Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessments

Additive Manufacturing

Advanced Materials Manufacturing

Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Combined Heat and Power Systems

Composite Materials

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Wide Bandgap Semiconductors for Power Electronics

U.S. DEPARTMENT OF ENERGY

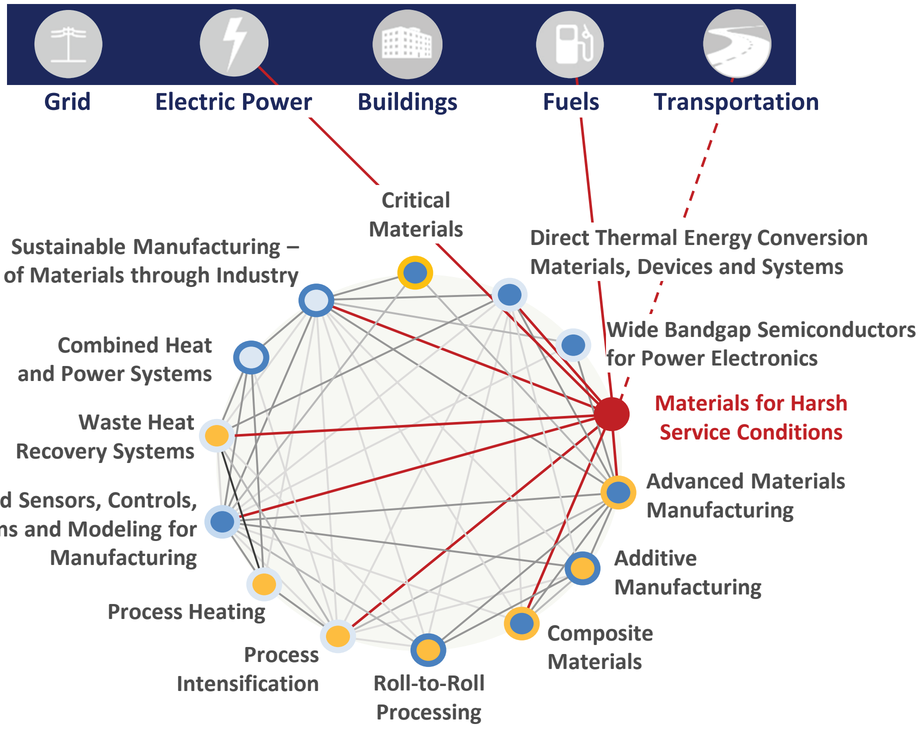
Quadrennial Technology Review 2015

Materials for Harsh Service Conditions

Chapter 6: Technology Assessments

NOTE: This technology assessment is available as an appendix to the 2015 Quadrennial Technology Review (QTR). Materials for Harsh Service Conditions is one of fourteen manufacturing-focused technology assessments prepared in support of Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. For context within the 2015 QTR, key connections between this technology assessment, other QTR technology chapters, and other Chapter 6 technology assessments are illustrated below.

Connections to other QTR Chapters and Technology Assessments



Representative Intra-Chapter Connections	Representative Extra-Chapter Connections
■ **Sustainable Manufacturing/Advanced Materials Manufacturing:** materials to increase durability or facilitate re-use; materials genome techniques for new materials development ■ **Composite Materials:** lightweight, durable structural components for automobiles; erosion-resistant composites for wind turbine blades and turbomachinery ■ **Direct Thermal Energy Conversion:** thermal conversion materials and devices for high-temperature or corrosive environments ■ **Advanced Sensors, Controls, Platforms and Modeling for Manufacturing:** computational modeling to support advanced materials development	■ **Fuels:** corrosion in offshore drilling equipment; ash fouling in biomass conversion equipment; hydrogen embrittlement in H_2 pipelines ■ **Electric Power:** radiation-resistant fuel cladding; high-temperature alloys for nuclear reactors and gas and steam turbines ■ **Transportation:** corrosion-resistant lightweight materials

Introduction to the Technology/System

Overview of Materials for Harsh Service Conditions

The physical limitations of materials in demanding environments have long constrained engineers in the design of innovative products and technologies. Aggressive service environments can involve, for example, high temperatures and thermal cycling, high pressures, corrosive chemicals, dust and particulates, mechanical wear, neutron irradiation, and hydrogen attack. These aggressive environments—and the associated materials durability challenges—are common across multiple applications and sectors. New materials and new materials processing solutions are needed to meet stringent application demands for future products that will provide energy savings, emissions reductions, and other benefits. Following are 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 and coatings 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 billion kilowatt hours of electricity annually, comprising about 46% of the country's total electricity production.[1]
- Process heating across the manufacturing sector consumes more on-site energy than any other energy-consuming system, and approximately 36% of this energy is lost as waste heat.[2] There are significant opportunities to recover waste heat from industrial process heating operations, but many sources of industrial waste heat are currently unrecoverable because existing heat exchanger alloys and power conversion materials are incompatible with corrosive, high-flow-rate, and/or high-temperature flue gases. Improved heat transfer equipment and hot gas cleanup operations would benefit from materials development.
- Corrosion of iron and steel pipelines can cause leakage of natural gas, 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.[3]
- Aluminum and other lightweight structural metals 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.[4] However, the use of lightweight metals in automobiles is limited by their resistance to corrosion and durability in high-friction environments as well as joining and repair challenges.
- 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.[5] Improved irradiation-resistant and phase-stable nuclear fuel cladding materials could mitigate the consequences of accidents at nuclear facilities.

Depending on the application, many different types of materials can be used in harsh environments, including metal alloys, polymers, ceramics and glasses, and composites. For some applications, materials that meet performance requirements are unavailable and new materials must be developed and qualified. In other cases, materials that meet the application's stringent operation requirements are available, but costs are too high to justify use of the material. In those cases, research is needed to improve the efficiency of processing techniques and equipment in order to bring the manufacturing costs of these materials down.

Challenges and Opportunities

Research needs can be roughly divided into three crosscutting materials challenges:

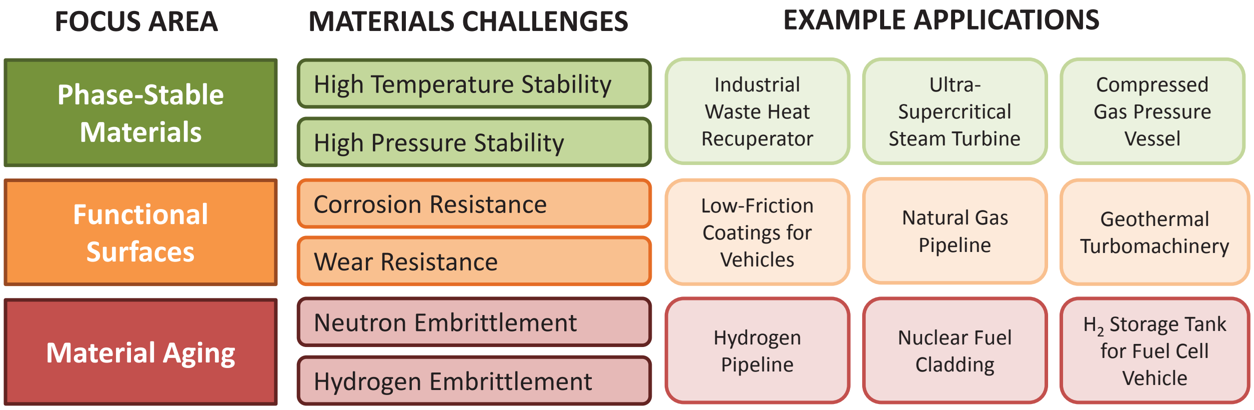
(1) **Phase-stable materials** are needed for extreme environments, such as ultrahigh pressure, ultrahigh temperature, or thermal cycling;

(2) 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; and

(3) 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).

Example applications within these three major research areas are illustrated in Figure 6.H.1. Note that, while this framework is useful for grouping applications based on shared materials challenges, some applications cross multiple research focus areas or materials challenges; for example, a pipeline designed for blended transmission and distribution of natural gas and hydrogen is susceptible to both corrosion and hydrogen embrittlement.[6]

Figure 6.H.1 Major Research Areas Include Phase-Stable Materials, Functional Surfaces, and Material Aging. Within each cross-cutting area, numerous clean energy applications provide opportunities for energy savings and emissions reductions.



FOCUS AREA	MATERIALS CHALLENGES	EXAMPLE APPLICATIONS		
Phase-Stable Materials	High Temperature Stability High Pressure Stability	Industrial Waste Heat Recuperator	Ultra-Supercritical Steam Turbine	Compressed Gas Pressure Vessel
Functional Surfaces	Corrosion Resistance Wear Resistance	Low-Friction Coatings for Vehicles	Natural Gas Pipeline	Geothermal Turbomachinery
Material Aging	Neutron Embrittlement Hydrogen Embrittlement	Hydrogen Pipeline	Nuclear Fuel Cladding	H_2 Storage Tank for Fuel Cell Vehicle

Public and Private Research and Development (R&D) Activities

A representative list of ongoing public and private research activities related to durable materials is detailed in Table 6.H.1. A common link between programs is that they are generally application focused: research is initiated and carried out with an aim to solve a particular problem. This focused approach fails to recognize that many materials challenges are shared by many applications, and programs may have substantial overlap. A gap in current public and private research activities is a convening power to unify research under the durable materials umbrella, which could provide tremendous new opportunities for collaboration among researchers investigating materials for different applications.

Table 6.H.1 Ongoing Public and Private R&D Programs in Key Application Areas for Materials in Harsh Environments

Application	Significant Programs	R&D Focus Areas
High-Temperature Materials for Gas and Steam Turbines	■ Department of Energy (DOE) Clean Coal Plant Optimization Technologies Program ■ Electric Power Research Institute (EPRI) Fossil Fleet for Tomorrow Program ■ EPRI Fossil Materials and Repair Program	The DOE Clean Coal Plant Optimization Technologies Program includes R&D on high-temperature turbine alloys in its focus. EPRI programs are conducting research on corrosion, fabrication methods, and joining techniques for advanced ferritic and austentitic alloys.
Durable Nuclear Fuel Cladding Materials	■ DOE Light Water Reactor Sustainability Program ■ EPRI Long-Term Operations Program	The DOE Light Water Reactor Sustainability Program includes cladding research as a subtopic within the "Advanced Light-Water Reactor Nuclear Fuels" R&D pathway.
Materials for Waste Heat Recovery in Harsh Environments	■ Oak Ridge National Laboratory (ORNL)/Gas Technology Institute Project: Advanced Energy and Water Recovery Technology from Low Grade Waste Heat	Research in the DOE Advanced Manufacturing Office includes as a focus “innovative waste-heat recovery to improve sustainability, reduce water usage, and decrease the energy footprint of U.S. manufacturing.”
Corrosion- and Embrittlement-Resistant Materials for Gas Pipeline Infrastructure	■ DOE Hydrogen and Fuel Cells Program ■ National Institute of Standards and Technology (NIST) Hydrogen Pipeline Material Testing Facility ■ NIST Pipeline Safety Program ■ Energy & Environmental Research Center’s National Center for Hydrogen Technology	Related research is underway at the National Center for Hydrogen Technology, NIST, and the DOE Hydrogen and Fuel Cells Program, but no program ties together durability issues for natural gas and hydrogen pipelines. This could be especially important to enable a shared hydrogen/natural gas pipeline infrastructure (mixed-gas pipelines).
Corrosion- and Wear-Resistant Lightweight Structural Metals in Vehicles	■ DOE Vehicle Technologies Office: Materials Technologies ■ Lightweight Innovations for Tomorrow (LIFT) Institute ■ ORNL Carbon Fiber Technology Facility (CFTF) ■ Institute for Advanced Composites Manufacturing Innovation (IACMI) ■ Army Research Laboratory (ARL) Coatings Team ■ Office of Naval Research (ONR) Antifouling/Fouling Release Coatings Program ■ ONR Propulsion Materials Program ■ Naval Air Systems Command (NAVAIR) Corrosion Program ■ United States Automotive Materials Partnership (USAMP)	Academic and industry researchers are currently developing advanced processing methods and anticorrosion coatings for lightweight alloys and composites. ARL is performing research on corrosion-resistant coatings for vehicles, munitions, and other equipment, while ONR and NAVAIR are actively researching surface treatments that resist fouling, corrosion, and degradation in marine and aerospace applications. The new LIFT Institute will focus on manufacturing and scale-up of innovative lightweight alloys. The CFTF is (and on commission, IACMI will be) investigating advanced manufacturing technologies for carbon fiber composites. USAMP is an industry partnership focused on the development of new materials and processes for lightweight vehicles.

Table 6.H.1 Ongoing Public and Private R&D Programs in Key Application Areas for Materials in Harsh Environments, continued

Application	Significant Programs	R&D Focus Areas
Corrosion-resistant materials for geothermal applications	■ DOE Geothermal Technologies Office ■ Frontier Observatory for Research in Geothermal Energy	No major government research programs are investigating corrosion-resistant geothermal turbomachinery,[7] but a U.S. start-up company showcased at the 2014 DOE National Clean Energy Business Plan Competition is now developing corrosion-resistant, low-cost carbon fiber turbocompressors.[8]
Other applications	■ ONR Ultra-High Temperature Materials Program ■ Air Force Office of Scientific Research (AFOSR) Aerospace Materials for Extreme Environments	ONR is investigating materials with stability at temperatures of 2500°C and higher for missiles and thermal isolation systems. AFOSR is seeking new materials with outstanding structural and multifunctional characteristics at temperatures above 1000°C for aerospace applications.

Technology Assessment and Potential

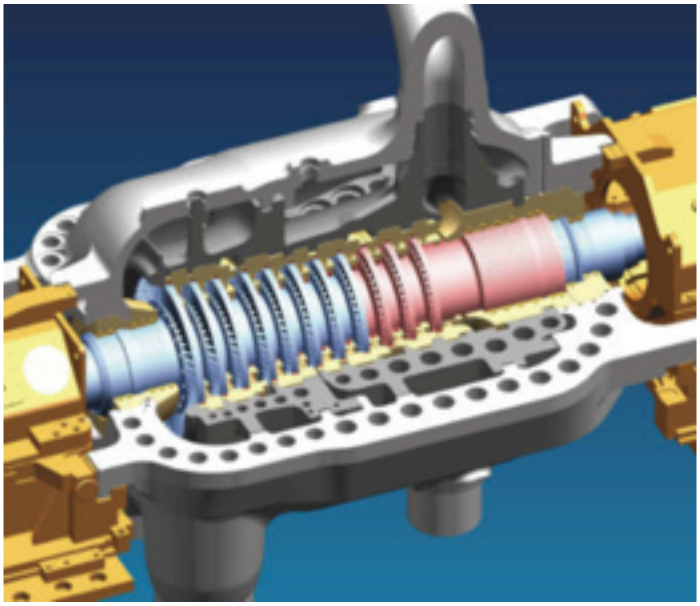
Considering the broad cross-cutting applicability of durable materials, it is not possible to identify and sum every current and future energy-savings opportunity in this area. Instead, a case study approach was used to identify the opportunity space and potential benefits for important known applications. Impacts for six applications are explored in this section.

Gas and Steam Turbines

Gas, steam, and combined-cycle turbine power plants in the United States consume an estimated 16.7 quads of primary energy to produce 1,800 billion kWh (6.2 quads) of electricity output.[9] These power plants account for almost all of the electric power industry's emissions, with 1.7 billion tons of greenhouse gases (carbon dioxide [CO_2] equivalent) released into the environment annually from coal-fired plants alone.[10] The majority of U.S. gas and steam turbine power plants operate in the subcritical regime, resulting in an overall fleet average efficiency of

Figure 6.H.2 Schematic of an Advanced Ultra-supercritical Steam Turbine with 1400°C Superalloy Inlet[16]

Credit: GE Power and Water



just 37%.[11] Advanced ultra-supercritical turbines operating at main steam temperatures of 1300°F and above, shown schematically in Figure 6.H.2, could boost efficiencies of steam turbines beyond 50%.[12] Combined cycle power plants—which utilize both a gas and steam turbine working from the same source of heat for increased efficiency—can reach even higher efficiencies.[13] The relationship between operating conditions, typical net plant efficiency, and net plant heat rate is shown in Table 6.H.2 for coal-fired plants.

Table 6.H.2 Relationship Between Operating Conditions, Plant Efficiency, and Heat Rate for Coal-fired Power Plants[14]

Operating Regime	Typical Conditions		Net Plant Efficiency (%)	Net Plant Heat Rate*
	Temperature (Main Steam)	Pressure		
Subcritical	<1000°F	2,400 psi	35%	9,751 Btu/kWh
Supercritical	1050°F	3,600 psi	38%	8,981 Btu/kWh
Ultra-Supercritical	1100°F	4,200 psi	>42%	8,126 Btu/kWh
Advanced Ultra-Supercritical	>1300°F	5,000 psi	>45%	7,757 Btu/kWh

*Net plant heat rate calculated on the basis of fuel higher heating value.

Ultimately, turbine efficiencies are thermodynamically limited by their upper operating temperature. The maximum theoretical efficiency for a heat engine is given by the Carnot relationship ($\eta = 1 - T_H/T_C$, where η is the efficiency and T_H and T_C are the hot and cold operating temperatures). As the temperature increases, so does the efficiency envelope, and typically this also means an increase in the efficiency that can be achieved in practice. Materials research could boost efficiencies by expanding the theoretical envelope. Further R&D is needed to qualify materials with the following minimum characteristics:

- Temperature stability exceeding 1300°F at 5,000 psi pressure
- Minimum 100,000 hour rupture strength of 14,500 psi at the operating temperature[14]
- Steam-side oxidation and erosion resistance over component lifetime
- High-temperature fire-side corrosion resistance to gas mixtures containing deposits of coal
- Good fabricability and joining characteristics, including ability to press-form, machine, and weld material

Key advantages and disadvantages of alloy materials under development for advanced supercritical turbines (ferritic steel, austenitic steel, nickel alloys, and advanced aerospace alloys) are summarized in Table 6.H.3. In addition to the base alloys, research on related technologies such as thermal barrier coatings and advanced blade cooling systems will also help to drive advanced ultra-supercritical turbines towards high-temperature, high-pressure operation goals.

Table 6.H.3 Advantages and Disadvantages of Advanced Ultra-Supercritical Alloys[14,15,16]

Material	Example Alloys	Maximum Operating Temperature (at 5,000 psi)	Advantages	Disadvantages	Possible Applications in an Ultra-Supercritical Turbine
Ferritic Steels	SAVE12, NF12, VM12, MARB2	<650°F	High strength at low-end temperatures; low cost; can be welded readily	Low temperature resistance and sensitive to oxidation, but could be used in some applications with protective coatings	Low-temperature components such as furnace tubing/piping
Austenitic Steels	Super 304H, HR3C, T92, T22	1,000°F–1,270°F	High strength at intermediate temperatures; low cost; can be welded readily	Sensitive to oxidation; low conductivity; high thermal expansion; not suitable for thick-section applications	Mid-temperature applications, including superheater and reheater tubes
Nickel-based Alloys	Haynes 230, Inconel 617, Haynes 740, HR6W	1,370°F–1,460°F	High temperature compatibility; high oxidation resistance	Very high cost; not all alloys are code approved, so extensive testing required	Highest temperature, highest stress components, such as heavy-wall piping
Advanced Aerospace Alloys and Composites	Cobalt- and rhenium--based alloys	1,830°F–2,370°F	Very high temperature compatibility; high oxidation resistance	Extremely high costs; use of critical materials; early technology readiness level	Highest temperature components, including thermal barrier coatings for turbine blades

Waste Heat Recovery

In 2012, the U.S. industrial sector consumed 30.5 quads of primary energy—31% of U.S. primary energy consumption.[17] Roughly one-third of industrial energy use is released as waste heat, and recovery of this excess thermal energy offers substantial opportunities for energy savings and emissions reductions for industrial facilities.[18] Waste heat can be recycled either by redirecting the waste stream for use in other thermal processes (e.g., flue gases from a furnace could be used to preheat a lower-temperature drying oven) or by converting the waste heat to electricity in a process called waste heat-to-power. According to Energy Information Administration (EIA) Manufacturing Energy Consumption Survey data, only about 6% of U.S. manufacturing facilities were using any type of waste heat recovery as of 2010.[19] Among the energy-intensive industries (chemicals, petroleum refining, primary metals, food, and paper products), average usage was somewhat higher, with 13% of facilities using waste heat recovery, but reported use is still low overall.

Opportunities for waste heat recovery are analyzed in greater detail in separate technology assessments (see technology assessments 6.M *Waste Heat Recovery Systems* and 6.G *Direct Thermal Energy Conversion Materials, Devices, and Systems*), but it is worth noting the challenges in recovering waste heat in harsh industrial environments. Many medium- to high-temperature waste streams are contaminated with corrosive chemicals or particulate matter. 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.[20] Furthermore, materials that are suitable for use at temperatures above 1200°F, where the highest energy gains are possible, are costly. There is a strong need for durable, low-cost materials for heat exchanger systems and heat-to-power conversion. Also needed are advanced thermal barrier coatings, adhesion layers, and protective surface treatments that resist wear and corrosion damage from chemical attack, high-flow-rate gases, and particulates in the waste stream. Industries with high potential for energy savings through waste heat recovery in harsh environments include the steel, glass, aluminum, and cement/lime industries. The estimated recoverable energy from high-temperature and corrosive waste heat streams in these industries is estimated to be nearly 250 TBtu annually, as shown in Table 6.H.4. Corresponding emissions reductions from reduced demand for fossil fuels total 14.5 million tons of CO_2 avoided.[21]

Table 6.H.4 Estimated Recoverable Energy from Corrosive and High-Temperature Manufacturing Waste Heat Sources[22]

Manufacturing Industry	Waste Heat Sources	Waste Heat Stream Characteristics	Temperature Range	Technology Challenges	Annual Recoverable Potential*
Steel	Blast furnace	Contains combustibles and particulates	750°F –1112°F	Blast furnace pressures are typically too low for top gas pressure recovery. Contaminated wastewater produced during chemical energy recovery presents disposal challenges. Recuperator corrosion from particulate content in exhaust gas is an issue.	188 TBtu/yr
	Electric arc furnace	Contains combustibles and particulates; variable gas flow	2730°F –2910°F	Exhaust gases can be used to preheat scrap, but process control is challenging owing to variable flow rates, exhaust gas temperature cycling, and flammable contaminants in the scrap. Toxic compounds can form during scrap preheating, raising safety issues.	62 TBtu/yr
	Basic oxygen processes	Contains combustibles and particulates; variable gas flow	2280°F –3090°F	Combustible volatiles present in gases can lead to undesired temperature increases and reactions with constituents of heat exchanger equipment.	30 TBtu/yr
Glass	Glass furnace	Contains particulates and condensable vapors	810°F –2610°F	Regenerators are widely used for primary heat recovery, but unrecovered heat remains significant. Batch/cullet preheating is limited by cleanliness of available cullet. Electric power generation from primary heat recovery unit has not been demonstrated for gases containing particulates.	43 TBtu/yr

Table 6.H.4 Estimated Recoverable Energy from Corrosive and High-Temperature Manufacturing Waste Heat Sources,[22] continued

Manufacturing Industry	Waste Heat Sources	Waste Heat Stream Characteristics	Temperature Range	Technology Challenges	Annual Recoverable Potential*
Aluminum	Aluminum melting furnace	Contains combustibles and particulates	1380°F –1740°F	Combustion air preheating systems are frequently used in the United States, but maintenance costs are high because of corrosion and fouling. Metallic tube heat exchangers can have a lifetime of as little as 6-9 months. Overheating of systems is possible as a result of combustible content in flue gases.	16 TBtu/yr
	Anode baking	Contains combustibles, particulates, and organic matter	570°F –930°F	Technology not yet demonstrated; corrosion, fouling, and overheating are known issues.	2 TBtu/yr
Cement/Lime	Cement kiln (clinker)	Contains particulates, but relatively easy to handle	390°F –750°F	Waste heat is widely used in new plants to preheat charge material, although use increases maintenance costs and retrofitting is difficult for older plants.	53 TBtu/yr
	Lime kiln (rotary)	Contains particulates, but relatively easy to handle	390°F –1110°F	Waste heat is widely used in new plants to preheat charge material, although use increases maintenance costs and can generate excess dust. Costs generally cannot be justified for smaller facilities and retrofits. Regenerators are available, but fouling can be an issue.	41 TBtu/yr
Total					**247 TBtu/yr**

* Includes a small amount of waste heat that is already being recovered using existing waste heat recovery technologies.

Pipeline Infrastructure

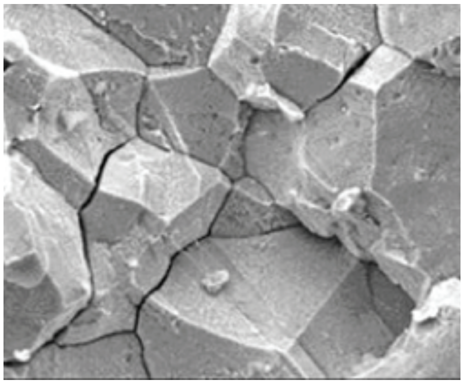
Over 2.1 million miles of natural gas pipelines and 187 thousand miles of hazardous liquid pipelines serve the United States,[23] delivering 24 trillion cubic feet of natural gas[24] and 14.9 billion barrels of oil and petroleum[25] to consumers annually. About 40% of U.S. natural gas pipelines and 50% of hazardous liquid pipelines date from the 1960s or earlier, before the first federal pipeline safety regulations.[26,27] In an aging fleet, pipeline corrosion has emerged as a significant safety issue; corrosion has accounted for over 1,000 significant pipeline incidents over the past 20 years, directly resulting in 23 fatalities and over $822 million in property damage.[28] Older pipelines manufactured from cast or wrought iron are the most susceptible to corrosion and leaks. These materials are especially common in urban areas, where it is difficult to access and replace gas mains. In a recent study, U.S. researchers surveyed the streets of Washington, D.C., for natural gas leaks and found nearly 6,000 leaks beneath 1,500 miles of roadway—an average of four leaks per mile.[29] Fugitive emissions from U.S. pipelines are responsible for the release of 1.1 million tons of methane gas annually into the environment (28.6 million tons CO_2 equivalent).[30]

Modern pipelines are protected from external corrosion (from the soil or water surrounding the pipeline) through anticorrosion coatings and cathodic protection. However, most pipelines are still unprotected against internal corrosion, the reported cause of 10% of significant pipeline incidents.[28] Corrosion mitigation techniques for legacy pipelines include the introduction of corrosion inhibiters into the pipeline, reduction of moisture in the lines, and the use of robotic devices or "pigs" that detect corrosion failure before it becomes catastrophic. For new pipelines, it is possible to coat the inside of a steel pipeline with a corrosion-resistant coating or paint. While corrosion-resistant coating materials exist, they are costly and may be difficult to apply as a retrofit in the field. Alternatively, a corrosion-resistant material can be selected for the entire pipeline structure. Nonmetallic pipeline materials offer corrosion resistance without the need for coatings and cathodic protection. Fiberglass and polyethylene pipelines have begun entering the market owing to maintenance advantages; however, adoption has been limited by the comparatively high cost of fiberglass and plastic pipelines and by their susceptibility to damage during excavation and digging.[31] Emerging solutions, such as metal/plastic hybrids, are also under active development.[31] Some of the most important areas for R&D, as identified by the Pipeline and Hazardous Materials Safety Administration (PHMSA),[32] include the following:

- **Advanced pipeline coating technologies.** Coatings must provide uniform corrosion resistance and durability to construction and handling, and the coating should be low-cost and able to be applied in a mill or in the field. Thermal sprayed metallic coatings (aluminum and zinc) are emerging technologies that could provide excellent corrosion resistance at a low cost.
- **Pipeline corrosion detection.** Long-range guided-wave ultrasonic testing is being developed to detect metal loss in pipelines. This technique could be especially valuable in difficult-to-access locations. R&D is needed to reduce false positives from these devices and enable the calculation of failure pressures.
- **Computational modeling to support direct assessment of corrosion.** Direct corrosion assessment techniques are only effective if the locations that are most susceptible to corrosion are known. R&D is needed to understand where the likelihood of corrosion is highest and to determine the appropriate intervals for reassessment based on corrosion and crack growth rate modeling.
- **Prevention of stress corrosion cracking.** Stress corrosion cracking (SCC) is known to occur in high-pH (pH 9.0–10.5) and near-neutral (pH 6.0–7.0) environments. High-pH stress corrosion cracks are intergranular (propagating along the grain boundaries), while near-neutral stress corrosion cracks are transgranular (propagating through the grains). Internal SCC is emerging as a major concern for the pipeline transport of ethanol because SCC has been observed in ethanol storage tanks. R&D is needed to prevent internal SCC in pipelines carrying ethanol and ethanol blends and to determine safe conditions for pipeline transport of ethanol.

Figure 6.H.3 Hydrogen-Induced Embrittlement of a Steel Alloy's Microstructure[33]

Credit: National Institute of Standards and Technology



Corrosion-resistant pipelines could also benefit the development of a hydrogen energy infrastructure. The storage and transportation of hydrogen fuels are complicated by the fact that structural steels are sensitive to hydrogen embrittlement and fatigue fracture (as shown in Figure 6.H.3), which can lead to hydrogen leakage. Research objectives to address the nation's needs for hydrogen-resistant pipelines overlap those for corrosion-resistant natural gas pipelines, including advanced steel and nonferrous pipeline materials, protective coatings, and improved welding techniques.

Energy-Efficient Vehicles

The United States consumes more motor gasoline than any other country in the world at 9 million barrels per day, equivalent to 19 quads annually—more than five times the consumption of China, the second largest consumer.[34] In 2012, the U.S. transportation sector released 1.8 billion metric tons of greenhouse gases (CO_2 equivalent) into the environment.[30] The use of advanced lightweight structural materials is key to improving fuel economy and reducing vehicle emissions (see the technology assessment 8.D *Lightweight Automotive Materials* for a detailed analysis of the impacts of lightweight materials on energy use in the transportation sector). However, lightweight alloys such as aluminum and magnesium suffer from low wear and corrosion resistance compared to steel, leading to short lifetimes in service. Lightweight alloys and structural composites also introduce unique joining and repairability challenges because they cannot be welded like traditional steel. Coatings and surface modifications can be used to improve corrosion and wear resistance, while new joining techniques and processing methods are needed to ensure practical usability in vehicles. As Corporate Average Fuel Economy standards ramp up in coming years, developments in this area will become increasingly important to enable the use of more advanced lightweight materials in vehicles for fuel economy savings.

Geothermal Energy

In the United States, geothermal energy currently accounts for 15 million megawatt-hours of annual electricity production, with a generating capacity of 2.6 GW.[35] While geothermal represents only a small fraction of the electricity generated in the United States today, interest in this resource is growing because geothermal energy is a sustainable energy source with minimal environmental impacts. A recent U.S. Geological Survey assessment estimated that known hydrothermal geothermal systems in the United States have a potential capacity of 9.1 GW and that undiscovered resources could boost hydrothermal geothermal capacity to 30 GW or more.[36] The potential of Enhanced Geothermal Systems is much greater still, as detailed in the Chapter 4 Technology Assessment 4.I *Geothermal Power*.

A major technical barrier for geothermal power plants is that geothermal fluid is highly corrosive. Non-condensable gases (NCGs) in the steam such as dissolved CO_2 and hydrogen sulfide attack metals, causing stress corrosion cracking, fatigue, and other issues in geothermal equipment.[37] Further, the presence of NCGs substantially reduces power plant efficiency if not removed. Steam ejectors—the most common equipment for removing NCGs—utilize high-pressure steam from the geothermal well to compress the NCG/steam mixture and separate out the NCGs before directing the steam to the turbine.[38] Steam ejection is an energy-intensive process that utilizes large amounts of well steam that would otherwise be used to generate electricity. Conversely, mechanical pumps can be used to remove NCGs without using well steam, but mechanical solutions are limited owing to poor corrosion resistance of the mechanical equipment and the high cost of large turbomachinery. R&D efforts could help overcome these barriers. For example, a U.S. start-up company showcased at the 2014 Department of Energy (DOE) National Clean Energy Business Plan Competition is now developing corrosion-resistant carbon fiber turbocompressors.[39,40] Technical advances in this area could lead to efficiency gains for geothermal power plants and increased utilization of this clean, sustainable resource. In addition, carryover effects from this R&D could make an impact in the natural gas and oil drilling industries.

Nuclear Power

The U.S. nuclear fleet generates about 800 million megawatt-hours of electricity annually and is the largest source of emission-free electricity.[41] Most nuclear power plants have exceeded their initial 40-year license period and are now operating under 20-year license renewals from the Nuclear Regulatory Commission (NRC).[42] The NRC expects to receive further renewal requests, extending total reactor lifetimes to 80 years, within the next five years.[42] In consideration of the extended expected lifetimes of nuclear reactors, irradiation-induced material degradation is a critical area of research. A summary of the environmental conditions expected in advanced nuclear fission reactors is given in Table 6.H.5.

Table 6.H.5 Environmental Conditions Expected for Structural Materials in Advanced Nuclear Fission Reactors[43]

Fission reactors	Structural Materials	Maximum Temperature	Maximum Radiation Dose	Peak Steady- State Stresses (from coolant pressure)	Chemical Reactivity
Commercial light water reactors	Zirconium alloys, stainless steels, Incoloy® nickel-based alloys	<570°F	1 dpa	870–2175 psi	Water/steam
Gas cooled thermal reactors	Graphite	~1830°F	1–2 dpa	2900 psi	Helium gas
Molten salt reactors	Graphite	~1830°F	1–2 dpa	145 psi	Fluoride salt
Liquid metal cooled reactors	Martensitic steels	<1110°F	30–100 dpa	145 psi	Sodium; lead bismuth

*dpa = displacement per atom

Reactor pressure vessels are generally permanent fixtures of a facility and must resist various modes of irradiation-induced degradation, including stress corrosion cracking, embrittlement, radiation creep, and swelling.[44] Fuel cladding is another important area for advanced materials development. Fuel assemblies are generally refueled every 18 months, with an average refueling outage of 41 days,[45] costing U.S. nuclear plants an average of 67 billion kilowatt hours of energy generation per year.[46] Improved, longer-lasting cladding materials could help increase the service life of fuel assemblies for increased reactor availability, greater energy derived from the nuclear fuel, and reduced disposal of radioactive materials. Accident-resistant cladding is an emerging area of interest. At temperatures beyond 2200°F, zirconium alloys react exothermically with steam, potentially producing large amounts of hydrogen and contributing to nuclear core damage in a loss-of-coolant accident.5 Silicon carbide, a ceramic material with thermal stability to 4900°F and low chemical reactivity, is a candidate cladding material that may reduce the risk and severity of damage in the event of an accident.[5] Silicon carbide, a ceramic material with thermal stability to 4900°F and low chemical reactivity, is a candidate cladding material that may reduce the risk and severity of damage in the event of an accident.[47]

Program Considerations to Support R&D

Key Research Needs

Durable materials have a strong impact on national infrastructure, including pipelines and power generation plants. While private entities such as electric utilities providers and vehicle manufacturers 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 R&D efforts across fields. Resource sharing is one key benefit from such efforts. For example, advanced metrology—such as techniques involving *in situ* microscopy—is useful for the characterization of material behavior in extreme environments, but the equipment can be costly and in some cases is not commercially available. An investment in advanced characterization and analysis tools could have benefits for many projects and industry partners. Also, new physics-based modeling and simulation tools are needed to gain deeper insight into material characteristics in operating environments, accelerate testing, address limiting criteria for material failure, and capture long-term mechanical behavior. Data from laboratory experiments or operational environments will need to validate these models. In many cases, models and the knowledge of subject-matter experts could be shared across applications. Additional research needs for materials in harsh environments were identified at a 2015 workshop held by DOE's Advanced Manufacturing Office.[48]

Engagement Strategy

The United States boasts a broad network of durable materials researchers in government, industry, and academic settings. However, most researchers are not united by any one community or objective; their research spans many applications and nearly all categories of materials. Seemingly disparate research programs can have work that overlaps quite substantially (as shown in Table 6.H.6), but investigators work in separate research communities and independent facilities. This slows transfer of technology and expertise between applications (e.g., an innovative high-temperature steel developed for a steam turbine may not immediately find itself used in a waste heat recuperator), a scarcity of shared metrology and equipment resources, and duplications of effort. An understanding of gaps in industry capabilities is needed to inform the basic and applied research ongoing at universities and national laboratories.

Table 6.H.6 Overlap of Materials Research Efforts for Different Applications. Roadmaps (shown in brackets) often cover a single application or set of related applications, rather than addressing fundamental materials challenges.

	Phase-Stable Materials		***Functional Surfaces***		***Material Aging***	
	High-Temperature Stability	High-Pressure Stability	Corrosion Resistance	Wear Resistance	Neutron Embrittlement	Hydrogen Embrittlement
Waste Heat Recuperator	**X**[A]		**X**[A]			
Gas Transmission Pipeline		**X**[B]	**X**[B]			**X**[C]
Vehicle Structural Component	**X**[D]		**X**[D]	**X**[D]		
Nuclear Fuel Cladding	**X**[E]	**X**[E]			**X**[E]	**X**[E]
Ultra-Supercritical Turbine	**X**[F]	**X**[F]	**X**[F]			

A *Energy Loss Reduction and Recovery in Industrial Systems,* U.S. DOE / EERE (2004)[49]

B *Interagency Research and Development Five-Year Program Plan for Pipeline Safety and Integrity,* U.S. DOT, U.S. DOE, and NIST (2007)[50]

C *Hydrogen Delivery Technical Team Roadmap,* U.S. DRIVE Partnership (2013)[51]

D *Materials Technical Team Roadmap,* U.S. DRIVE Partnership (2013)[52]

E *Nuclear Energy Research and Development Roadmap,* U.S. DOE / Office of Nuclear Energy (2010)[53]

F *High-Efficiency Coal-Fired Power Generation,* International Energy Agency (2012)[54]

One potential engagement strategy is the formation of a research hub or institute, which could potentially unite a network of researchers focused on a particular materials development challenge by facilitating collaborations and industry partnerships. Addressing these disconnects is challenging. Germany's Fraunhofer Institute for Structural Durability is a successful example of a government-funded research institute that has adopted an industry-partnership strategy. The Institute for Structural Durability is actively researching carbon fiber lightweighting technologies, aging effects in polymers, non-destructive evaluation techniques for aluminum castings, and other structural durability projects, and has been successful in securing 70% of its funding from contract work. A second, complementary engagement strategy involves the development of computational materials analyses to accelerate the identification of new materials based on key performance metrics for a given application. This type of activity is underway already through the federal government's multi-agency Materials Genome Initiative (MGI), discussed further in the Technology Assessment 6.B *Advanced Materials Manufacturing*.[55]

Endnotes

[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). Note that the 1,800 billion kilowatt hours figure therefore includes only fossil-fuel-burning power plants reported as employing gas, steam, and combined cycle turbines as the prime mover for electricity generation in Energy Information Administration (EIA) Form 860; the contribution would be greater if including other, non-fossil-fuel-based power plants that employ turbines in power generation, such as nuclear power plants. For details of EIA prime mover classifications, see EIA Form 860 Instructions, available from: http://www.eia.gov/survey/form/eia_860/instructions.pdf

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Acronyms

AFOSR	Air Force Office of Scientific Research
ARL	Army Research Laboratory
CFTF	Carbon Fiber Technology Facility
DOE	U.S. Department of Energy
dpa	Displacements per atom (measure of radiation dose)
EPRI	Electric Power Research Institute
FORGE	Frontier Observatory for Research in Geothermal Energy
MGI	Materials Genome Initiative
NAVAIR	Naval Air Systems Command
NCG	Non-condensable gas
NIST	National Institute for Standards and Technology
NRC	Nuclear Regulatory Commission
ONR	Office of Naval Research
ORNL	Oak Ridge National Laboratory
PHMSA	Pipeline and Hazardous Materials Safety Administration
SCC	Stress corrosion cracking
TRL	Technology Readiness Level
USAMP	United States Automotive Materials Partnership

Glossary

Advanced Ultra-Supercritical	Describes a steam turbine power plant (or combined cycle plant that includes a steam cycle) that operates at a steam inlet temperature of 1292°F or above. In many cases, the temperature of metal components in the superheater and final reheater can be much higher.
Anode baking	The process of baking a carbon anode in a furnace to prepare it for use in aluminum smelting (an electrolysis process). Carbon anodes are consumed during aluminum smelting.
Blast furnace	A furnace used in metal smelting in which ores, fuel, and limestone flux are continuously added to the top of the furnace while hot air is blasted into the furnace from the bottom. Chemical reactions occur in a countercurrent exchange process as the ore and flux meet the combustion gases.
Cathodic protection	An electrochemical technique used to mitigate corrosion of a metal by coupling it with a sacrificial anode, such as zinc. Oxidation reactions are concentrated in the active anode and suppressed in the cathode, protecting the metal from corrosion.
Cullet	Scrap glass that has been sorted, crushed, and processed to remove contaminants in preparation for re-melting to produce new glass.
Electric arc furnace	A furnace that uses a high-power electric arc to heat charged material. Electric arc furnaces are widely used to recycle ferrous scrap into steel.
Fouling	The accumulation of undesired materials (such as particulates or scale) on a surface, reducing functionality of the affected component. For example, fouling of a heat exchanger surface can reduce the thermal efficiency of a waste heat recovery system, and fouling of a pipeline can reduce flow rates and cause flow oscillations.
Fuel cladding	The outer layer of a nuclear fuel rod, separating the coolant and nuclear fuel. Most modern nuclear reactors utilize zirconium alloy fuel claddings.
Gas cooled thermal reactor	A nuclear fission reactor that uses a gas such as helium or carbon dioxide as the primary coolant. This type of reactor system has not yet been commercialized.
Light water reactor	A nuclear fission reactor that uses ordinary water (rather than heavy water) as the primary coolant. The majority of nuclear reactors in service today are light water reactors.

Liquid metal cooled reactor	A nuclear fission reactor that uses a liquid metal as the primary coolant. Liquid metal coolants used in nuclear reactors include sodium, mercury, lead, and lead-bismuth alloy.
Molten salt reactor	A nuclear fission reactor that uses a molten salt as the primary coolant. The nuclear fuel itself is generally dissolved in the molten salt coolant (thus providing a liquid fuel rather than a conventional system of solid fuel rods).
Non-condensable gas (NCG)	Air or other gas (often consisting of nitrogen, oxygen, light hydrocarbons, and carbon dioxide) that is not easily condensed by cooling. NCGs in steam can be detrimental to steam system performance because the gases collect as a stagnant, insulating layer on heat transfer surfaces, reducing heat transfer efficiency. NCGs can also cause corrosion.
Radiation dose	The irradiation-induced change in a material's properties, measured in displacements per atom (dpa). The flux or dose rate, measured in dpa/s, describes the rate of such changes.
Recuperator	A counter-flow heat exchanger that transfers heat from an exhaust gas to a cooler incoming gas stream, keeping the fluid streams separate. In a typical "shell-and-tube" configuration, the supply gas stream is passed through a system of tubes within a chamber containing the hot exhaust gas. The term "recuperator" can also refer to a liquid/liquid or gas/liquid heat exchanger of similar configuration.
Regenerator	A heat exchanger in which waste heat is transferred from a hot fluid to an intermediate thermal storage medium before being transferred to the cold incoming fluid. Unlike recuperators, regenerators generally involve some mixing of the fluid streams.
Subcritical	Describes a steam turbine power plant (or combined cycle plant that includes a steam cycle) that operates at a steam inlet temperature of 1000°F or below (i.e., beneath the critical point of water at the inlet conditions).
Supercritical	Describes a steam turbine power plant (or combined cycle plant that includes a steam cycle) that operates at a steam inlet temperature of 1050°F to 1100°F (i.e., beyond the critical point of water at the inlet conditions). Plants operating at a steam inlet temperature above 1100°F are termed ultra-supercritical.
Stress corrosion cracking	Crack growth resulting from the combined effect of tensile stresses and a corrosive environment.
Ultra-Supercritical	Describes a steam turbine power plant (or combined cycle plant that includes a steam cycle) that operates at a steam inlet temperature of 1100°F to 1300°F. Plants operating at a steam inlet temperature above 1300°F are termed advanced ultra-supercritical.