fuel type was drawn from Annual Energy Outlook data (http://www.eia.gov/forecasts/aeo/data.cfm#summary).
[2] *Annual Energy Outlook 2014, Reference Case Data*
[3] "Manufacturing Energy and Carbon Footprint: All Manufacturing (NAICS 31-33)", U.S. DOE Advanced Manufacturing Office (2014), available from: http://energy.gov/sites/prod/files/2014/02/f7/2014_all_manufacturing_energy_carbon_footprint.pdf.
[4] "Manufacturing Energy and Carbon Footprint: All Manufacturing (NAICS 31-33)", U.S. DOE Advanced Manufacturing Office (2014).
[5] P. Hofmann, S. Hagen, G. Schanz, and A. Skokan, "Chemical Interaction of Reactor Core Materials Up to Very High Temperatures," Kernforschungszentrum Karlsruhe Report No. 4485 (1989).

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Research needs can be roughly divided into three crosscutting materials challenges. For example, **phase-stable materials** are needed for extreme environments such as ultra-high pressure, ultra-high temperature, or thermal cycling. Research in **functional surfaces** is needed to develop advanced coatings and surface treatments that provide outstanding material properties at surfaces, such as corrosion and wear resistance. **Embrittlement-resistant materials** are needed to resist material aging effects in certain extreme environments, including exposure to hydrogen (which can cause hydrogen embrittlement) and radiation (which can cause neutron embrittlement and radiation-induced swelling). Key technology opportunity areas include:

- ***High Temperature and Corrosion Conditions:*** Heat recovery is often not possible for contaminated heat sources because heat recovery equipment lacks adequate resistance to corrosion, oxidation, and fouling, processes which are accelerated at high temperatures. Furthermore, materials that are suitable for use at temperatures above 2100°F, where the highest energy gains are possible, are costly. Cost-efficient technologies are also needed not only to recover heat from the exhaust gases at high temperatures, but also selective separation of water vapor or steam, CO_2, oil, or organic liquid vapors without the need for cooling the entire gas mass. Example applications include industrial waste heat recuperator, ultra-supercritical steam turbine, and desalination systems.
- ***Mechanical Wear in Gas Turbines, Rotary Machinery and Non-Rotating Machinery:*** Gas, steam, and combined cycle turbine power plants in the U.S. electric power sector collectively generate about 1,800 million-megawatt hours of electricity annually, comprising about 46% of the country's total electricity production. Gas and steam turbine power plants could achieve higher efficiencies if they operated at higher inlet temperatures, but operating temperatures are constrained by the thermal stability of existing turbine alloys and coatings at high temperatures and pressures. Example applications include oil and gas equipment and geothermal turbomachinery.
- ***Radiation and Hydrogen Embrittlement Environments:*** Conventional nuclear fuel cladding materials are unstable at very high temperatures (in excess of normal core operating conditions) and limit operating temperatures and thermal efficiency. Phase transitions and reactivity of zirconium alloys may contribute to nuclear core damage in loss-of-coolant accidents. Improved irradiation-resistant and phase-stable nuclear fuel cladding materials could mitigate the consequences of accidents at nuclear facilities. Example applications include nuclear fuel cladding and hydrogen pipelines and storage tanks.

One example of a specific opportunity is the class of materials known as Superalloys that are primarily used in turbine engines owing to their creep resistance, excellent strength, and stability at extremely high temperatures. Expanded opportunities for these materials could be realized if alloys and associated manufacturing methods are developed for components that are easy to fabricate and join. Benefits would include steamside oxidation and erosion resistance, and high-temperature fireside corrosion resistance over component lifetime

Potential Outcomes and Impacts:

Addressing *Materials for Harsh Service Conditions* challenges through collaborative industry/university/ government partnerships has multiple benefits. Pre-competitive technologies can be defined and addressed using shared resources. Productive collaborative relationships between industry competitors are used to advantage to provide crosscutting new materials and related technology developments with broad impacts. Self-sustained development of new materials is encouraged.

On the deployment and market acceptance side, technologies can be demonstrated and risk mitigated to accelerate real-world, specific applications. Investments would serve to enable innovations and development activities, moving technologies from TRL 3-4 to TRL/MRL 6-7 and toward deployment. Clear goals can be established to demonstrate and transition new materials to industry, with clear roadmaps towards cost competitiveness for high throughput manufacturing.

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In terms of competitiveness and value proposition, new materials and technologies will lead to less energy-intensive manufacturing and facilitated scale-up due to reduced factory capital costs. The manufacturability of products with new materials can be demonstrated at pilot-scale, enhancing development of manufacture-able products such gas turbines and desalination systems. As part of these efforts, facilities can be offered with test-beds for in-the-loop hardware testing in a relevant environment (TRL 5) to enable functional demonstration of high-throughput capabilities for crosscutting applications.

Further background is available at:

- QTR 2015 Materials for Harsh Service Conditions: Technology Assessment. http://energy.gov/sites/prod/files/2015/02/f19/QTR%20Ch8%20-%20Materials%20for%20Harsh%20Service%20Conditions%20TA%20Feb-13-2015.pdf
- QTR 2015. http://www.energy.gov/sites/prod/files/2015/09/f26/QTR2015-06-Manufacturing.pdf
- Technologies and Materials for Recovering Waste Heat in Harsh Environments. http://info.ornl.gov/sites/publications/files/Pub52939.pdf
- Materials: Foundation for the Clean Energy Age. http://energy.tms.org/docs/pdfs/Materials_Foundation_for_Clean_Energy_Age_Press_Final.pdf
- DOE Office of Energy Efficiency & Renewable Energy. http://energy.gov/eere/office-energy-efficiency-renewable-energy