



Update

Coal Gasification Comes of Age

Suzanne Shelley, Contributing Editor

Coal's fortunes tend to rise and fall in response to the price and availability of the other fossil fuels. Coal has been traditionally consigned to the sidelines as the dirtiest of the fossil fuels. However, in recent years, a variety of factors — including burgeoning demand for oil by China, India and other developing countries, supply disruptions resulting from worldwide geopolitical events, a growing belief that traditional crude oil production is peaking, and inadequate investment in upstream exploration — have caused the price of oil and natural gas to skyrocket (*CEP*, Apr. 2006, pp. 24–32). For instance, as recently as late April, crude oil hit historic highs of \$75/bbl, while natural gas hit historic highs of \$16/mcf in late 2005 (after hovering around \$2/mcf for the decade leading up to 2000).

These factors have brought renewed interest in coal-gasification technologies, such as integrated gasification combined cycle (IGCC), coal-to-chemicals and coal-to-liquids (CTL) processes, that allow this once-maligned natural resource to be used — with significant environmental and lifecycle cost advantages — over conventional oil- and natural-gas-based processes for producing power, chemicals and liquid transportation fuels. As a result, an unprecedented number of grassroots projects based on coal gasification have been announced over the past year or two (box, p. 7).

While first-generation IGCC power plants came online in the U.S. and Europe in the 1990s and are still in operation today, persistently low natural gas prices have forced IGCC into hibernation since then. Now, after a decade-long hiatus during which only one IGCC plant was built in the U.S., at least a half dozen commercial-scale IGCC plants have been announced in the U.S. alone in

the past year or so, and additional projects are being scoped.

And, underscoring their developers' bullishness, nearly all of the IGCC plants announced recently — by American Electric Power (Columbus, OH; www.aep.com), Duke Energy (Charlotte, NC; www.duke-energy.com), which recently merged with Cinergy (Cincinnati, OH), ERORA Group LLC (Louisville, KY; www.erora.com), Excelsior (Holman, MN; www.excelsiorenergy.com), and others — are slated for 600- to 700-MW capacity, more than twice the size of the first-generation IGCC plants in operation today (all of which have 250–300 MW capacity).

Taking aim at high costs

“While the capital costs of IGCC plants are currently referenced as being 10–15% higher than comparably sized coal-combustion plants, this widely accepted cost gap becomes more of a myth than a reality when overall lifecycle costs are compared,” says David Denton, business development director for Eastman Gasification Services (Kingsport, TN; www.eastman.com). In particular, conventional coal-fired power plants face the risk of considerable additional capital costs and long-term operating expenses to meet tightening control requirements related to SO₂, NO_x, particulate and mercury emissions that are produced when coal is combusted. By comparison, in an IGCC facility, these pollutants are removed much more cost-effectively from the concentrated, high-pressure (400–1,200 psig) syngas stream produced by coal gasification — before it is combusted in the gas turbine.

The operating experience that will be gained from the pending wave of IGCC installations should also help to eliminate this cost differential, says Jeff Phillips, senior project man-

ager for future coal generation options at the Electric Power Research Institute (EPRI; Charlotte, NC; www.epri.org). “As we get more of these IGCC plants built, we'll get farther along the learning curve, and the price will surely come down as standardized designs, with their associated reductions in equipment-related costs, become available.”

To help trim IGCC-related costs, each of today's leading coal gasifier manufacturers — GE Energy (Atlanta, GA; www.gepower.com), Shell (Houston; www.shell.com) and ConocoPhillips (Houston; www.conocophillips.com) — has recently created a strategic alliance with a major engineering-and-construction firm, through which the partners bundle all IGCC-related engineering, design, procurement and construction services into one standardized package. For instance, GE Energy has partnered with Bechtel Corp. (San Francisco, CA; www.bechtel.com); Shell has partnered with both Black & Veatch (Kansas City; www.bv.com) and Uhde (Dortmund, Germany; www.uhde.biz); and ConocoPhillips has partnered with Fluor (Irvine, CA; www.fluor.com).

“Everything started rolling for IGCC when the first of these alliances [GE-Bechtel] was announced around mid-2004,” says EPRI's Phillips. “These companies have the financial horsepower to back a billion-dollar power plant, and they offer a single point of responsibility that makes everything easier for project developers.”

Hefty oxygen demands

Today, the vast majority of coal gasification processes use oxygen-blown gasifiers, with oxygen produced onsite using a high-tonnage air-separation unit (ASU) based on cryogenic distillation. The ASU represents one of the biggest-ticket

items in the entire IGCC flowsheet, in terms of both the capital costs associated with the giant distillation columns and refrigerated enclosures, and the massive amounts of energy required to both compress the inlet air that is to be separated, and to maintain cryogenic temperatures (on the order of -185°C) within the cryogenic distillation columns.

For instance, according to Edward Lowe, general manager of gasification for GE Energy, the forthcoming fleet of 600+ MW IGCC facilities will require 5,000 short tons/d of oxygen — a marked increase over the 2,000 short tons/d needed by the smaller, first-generation IGCC facilities that are still in operation today.

“For years, engineers have been incrementally reducing the cost of oxygen required by these oxygen-intensive processes, but cryogenic air separation is a mature technology, so technical breakthroughs that could lead to greater economic improvements are harder and harder to come by,” says industry expert Jim Sorensen, who spent 40 years with Air Products, and was the founding chairman of the Gasification Technologies Council (GTC; Arlington, VA.; www.gasification.org) before starting his own consultancy, Sorensenergy LLC (Allentown, PA).

Cost-cutting advances

Today, a variety of engineering advances are being pursued to bring down the cost of coal gasification — with a particular focus on the ASU. Several are discussed below.

Integration between the ASU and the gas turbines. To maximize efficiency while reducing both capital and energy/operating costs, today’s IGCC flowsheets are increasingly using partial integration between the upstream ASU and the downstream turbines.

In a typical example of such an approach, a slipstream of compressed air is extracted from the gas turbine and used as the source of some of the compressed inlet air to the ASU. When properly engineered, this can significantly reduce the size of the

A Sharp Rise in World Gasification Capacity

According to the Gasification Technologies Council (GTC; Arlington, Va.; www.gasification.org), world gasification capacity in 2000 was 45,000 megawatts thermal (MWth), representing 117 plants using 385 gasifiers — a 5% increase over the 1999 total. However, between 2005 and 2010, total gasification capacity is projected to grow by a whopping 56%, based on the addition of 25,282 MWth to the world capacity (based on 38 plants using 66 gasifiers that had already been announced at the time of the 2004 survey), “and these numbers are conservative,” says James Childress, GTC executive director, who notes: “Within a year, we expect these numbers to skyrocket because so many additional IGCC, coal-to-liquids (CTL) and gas-to-liquids (GTL) projects have been announced since 2004.”

Coal remains the predominant gasification feedstock (49% of the 2004 worldwide syngas capacity). Petroleum accounts for 37%, while the remaining 14% is supplied by natural gas, petroleum coke or biomass. The majority (29 of 38) of the new plants reflected in GTC’s latest world survey will be coal-based. “Coal is not only the most plentiful fossil fuel in the world and in the U.S., but — perhaps more important — it offers coal-rich countries the chance to improve national security by increasing reliability on a relatively cheap domestic resource — one whose price is not going to be set by a cartel,” says Phillips of EPRI. “Eventually, it’s going to be coal that’s going into your gas tank,” adds Childress of GTC.

standalone air compressor, trimming capital and energy costs. In other cases, a turbine can be used as the power driver for the ASU compressor, again reducing capital and energy costs by eliminating the compressor’s need for a standalone electric motor (although this is practiced more commonly in CTL and coal-to-chemicals plants than IGCC facilities).

Today’s IGCC operators are taking lessons from the first generation of IGCC plants, which have experience at both ends of the integration spectrum. For instance, the decade-old Polk IGCC facility in Tampa, FL, and the Wabash IGCC plant in Terre Haute, IN, both use standalone air compressors to supply their ASUs, with the Tampa plant also having a compressor to compress byproduct nitrogen for return to the gas turbine combustor, where it dilutes the syngas to lower the point flame temperature and thereby reduce the formation of thermal NO_x .

However, the comparably-sized IGCCs that started up about the same time in Europe (the Demkolec plant in the Netherlands, and the Elcogas facility in Spain) are both fully integrated, with 100% of the feed air needed for their ASUs supplied via extraction from the gas turbine, and byproduct nitrogen produced by the ASU being returned to the gas turbine combustor.

“On paper, this looked really good, but now you have processes that are too tightly integrated, so if one goes down, they all go down like domi-

noes,” says Phillips of EPRI. Lowe of GE Energy adds: “Full ASU-turbine air integration provides higher efficiency and lower capital costs, but often results in a plant that is difficult to start up and operate at reduced loads.”

“No one will ever go the route of the two European IGCCs with total integration — it’s been too problematic,” says Phillips. “Going forward, the thinking is that partial integration is better.” According to Lowe, “Our studies on air integration show that 30–50% is an optimal level of air integration between the ASU and turbine.”

The Ion-Transport Membrane (ITM). Taking aim at the entrenched incumbent technology, Air Products and Chemicals (Allentown, PA; www.airproducts.com) has been working since 1988, and in partnership with the U.S. Dept. of Energy (DOE; Washington, D.C.; www.doe.gov) since 1998, to develop high-temperature ceramic membranes that can produce tonnage oxygen needed for IGCC plants at substantially lower cost than cryogenic distillation. Today, commercial-scale availability is finally within reach. Air Products’ ITM is based on a patented ceramic (a perovskite oxide containing selected metals and rare earth elements), and achieves high-purity, high-flux separation of oxygen ions from hot, compressed inlet air.

This past fall, the company began commissioning tests with a commercial-scale module in a prototype mem-



■ **Figure 1.** The Air Products' ITM Oxygen system uses stacks of ceramic wafers, which separate oxygen from hot, compressed inlet air, as a cost-effective alternative to conventional cryogenic distillation. Credit: Air Products and Chemicals.

brane-based air separation system. Each module is composed of “tens of dozens of membrane wafers with gaps in between each one for air flow,” says Phil Armstrong, ITM Oxygen program manager. Each wafer is roughly the size of a CD-ROM (Figure 1) and is capable of producing 0.5 ton/d of oxygen. The commercial-scale module will be just two feet tall — “the size of a couple of loaves of bread end to end,” says Armstrong — and will eventually be able to produce one ton/d of oxygen. The prototype system produces up to 5 ton/d of oxygen by using multiple modules in parallel, a model for larger-scale installations.

A typical cryogenic distillation column is 200-ft tall, and a given ASU used for IGCC may require two or more columns to be operated, housed within insulated cold boxes. With such compact dimensions, the ITM Oxygen modules are “off the charts in terms of space efficiency,” says Armstrong. “A comparably sized ITM Oxygen system, including all vessels and piping, would be three-quarters the size of just one distillation tower — a striking difference.”

“We fully expect the ITM approach to reduce both capital costs and the operating (power) costs associated with large-tonnage cryogenic facilities by 30-40%,” he adds.

Each wafer consists of two proprietary perovskite ceramic outer layers surrounding a structured, porous layer in the center. During operation, hot, high-pressure air (800–900°C,

FutureGen Keeps Rolling Along

While the site has not yet been selected (although more than a dozen U.S. states are vying for it), and the technology selection has not yet been finalized, the “state-of-the-art IGCC plant” being developed by the FutureGen Industrial Alliance (www.futuregenalliance.org) is expected to eventually become the jewel in the crown of DOE's long-running Clean Coal R&D program. The broad industrial coalition is working toward building a coal-gasification-based power plant — targeted to be online by 2012 — that combines zero emissions, hydrogen co-production, and long-term underground CO₂ sequestration.

Members of the international coalition — which represent some of the world's largest coal and energy companies — have committed more than \$250 million to help fund project development. They include American Electric Power (Columbus, OH; www.aep.com); Anglo American Coal (London; www.angloamerican.co.uk); BHP Billiton (Melbourne, Australia; www.bhpbilliton.com); the China Huaneng Group (Beijing; www.chng.com.cn); Consol Energy (Pittsburgh, PA; www.consolenergy.com); Foundation Coal (Linthicum Heights, MD; www.foundationalcoal.com); Kennecott Energy (Gillette, WY; www.kenergy.com); Peabody Energy (St. Louis, MO; www.peabodyenergy.com), and Southern Co. (Atlanta; www.southerncompany.com). In April, India's government agreed to join the alliance and contribute \$10 million (*CEP*, Apr. 2006, p. 17). DOE is set to invest about \$700 million in the project.

While most existing IGCC plants don't carry out the water-gas shift reaction that is commonly used to increase hydrogen yield in gas-to-liquids (GTL) and coal-to-chemicals facilities, the FutureGen IGCC power plant is expected to incorporate a water-based shift reactor to convert the syngas (CO + H₂), by reacting it with steam over a catalyst, into CO₂ + H₂. The goal is to both maximize hydrogen production, and convert and capture over 90% of the carbon into CO₂ — at least a million tons/yr of CO₂ — for long-term sequestration in deep, underground geological reservoirs. “This will be the first large-scale demonstration of underground CO₂ sequestration,” says Phillips of EPRI, who notes that because the syngas already starts out at high pressure (at least 600 psi), the partial pressure of the CO₂ in the shifted coal syngas is roughly 360 psi. FutureGen process developers envision “pressurizing CO₂ to supercritical fluid conditions (above 2,000 psi) to facilitate underground pumping, so by starting at 360 psi, you're already ahead of the game,” says Phillips.

200–300 psig) flows along the outside of the dense outer layer, and the elevated oxygen partial pressure drives oxygen ions through the dense ceramic membrane. Oxygen moving through the porous inner spaces within each membrane wafer passes into a central piping manifold. The oxygen-depleted, nitrogen-rich air that passes out of the module at elevated temperature and pressure can then be returned to the gas turbine compression section.

The degree of turbine integration that has been envisioned right from the start makes this design even more appealing for IGCC applications and other energy-intensive applications. “The fact that the ITM needs hot, high-pressure gas from the turbine, and can then return hot, high-pressure gas to the turbine without additional heating or compression, significantly reduces the ITM system's net power use relative to cryogenic distillation,” says Armstrong.

However, “mastering the turbine integration challenges is not a trivial task,” he notes. For instance, “most of today's commercially available gas

turbines afford a maximum of 20% air extraction, but with 20% we don't have sufficient air flow for our ITM. Ideally we'd love to see at least 80% availability, but systems that yield an excess of 50% air extraction still enjoy excellent economic benefits.” Air Products is working with Siemens Power Generation to design appropriate turbine modifications that will “open the door for tighter integration between our ITM system and IGCC-class turbines,” says Armstrong.

By 2009–2010, Air Products expects to christen a 150-ton/d test facility. “This scale of development will also be the next major hurdle for ITM Oxygen to clear on the way to eventually meeting IGCC-appropriate capacities of 1,000- to 2,000-ton/d or more,” says Armstrong, and positions the technology well to be part of the showcase IGCC facility being developed by the FutureGen Alliance (box, above). And, once demonstrated at this scale, the ITM Oxygen system could also be used to produce oxygen for glassmaking, pulp-and-paper and chemicals applications.

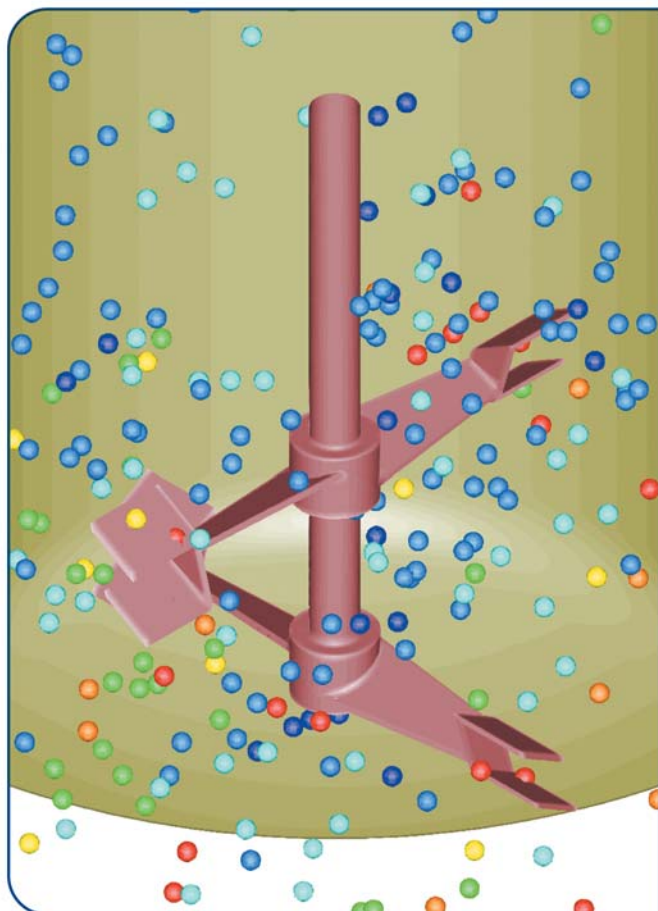
Air-blown, rather than oxygen-blown, gasification. Through the DOE-subsidized Clean Coal Power Initiative, Southern Company (Atlanta, GA; www.southernco.com), the Orlando (FL) Utilities Commission (OUC; www.ouc.com), and Halliburton-subsi-dary Kellogg, Brown and Root (KBR; Houston; www.halliburton.com) are building a 285-MW IGCC facility at OUC's Orlando-area Stanton Energy Center, which will be the first commercial-scale application of the air-blown (not oxygen-blown) coal gasifier (dubbed the Transport Gasifier) that Southern and KBR have been developing for the past several years at the Power Systems Development Facility (PSDF; www.psdf.southernco.com) near Wilsonville, AL. The group is expecting to break ground in late 2007, and bring the plant online by mid-2010.

"The anticipated cost savings associated with air-blown gasification — 10% or greater reductions in the cost of electricity compared to IGCC using oxygen-blown gasification," says Randall Rush, director, Southern Company's PSDF — "come not just from the elimination of the ASU, but from the lower operating temperature of the Transport Gasifier" (around 1,800°F compared to the 2,500–2,800°F gasification temperatures for gasification in the prevailing oxygen-blown slagging gasifiers, which are designed to melt the ash that is produced when coal is gasified).

"Lower operating temperatures lead to more reliable design and operations, and the ability to use lower-cost materials of construction," says Rush, who notes, "Most of today's existing IGCC oxygen-blown gasifiers require major refractory overhauls every two to three years, but we've been operating for ten

years at Wilsonville without significant refractory problems."

Meanwhile, because the Transport Gasifier, which consists of simple, refractory-lined pipe sections (Figure 2) operates at lower temperatures than oxygen-blown units, Southern Company and KBR have focused on using cheaper, low-rank coals (which tend to have higher levels of volatiles, ash and moisture compared to bituminous and anthracite coals). These low-rank coals make up half the U.S. and world proven reserves, according to Rush. "We chose to focus first on low-rank coals because they have higher inherent reaction rates than bituminous coals [thus they can be processed effectively at lower gasification temperatures]," he says. "The economics of oxygen-blown slagging gasifiers tend to fall off when they process lower-rank coals."



Take advantage of our experience in the Chemical Process Industry

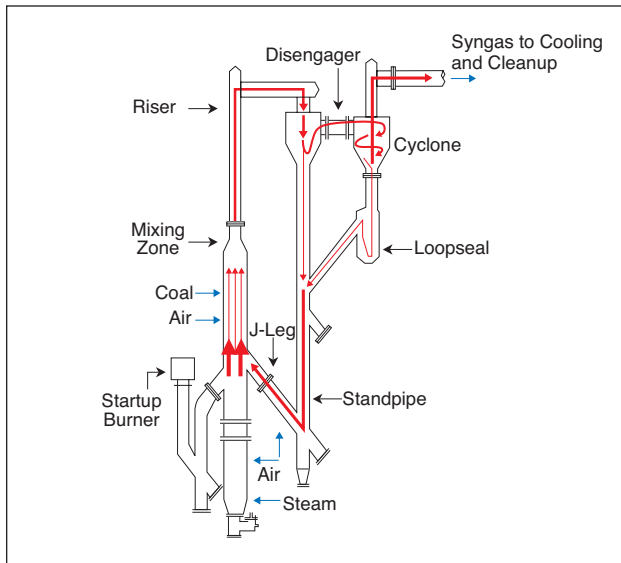
With its comprehensive range of physical models, STAR-CD from CD-adapco gives you the ability to simulate a wide range of flow processes in the CPI, including bubble columns, mixing vessels, cyclone separators, fluidised beds, heat exchangers and chemical reactors.

With 25 years experience in the Chemical and Process Industry, you can rely on CD-adapco to offer you the full spectrum solution that you need. We won't just offer you CAE software; we will back you up with Training, Consulting and Engineering Services. Optimize your designs, improve your process and meet your legal requirements; talk to us today to find out how you can benefit from our experience.



Your CAE Partner for Success
info@us.cd-adapco.com • www.cd-adapco.com

www.cepmagazine.org or Circle No.118



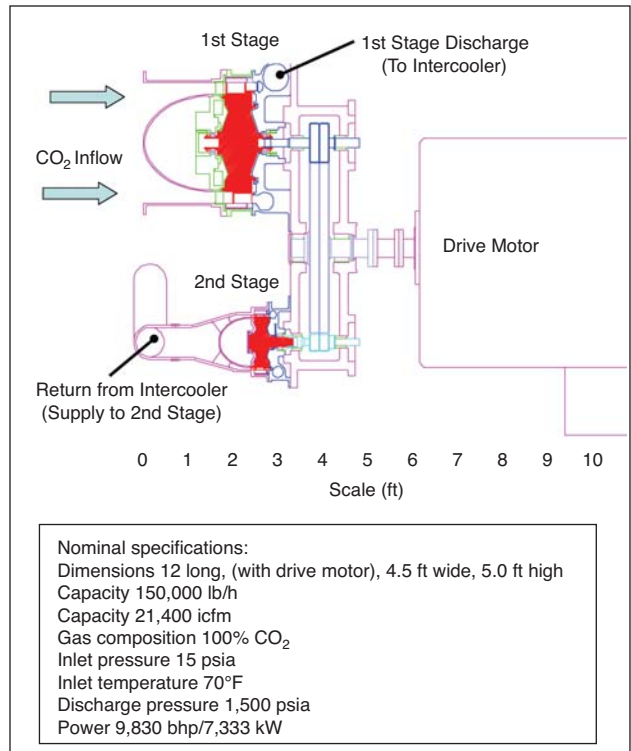
■ Figure 2. Unlike conventional oxygen-blown slagging gasifiers, Southern Company's Transport Gasifier consists of simple refractory-lined pipe sections and uses air to gasify low-rank coals. The cyclone is used to capture and recycle ash back to the fluidized-bed gasifier section. Source: Southern Company.

Furthermore, "because the Transport Gasifier is a fast, fluidized-bed gasifier that operates in the transport regime, we like a lot of ash, so even coal with 40% ash content doesn't bother us," he adds.

While nitrogen in air (present at 79 vol.%) is removed when air is cryogenically distilled to produce oxygen for conventional oxygen-blown gasifiers, the nitrogen in air travels through the Transport Gasifier when it is configured as an air-blown gasifier, and ends up in the coal-derived syngas. According to Rush, the presence of this large volume of hot nitrogen-rich gas offers a cost-effective way to power both the steam and gas turbines used during combined-cycle power generation.

'Supersonic compression.' As noted above, two of the fundamental cost drivers associated with IGCC are the upstream air compression at the inlet of the ASU, and the downstream compression of byproduct CO₂. For now, CO₂ is typically compressed to achieve pressure levels needed for pipeline transport and use in enhanced oil-recovery applications, but, looking down the road, should underground sequestration ever become viable or required, even higher pressures will need to be achieved. "To drastically reduce the cost of both upstream air and downstream CO₂ compression," Ramgen Power Systems (Bellevue, WA; www.ramgen.com) is developing a compressor "based on supersonic compression technology," that is "capable of simultaneously achieving very high single-stage pressure ratios, and very high efficiency," says Ramgen president Peter Baldwin. Being developed with funding from the DOE, Ramgen's compressor technology combines aspects of shock compression systems used in supersonic flight inlets with turbomachinery design practices used in today's conventional axial and centrifugal compressors (Figure 3).

"For CO₂ compression during IGCC, a conventional centrifugal compressor system would typically require eight stages (with a corresponding number of stainless steel inter-



■ Figure 3. Ramgen's supersonic compressor, which can achieve exceptionally high compression efficiency at very high single-stage compression ratios, is first being developed for inlet air and CO₂ compression related to IGCC facilities, but has the potential to improve compressor capabilities for other industrial applications, as well. Source: Ramgen Power Systems.

coolers between stages) to achieve 100:1 compression," says Baldwin. By comparison, the Ramgen compressor "can achieve comparable compression ratios using just two stages with a single intercooler," says Baldwin. "This can dramatically reduce overall package size, weight and complexity, and allow the heat of compression to be recovered and used elsewhere in the process."

A proof-of-concept rotor has been tested on air at a low pressure ratio, with a high-pressure rotor scheduled to be tested shortly. The DOE has committed to fund the development of a two-stage, 100:1 pressure ratio demonstration unit that will be nominally rated at one-fourth of the commercial-scale flowrate of 600,000–700,000 lb/h.

As long as prevailing economic, environmental and geopolitical factors continue driving the commercial-scale application of world-class coal-gasification facilities to produce power, chemicals and fuels, the engineering community is sure to continue pursuing advanced technologies and improved designs and operating strategies to trim the costs of these promising, yet capital- and energy-intensive, fossil-fuel-conversion processes.



SUZANNE SHELLEY is a Manhattan-based freelance writer specializing in science, engineering and technology (Email: suzanneashelley@yahoo.com). A 16-year veteran and former managing editor of *Chemical Engineering* magazine, Shelley now writes about a broad array of chemical process, petroleum refining, pharmaceutical and related engineering and business topics, for both corporate clients and various technical trade magazines. She holds a BS in geology from Colgate Univ. and an MS in geology from the Univ. of South Carolina (Columbia). Shelley was also profiled in the 2005 book, "Be Happy at Work: 100 Women Who Love Their Jobs and Why," Gordon, J., Ballantine Books.