

# **Oak Ridge National Laboratory's Industrial Technologies Program: Partnering with Industry to Reduce Energy Use and Improve Industrial Competitiveness**

*Sharon M. Robinson, Oak Ridge National Laboratory*

## **ABSTRACT**

Oak Ridge National Laboratory's (ORNL's) Industrial Technologies Program (ITP) is actively engaged with industry to reduce industrial energy use and improve economic and technological competitiveness. Examples of industrial partnership projects in advanced materials, separations technologies, nanomanufacturing, alternative fuels and feedstocks, wireless sensors, and industrial energy assessments are highlighted in this paper. These projects include both examples of state-of-the-art technologies for improving industrial energy efficiency as well as industrial assessments of research and development needs to improve industrial competitiveness. The paper also describes how companies can access the unique capabilities and facilities available at Oak Ridge National Laboratory.

## **Background**

Oak Ridge National Laboratory is the U.S. Department of Energy's (DOE's) largest multipurpose science and energy laboratory, with strengths in materials and chemical processing research and strong industrial partnerships. ORNL provides a wide range of technical capabilities to support the DOE's missions and partner with industry to reduce energy use and improve industrial competitiveness. The laboratory's six major mission roles include energy, materials science at the nanoscale, neutron science, high-performance computing, systems biology, and national security. The laboratory has a \$1 billion annual budget, over 4,000 employees, and serves over 3,000 research guests annually.

The Energy Efficiency and Renewable Energy (EERE) program at ORNL leads technology research, development, analysis, and deployment projects of strategic importance to energy efficiency, renewable energy, and electric grid technologies in order to help enhance capacity and strengthen America's energy security, environmental quality, and economic vitality. We have research, development, and demonstration activities supporting all areas of the U.S. DOE's EERE program: industrial technologies, vehicle technologies, building technologies, renewables, hydrogen and fuel cells, and weatherization.

This paper focuses on the Industrial Technologies Program at ORNL which receives primary financial support from the overall DOE Office of Energy Efficiency and Renewable Energy ITP effort. ORNL's program supports all current and emerging technical areas of the DOE ITP, including:

- Best Practices, which facilitates broader market adoption of energy-efficient technologies and practices by conducting energy assessments, developing software tools, and demonstrating advanced energy savings technologies,

- Industry-specific R&D that supports high-risk, high-return R&D identified in technology roadmaps to reduce manufacturing energy intensity in the aluminum, chemicals, forest products, glass, metal casting, mining, and steel industries, and
- Cross-cutting R&D that supports leading-edge R&D in crosscutting technologies, such as advanced materials, combustion, and intelligent sensors and controls.

The paper provides examples of recent projects where ORNL has partnered with industry to reduce energy use and improve industrial competitiveness, two areas of increasing importance due to recent high prices for natural gas and petroleum products. The example projects were selected to highlight the range of ORNL's unique facilities, staff expertise, and diverse partner base.

## ORNL Energy Savings Projects

### Chemical and Petroleum Industries

The United States is the largest producer of refined petroleum products in the world, with 29 percent of global production and 155 operating refineries. In 1999 refineries supplied more than 6 billion barrels of finished products and employed about 64,000 people. Petroleum refining is the largest energy consumer among manufacturing industries in the United States and accounts for about 7.5% of total U.S. energy consumption. Energy consumption in refineries is dominated by a few processes such as atmospheric and vacuum distillation, which account for 35-40% of total process energy consumption (Energy Information Administration 2007).

The chemical industry is a keystone of the U.S. economy, converting raw materials (oil, natural gas, air, water, metals, minerals) into more than 70,000 different products. Chemicals production is nearly a \$1.67 trillion global enterprise, and the U.S. chemical industry is the world's largest producer. There are over 9,500 chemical firms with more than 13,000 facilities operating in the United States. The industry employs almost 900,000 people in the United States alone. The chemical industry is also the second largest consumer of energy in manufacturing. The chemical industry uses energy resources both to supply heat and power for plant operations and as a raw material for the production of petrochemicals, plastics, and synthetic fibers. The U.S. chemical industry consumed about 6.1 quads (quadrillion Btu, or  $10^{15}$  Btu) of energy in 1998. This represents about 6% of domestic energy use and about 25% of all U.S. manufacturing energy use (Energy Information Administration 2007). ORNL has been actively working with this industrial sector to improve efficiency through advanced materials and processes.

**Distillation column modeling.** Distillation is the primary separations technology for existing chemical and petrochemical processes, and will play a major role in emerging systems, such as the biorefinery of the future. Distillation accounts for almost 12% of the total in-plant energy use of the manufacturing industries in the United States. ORNL has worked in partnership with vendors, suppliers, and end users to develop a unique computational tool to accelerate computational process development for advancing efficiency of distillation.

The Graphical Structured Packing Interface (GraSPI) software is the only simulation toolset on the market that allows for first-principles simulation of flow through structured packed towers. Because the current design of distillation towers is largely empirical, this tool enables a

revolutionary opportunity to employ powerful new computing capabilities to develop economical tower designs. Better modeling enables improved distillation column design, leading to purer products, energy savings, and decreased emissions.

Users of GraSPI may choose from packing geometries characteristic of several commercially available materials (data for these materials are provided through agreements with commercial partners), or they may use GraSPI to create completely new geometries. GraSPI software has been developed to enable it to be a plug-in for GAMBIT (a computational fluid dynamics (CFD) preprocessor), and as a driver for FLUENT software (Modern Tools for Distillation Dynamics, 2007). Partners on the project included Fluent Inc., the Dow Chemical Company, Praxair, Sulzer Chemtech USA, Koch-Glitsch, the University of Texas Separations Research Program Consortium, and ORNL. GraSPI has been registered with the U.S. Copyright Office, effective January 19, 2005.

Improved design of distillation could help to save 1 to 10% of total distillation energy consumption. In the petrochemical industry, the savings would represent 15 to 150 TBtu/year. In addition, higher efficiency processes lead to higher profits, thereby increasing the global competitiveness of this industry sector.

**Alloys for high temperature applications.** Oak Ridge National Laboratory has a long history of innovation in alloy design of high performance materials for use in a wide range of industrial applications. One recently completed project developed a new class of Fe-Cr-W steels for the chemical and petrochemical industries in a joint research project with Nooter Corporation.

Composition modification by ORNL was used to create microstructures during heat treatment that maximize elevated-temperature strength and toughness accompanied by improved resistance to creep, fatigue, and thermal fatigue. The new steel grades 315 and 315T exhibit 50% higher strength and superior toughness compared to commercial grades such as ASTM Grade 22, and will reduce the weight of large-pressure-vessel components by 25%, reduce fabrication cost, and improve in-service modification feasibility. Production of the alloys has been scaled up to commercial-size batches of 50 tons each by Ellwood Quality Steel, and processed commercially into forgings, plate, and tubing by other industry partners. The alloys are weldable by both submerged-arc and gas-tungsten-arc processes. Principle applications in the petrochemical industry for the alloys are expected to be hydrotreaters and coke drums, where fabrication with these new alloys can reduce wall thickness and reduce thermal fatigue. In the power generation industry, thinner-walled tubing from 315 and 315T steels can reduce material use by 50%, and enable more efficient operation at higher temperatures and pressures (Jawad and Sikka 2005).

The alloys have approved ASTM specifications for plate and forgings and are currently undergoing the ASME approval process for use in pressure vessels. These new steels will save up to 21 trillion Btu/year by 2020 by allowing lighter weight equipment and by requiring less welding (Industrial Technologies Program 2005). A U.S. patent for the alloys has been issued.

## **Forest Products Industry**

The forest products industry is a multinational enterprise with plantations and mills around the world. With over 16,000 facilities in the United States, the industry produced shipments valued at close to \$243 billion in 2001. As a strong contributor to the nation's economy, the industry employs close to 1.1 million people in all regions of the country and ranks

among the top 10 manufacturing industries in 46 states. The forest products industry consumed almost 3.3 quads of energy in 1998. This represents about 14% of domestic manufacturing energy use, making the forest products industry as a whole the third largest industrial consumer of energy, behind only petroleum and chemicals. The pulp and paper industry uses 84% of the fuel energy consumed by the forest products industry as a whole (Energy Information Administration 2007). Paper mills, many of which have integrated pulping operations, consumed almost half of the 2.4 quads used in the pulp and paper industry in 2002 (American Institute of Chemical Engineers 2006). ORNL has been actively working with this industrial sector to improve efficiency through advanced materials and processes

**Novel refractory materials for black liquor gasification.** The replacement of standard recovery boilers with black liquor gasification technology results in a 14% increase in energy efficiency, and offers the potential to turn pulp and paper mills into net producers of energy. One barrier to widespread adoption of gasification is the high cost and short lifespan of the refractory materials used to line the gasifier vessels. Typical refractories only last six months, doubling the number of annual plant shutdowns otherwise needed.

High alkali concentrations, high temperature (~950°C) and severe gas/liquid flow characteristics inside gasifiers combine for a challenging environment for refractory materials. An ORNL project, with research partners from Weyerhaeuser Company, University of Missouri-Rolla, Process Simulations Limited, Simulent Inc., Vesuvius Monofrax, ANH Refractory Company, and SEPR Refractories, has designed new corrosion resistant fusion-cast magnesia-alumina spinel refractory materials (Keiser et al. 2006). Over 100 corrosion studies were carried out on experimental and commercial refractory materials utilizing an immersion test system constructed at ORNL to simulate the black liquor gasifier environment. Such testing has provided a screening tool for candidate materials to be used as the lining in Weyerhaeuser gasifier located at a mill in New Burn, NC. Materials passing the ORNL immersion test have been found to demonstrate similar success in the actual service environment of the New Bern gasifier.

New “hot face” refractory panels installed in October, 2004 at Weyerhaeuser’s New Bern mill showed much improved corrosion and spallation resistance when examined during the plant’s annual inspection and maintenance. The refractories show 3 times the improved useful life, and a potential for 6 times the life extension.

**Rapid electron-beam curable resins used in producing wood composites.** Approximately half of all wood construction products used today are glued-wood assemblies such as plywood and fiberboards. The manufacture of most glued-wood assemblies requires significant energy to dry the parent wood material, consolidate products, and to polymerize and cure the resin system. Electron-beam (E-beam)-curable resins are a new technology under investigation at ORNL that offers the potential for faster bonding at lower temperatures and higher wood moisture contents. E-beam is a form of radiation, similar to that used in a television picture tube, that can be directed and focused in a controlled way to deliver energy deep within wood.

ORNL is working to develop special resins that cure when excited by E-beam energy, to define processing parameters, (e.g. dosage or moisture levels), and ensure that e-beamed composites meet performance standards. This project was the first to explore high energy E-beam curable resins for wood adhesives and began by formulating the correct resin systems for

the main commodity composites. The project is producing prototypes of principal products and is working with equipment designers and the composite machinery manufacturers toward commercialization (Griffith 2006).

The E-beam resins can be cured at lower temperatures (250 to 300°F) than conventional systems (450°F). This could mean less energy for drying, reduced heating time, fewer drying-related emissions (VOCs), fewer manufacturing defects, and faster press cycles. In addition, wood products with higher moisture can be processed, process throughput rates are higher, and the resulting wood-resin bonds are more durable. Several wood composite and resin manufacturers are participating in the research, along with Sterigenics U.S., LLC, which is providing the E-beam services. This technology could save 65 trillion Btu/year at full market penetration (Griffith 2006).

### **Advanced Materials Development**

Advanced materials development is a technical area that impacts all the manufacturing industries. Examples of ORNL materials development projects that support multiple industries are given below.

**Infrared-based processing of metals.** ORNL has been investigating infrared-based processing for high temperature (above 800 °F) applications. The processing techniques developed at ORNL use two in-house fabricated 33-kW and 88-kW tungsten halogen-based systems uniquely designed for high temperature applications. These applications utilize a hybrid rapid infrared furnace which uses a two-zone heating approach. Zone one uses the high power available by the T-3 lamps to bring the load uniformly to the targeted process temperature, and zone two acts more like a convection furnace the bring the load uniformly to the targeted temperature. ORNL has successfully demonstrated infrared heating for several industrial applications.

ORNL, along with industrial partners Queen City Forging and KomTek, developed a new hybrid infrared heating system that permits rapid and uniform heating of aluminum alloy billets prior to forging. Field test data demonstrated that the technology reduces heating times by an order of magnitude, decreases energy consumption by a factor of three, and reduces costs by 40-50% through reduced energy consumption, increased throughput and improved consistency in the process and quality of the product.

In addition to saving energy, the process produces forgings with enhanced metallurgical and mechanical properties. A benefit of the shorter heating time is a finer grain size on 2019 Al, which results in the improved fatigue properties (Miller 2006).

A full-scale production-based infrared furnace is operating at Queen City Forging Company. This technology was selected by *R&D Magazine* as one of the 100 most technologically significant products introduced into the marketplace in 2004, and received a 2005 Ohio Governor's Emerging Technology Award. The technology has also been demonstrated for preheating forging dies, and is being investigated in a number of other applications.

**Metal Infusion Surface Treatment (MIST) technology.** MIST technology is a low-temperature coating process that infuses a new alloy several hundred nanometers (nm) deep into the surface of a metal under atmospheric conditions to create enhanced durability and extend the

service life of equipment. Coatings are applied by dipping or spraying with a patented fluid, then are thermally treated at temperatures below 450°C, producing a coating that is anchored to the substrate at the molecular level. These nanocoatings are 10 to 100 times thinner, require 10 to 100 times less coating material, and are independent of any coefficient of the thermal expansion mismatches that can lead to cracking or spalling in other coatings systems. MIST is scalable to large components, can be applied “in-field,” requires no expensive equipment, and is not limited to the type of coating or substrate material. This technology saves energy by extending product life, increasing yield, and reducing process downtime.

Based on collaborative projects with ORNL, Chemical Composite Coatings (C<sup>3</sup>) developed the MIST process and brought it to market in February 2005. C<sup>3</sup> has implemented the technology for a wide range of applications including metal cutting tool inserts (such as plates, drill, and blades), metal casting parts (such as mold dies, thermocouple sheaths, ladles and core pins), rollers used in hot-rolled steel production, and spark plugs and ceramic catalytic filters in exhaust systems for the automotive industry. In industrial trials, MIST-coated parts last 30 -50 times longer than conventional materials.

C<sup>3</sup> partners/customers include Hayes Lemmerz International Inc., Surface Engineering Associates, Infrared Heating Technologies, LLC, Magna-Tech Manufacturing, Advanced Materials Associates, Vitek Performance, Pyromation, Inc., Delaware Tool & Machinery, Heinz North America, and North American Die Casting Association (NADCA). This technology was selected by *R&D Magazine* as one of the 100 most technologically significant products introduced into the marketplace in 2006. The company now has two dedicated plants serving 35 aluminum die casting companies (Foundry M&T Staff 2006). The expected energy savings for the aluminum die casting industry is  $2.7 \times 10^{12}$  BTU/year.

**Thermal-Magnetic Field Processing.** ORNL researchers were the first to demonstrate Thermal-Magnetic Field Processing (TMFP) as a revolutionary materials processing technology for development of the next generation of advanced structural and functional materials. ORNL established the world’s first large-bore, superconducting, thermo-magnetic processing facility capable of controlling and tailoring bulk materials at the nanoscale to achieve stronger, more fatigue-resistant, and cost-effective materials by energy-efficient means.

ORNL is partnering with an automotive company to investigate thermo-magnetic processing as an enabling technology to make significant improvements in current and future product lines in a broad spectrum of material and component applications. Proof-of-principle results indicate that high magnetic field processing has the potential to reduce residual stress by up to 80%, enabling higher design stresses and lighter weight components, increase high cycle fatigue life by up to 50%, increase material strength up to 100% with no loss in toughness, and enable up to 50% lighter weight designs (Ludtka 2005).

## **Alternative Fuels and Feedstocks**

Oil and natural gas are not renewable, and reserves are largely situated offshore in areas that are politically unstable. President Bush emphasized in his 2007 State of the Union address that “It is in our vital interest to diversify America’s energy supply – and the way forward is through technology.”

Development of alternative fuels and feedstocks is critical to reducing U.S. dependence on foreign oil and maintaining the viability of the U.S. manufacturing industry. The

manufacturing sector is the second largest consumer of oil and natural gas on a combined basis in the U.S, accounting for ~30% of the total usage. The demand for transportation fuel is expected to account for 65% of the increase in total oil and natural gas demand by 2030 (up from 60 quads in 2003 to 80 quads in 2030). The manufacturing sector's use of oil and gas is expected to increase from 18 quads to 22 quads, accounting for 20% of the expected total increase (Energy Information Administration 2007).

Over half of the consumption of fossil resources by the chemical industry goes to feedstock chemicals – 3.4 quads in 2005, with 0.6 quads of that coming from natural gas, 1.4 quads coming from natural gas liquids, and 1.4 quads from heavy liquids. Clearly, there is great opportunity for reduced dependence on imported fossil resources through the development of alternative fuels and feedstocks (Energy Information Administration 2007).

ORNL worked in collaboration with the Chemical Industry Vision2020 Technology Partnership to assess state-of-the-art technology for using alternative, renewable, and/or novel feedstocks (such as coal; biomass; oil shale; tar sands; unconventional methane, i.e. “stranded” or “remote” sources, coal bed, and gas hydrates; etc) for large-scale chemical production. The focus was on commodity chemicals, with production greater than a million tons/year that have significant energy impact, rather than niche market chemicals or pharmaceuticals. The study evaluated the energy savings potential of alternative feedstocks, exploiting possible cross linkages between chemical industry feedstock and fuel production. Key technical barriers and research needs needed to implement alternative feedstocks were identified.

The study indicated that technology improvements are required to develop an adequate and diverse supply. The most promising near-term opportunities are on feedstock substitutions to make existing products with minimal changes in existing manufacturing facilities, or to overcome barriers to implementation of mature technologies. Longer-term opportunities will involve the manufacture of new products involving new chemical pathways and potentially new processing equipment. ORNL has research programs in gasification and bioprocessing that support these efforts. An example project is the production of carbon fiber and other products from lignin.

## **Characterization of Nanomaterials**

Nanotechnology has been recognized by industry as a key to national energy independence and industrial competitiveness. One barrier to the ability to translate nanoscience into useful technologies is the inability to characterize nanomaterials in real-time during production (Chemical Industry Vision2020 Technology Partnership, 2003; 2006). To better enable nanomanufacturing researchers at ORNL's NanoApplications Center have developed and applied novel real-time characterization techniques (See <http://nanotech.ornl.gov/>). A commercial differential mobility analyzer, which employs the deflection of charged particles in an electric field to segregate particles in a gas stream by electrical mobility size, was used to sample and characterize nanoparticles produced in real time. Two different types of gas-phase processes were studied - a chemical vapor deposition process for production of metal-oxide particles, and a laser-ablation process for synthesis of carbon nanomaterials (Cheng et al. 2007). Process parameters, including precursor feed rate, or laser power applied, and furnace temperature were investigated. The impact on the size distribution of the nanoparticles that were produced was observed in real time using this equipment. The results of the particle size distribution analysis for particles smaller than 50 nm were consistent with those determined by

microscopic analysis. The results indicated promising opportunities for rapid detection of process transients, and for the use of the instrument in process development. This innovation impacts process improvement by allowing scientific instruments to work in an industrial setting to measure nanoparticles both in process and in the workplace environment. The system was recently tested on a plasma arc process for production of carbon-based nanomaterials at Luna nanoWorks, a Division of Luna Innovations, Inc. (DePaoli 2006).

Success in these efforts indicates value in continued industry/national laboratory collaboration on research and development towards responsible nanomanufacturing. As nanotechnology commercialization emerges, ORNL is focused on working with industry to meet the growing need for effective approaches for monitoring of processes and workplace, and for process development for efficiency improvement, quality control, and reduction of wastes and emissions.

### **Advanced Wireless Sensors**

The ITP at ORNL is a major player in the deployment of advanced wireless technologies. An active R&D effort includes the commissioning and deployment of the DOE Extreme Measurement Communications Center (EMC<sup>2</sup>) to characterize and simulate the performance of candidate industrial wireless telemetry devices in harsh industrial environments. Under this program, ORNL supports industrial teams (Eaton, GE, and Honeywell) to move wireless technology into the marketplace. This technology has led to the filing of a dozen U.S. and international patent applications.

EMC<sup>2</sup> was commissioned on June 30, 2004. The center was assembled to ensure that the candidate wireless technologies being considered for deployment in U.S. industries are suitable in robustness, latency, throughput, and security. The Center, stocked with high-tech measurement, testing, and simulation equipment, allows users, suppliers, and researchers to verify the performance of candidate devices, comparing them with their own specifications as well as with emerging and existing standards. Portable instruments allow EMC<sup>2</sup> researchers to do field tests as well as confirming laboratory outcomes.

ORNL also supports the Wireless Industrial Networking Alliance (WINA), an industrial organization designed to facilitate the deployment of robust wireless sensors. WINA now has over 300 members, with 24 of those paying for more active participation (WINA 2007). The energy savings of wireless sensors is estimated to be 590 trillion Btu/year by 2020 (Manges 2007).

### **Best Practices' *Save Energy Now***

The DOE *Save Energy Now* program includes Energy Savings Assessments (ESA) of the country's largest 3% of industrial plants which have annual energy costs of over \$2 million and use 53% of all industrial energy. ESAs are 3-day assessments conducted by DOE Energy Experts, who are technical experts trained to use DOE energy efficiency software tools. ORNL directed the development of the steam and process heating software tools used in the ESAs, and the training programs for the qualified specialists who use the software.

The ESAs conducted in 2006 focused on steam and process heating systems which account for more than 70% of the energy used in large industrial plants. The impacts of the ESAs

have been tremendous. Of the 203 ESAs completed in 2006, reports are available for 198. The identified energy savings potential includes 52 trillion Btu/yr in natural gas, as well as 3.3 MMTCE/yr in carbon avoided and \$485 million in cost savings (Office of Public Affairs, 2007). 98 of these plants have completed energy saving projects worth over \$15 million in energy savings. 80% of the ESA opportunities identified have a payback period of less than two years (Gemmer 2007). In 2007, 250 ESAs are planned and the program scope expanded to include compressed air, pumps, and fans.

## **Ways to Work with ORNL**

Industry, government, and university groups have a wide range of opportunities to work with ORNL and to access some of the lab's unique equipment and world class researchers. For more information about the laboratory, see: <http://www.ornl.gov/>.

*Collaborative R&D:* ORNL uses Cooperative Research and Development (CRADA), Work for Others (WFO), and nondisclosure agreements for collaborative research performed with universities and industry. CRADAs are agreements to conduct research where the partner contributes to the project cost through in-kind, cash, or combination funding, and may obtain license rights to any created inventions. WFO agreements enable sponsors to fund ORNL researchers working at the lab. WFO agreements may also give the sponsor rights to ORNL inventions.

*User Facilities:* User facility agreements give outside researchers access to ORNL facilities. There is no cost for nonproprietary work, but the sponsors bear full cost for proprietary work at user facilities.

The High Temperature Materials Laboratory (HTML) is an example of a DOE User Facility established to help solve energy issues. HTML includes six user centers with extensive facilities and expertise in characterizing microstructures, microchemistry, and the physical and mechanical properties of materials. These facilities are available for both nonproprietary and proprietary research. Access to HTML is through proposals submitted via <http://www.ms.ornl.gov/htmlhome/>. In addition to HTML, ORNL has 16 other experimental user facilities that attracted 1,300 experimenters from over 405 organizations in FY 2005.

*Locating on the ORNL Campus:* The creation of the "Oak Ridge Science and Technology Park," to be located on the ORNL campus was announced in 2006. The technology park will be available for private sector companies such as Chemical Composite Coatings (see section on MIST Technology above) to locate on the ORNL campus.

## **Summary**

The United States is increasingly faced with energy and economic challenges that require enhanced collaboration and innovative technological solutions to compete in the international market. National laboratories provide important resources and capabilities to meet these challenges. Oak Ridge National Laboratory, through its Energy Efficiency and Renewable Energy program and partnerships with industry, seeks to help address these national issues.

## Acknowledgments

The projects described in this paper are the result of the dedication of many ORNL staff members and their partners. Principal investigators on these projects include Valmor de Almeida, M. Jawad, Vinod Sikka, Jim Keiser, James Hemrick, J. P. Gorog, R. Leary, Bill Griffith, Craig Blue, Mark Deininger, Norman H. Garrett, Puja Kadolkar, Robert Kervick, Robert Mayer, Gerry Ludtka, David DePaoli, Meng-Dawn Cheng, Wayne Manges, and Tony Wright. Ron Ott, David DePaoli, and Hiram Rogers contributed to the content of this paper. The research was sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

## References

- American Institute of Chemical Engineers. 2006. *Pulp and Paper Industry Energy Bandwidth Study*. U.S. Department of Energy, Industrial Technologies Program. [http://www.eere.energy.gov/industry/forest/pdfs/doe\\_bandwidth.pdf](http://www.eere.energy.gov/industry/forest/pdfs/doe_bandwidth.pdf).
- Chemical Industry Vision2020 Technology Partnership. 2003. *Chemical Industry R&D Roadmap for Nanomaterials by Design: From Fundamentals to Function*. [http://www.chemicalvision2020.org/pdfs/nano\\_roadmap.pdf](http://www.chemicalvision2020.org/pdfs/nano_roadmap.pdf).
- Chemical Industry Vision2020 Technology Partnership. 2006. *Implementation Plan for Chemical Industry R&D Roadmap for Nanomaterials by Design*. [http://www.chemicalvision2020.org/pdfs/ChemInd\\_Nanotech\\_Impl\\_Plan\\_9May06.pdf](http://www.chemicalvision2020.org/pdfs/ChemInd_Nanotech_Impl_Plan_9May06.pdf).
- Cheng, M.-D. et al. 2007 "Formation studies and controlled production of carbon nanohorns using continuous *in situ* characterization techniques," *Nanotechnology* 18 (18), 185604.
- DePaoli, D.W. 2006. *Real-Time Characterization Project Addresses a Priority Need in Nanomanufacturing*. <http://www.eere.energy.gov/industry/imf/pdfs/nanotechnology.pdf>. Washington, DC: Department of Energy, Industrial Technologies Program.
- Energy Information Administration. 2007. EAI Energy Analysis Briefs. <http://www.eia.doe.gov/emeu/mecs/iab98/index.html>. Washington, DC.: US DOE Energy Information Administration.
- Foundry M&T Staff. 2006. "Infusion Reigns as Dies, Tooling Gain New Strength." Foundry Management and Technology October, 134 (10):19-20.
- Gemmer, B. 2007. "Save Energy Now Energy Savings Assessments." Paper presented at Chemical Industry Vision2020 Meeting, Baltimore, MD., February 13.

Griffith, W.L. 2006. "Rapid, Low-Temperature Electron, X-ray, and Gamma Beam-Curable Resins." Paper presented at Industrial Technologies Program Forest Products Peer Review, Atlanta, GA., April 5-6. <http://www.eere.energy.gov/industry/forest/pdfs/griffith.pdf>

Industrial Technologies Program. 2005. "Development of a New Class of Fe-3Cr-W(V) Ferritic Steels for Industrial Process Applications." Fact Sheet. [http://www.eere.energy.gov/industry/imf/pdfs/1763\\_ferritic\\_steels.pdf](http://www.eere.energy.gov/industry/imf/pdfs/1763_ferritic_steels.pdf).

Jawad, M., and V.K. Sikka. 2005. *Development of a New Class of Fe-3Cr-W(V) Ferritic Steels for Industrial Process Applications*. ORNL/TM-2005/82. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Keiser, J. R., J. G. Hemrick, J. P. Gorog and R. Leary, 2006. *Improved Materials for High-Temperature Black Liquor Gasification*. ORNL/TM-2006/71. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Ludtka, G. M., 2005. *Exploring Ultrahigh Magnetic Field Processing of Materials for Developing Customized Microstructures and Enhanced Performance*, ORNL/TM-2005/79. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Manges, Wayne (Oak Ridge National Laboratory). 2007 Personal Communication. April 26.

Miller, R. 2006. "Infrared Heats Up." *Industrial Heating*. 73 (6): 42-45.

Modern Tools for Distillation Dynamics, 2007, GraSPI, <http://distillation.ornl.gov/public/GraSPI.shtml>. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Office of Public Affairs, US Department of Energy. 2007. *Department of Energy Achieves Goal of 200 Energy Savings Assessments*. <http://www.energy.gov/print/4831.htm>. Washington, D.C.: US Department of Energy.

(WINA) The Wireless Industrial Networking Alliance. 2007. <http://www.wina.org/>.