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SPECIAL REPORT

SUPERCRITICAL CO_2 THE NEXT BIG STEP?

MATCHING TURBINES & COMPRESSORS

CENTRIFUGAL COMPRESSOR PERFORMANCE

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SPECIAL REPORT

SUPERCRITICAL CO_2 — THE NEXT BIG STEP?

CO_2 TURBINES COULD BOOST SIMPLE CYCLE EFFICIENCY BEYOND 50% AND REDUCE TURBOMACHINERY FOOTPRINT BY 100 TIMES

DREW ROBB

In the 1960s, every engineer at Sandia National Laboratories probably wanted to work on the Apollo space program. Today, that excitement and enthusiasm is focused on the launch of supercritical CO_2 (S-CO_2) technology. "Supercritical CO_2 is the future; it is a game changing technology," said Darryn Fleming, Lead Mechanical Engineer for the S-CO_2 Power Conversion Program at Sandia National Labs. "It is a way to further improve power efficiency."

To be sure, S-CO_2 could be a game changer for power plant economics, efficiency and the environment: Simple cycle efficiency above 50%; footprints one hundredth of those of traditional turbomachinery for the same power output; and no nitrogen oxides (NOx) emissions. These are some of the purported benefits of S-CO_2 turbines which are now well along in the design and prototyping stage (Figure 1).

In addition, it may represent the next great frontier in turbine engineering. While steam turbines dominated much of the 20th century, gas turbines (GTs) absorbed most of the R&D resources and gradually came into their own, pushing plant efficiencies from the thirties into the sixties via combined cycle technology.

Similarly, S-CO_2 turbomachinery requires innovative designs because S-CO_2, at 468 kg/m3, is denser than the working fluids in GTs and steam turbines. Therefore, turbines designed for S-CO_2 can be roughly 1/100th the size of steam turbines for the same power output, said Fleming. That is why Closed Brayton Cycle (CBC) technology like S-CO_2 has been considered for applications with severe volume constraints, such as ships, spacecraft, and lunar power plants.

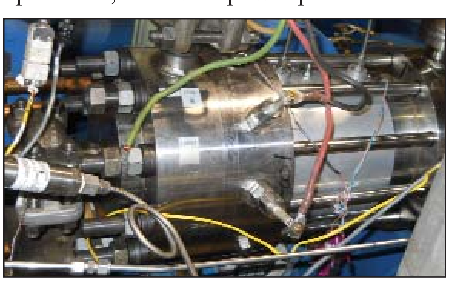

Figure 1: A supercritical CO_2 turbine-alternator-compressor operating at Sandia National Labs

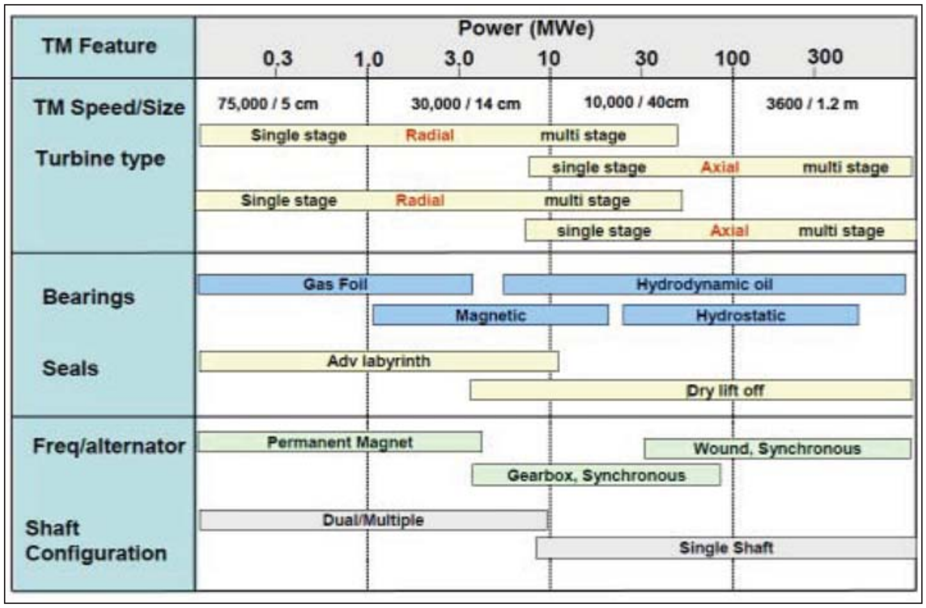

Figure 2: Component and technology options for S-CO_2 systems

Many of the major research bodies such as Sandia National Laboratories, Southwest Research Institute (SwRI) and Lawrence Berkeley National Laboratory are placing a lot of emphasis on S-CO_2. They are involved with companies such as Toshiba, Echogen, Dresser Rand, GE, Barber-Nichols and Bechtel in creating these next-generation turbines, though few details have emerged. What is clear is that different components and technology options will have to be considered as the manufactured systems scale upward (Figure 2).

"We have designed large S-CO_2 turbomachinery for corporate customers," said Robert Fuller, Chief Engineer at Barber-Nichols. "We continue to work on larger power systems for various customers; it is a very active field."

Given the pressures involved and high density (low volumetric flow rate), no GT or steam turbine modification could be made to work, explained Fuller. Neither comes even close to the energy density of CO_2 turbines and compressors which have energy densities that are in the range of rocket engine turbo-pumps.

However, barriers remain. Heat exchanger technology, for example, might be a stumbling block, either in terms of cost, footprint or ability to withstand high pressures. But companies such as Heatric, Brayton Energy and Thar Energy are hard at work solving these issues. In addition, existing systems remain too small to be considered commercially viable.

"The engineering challenge is to produce a machine that meets the reliability targets of the industrial marketplace," said Fuller.

Some estimate, though, that commercial models will hit the market as early as next year. "The initial deployment of SCO_2 turbomachinery will be in 2013 on a comm ercial basis, and possibly another ten to fifteen years to gain wide acceptance," said Fuller.

S-CO_2 cycle

Fleming explained that S-CO_2 power cycles offer the potential for better overall plant economics due to their high power conversion efficiency over a moderate range of heat source temperatures, compact size, and potential use of standard materials in construction. Carbon dioxide arrives at a supercritical fluid state when temperature and pressure reach their critical point (31°C/87°F and 73 atm). In this state, it has gas and liquid qualities (Figure 3). Theoretically, any heat source above this temperature can sustain an S-CO_2 power generation cycle, whereas water requires much higher temperatures.

S-CO_2, then, has applications for solar, gas and steam turbines, nuclear, waste heat and geothermal. One central approach is to improve efficiency by transferring exhaust thermal energy into power via heat exchangers.

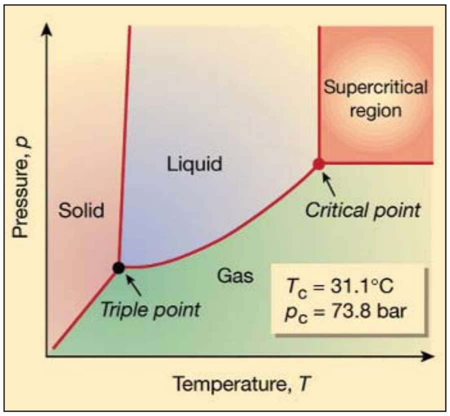

Figure 3: Phase diagram for CO_2

Sandia National Labs and the U.S. Department of Energy (DOE) have built and begun operating a supercritical CO_2 split-flow recompression Brayton cycle in conjunction with contractor Barber-Nichols. This facility is among the first S-CO_2 Brayton cycles anywhere in the world.

"An initial test was completed at low temperature and low speeds that yielded a 30 kW output," said Fleming. "Higher speeds and temperatures will yield much higher power levels."

The loop has been primarily operated as a simple recuperated Brayton cycle, i.e., a single turbine, single compressor, and undivided flow paths. In this configuration, the test facility has reached a turbine inlet temperature (650°F/615K), a shaft speed of 52,000 rpm, a pressure ratio of 1.65, a flow rate of 2.7 kg/s, and 20 kW of power generated (Figure 4).

Figure 4: Sandia's S-CO_2 test loop

Toshiba CO_2 turbine

One of the surprising aspects of S-CO_2 is the sheer number of companies actively pursuing the technology. The R&D investment is already major and is expected to soar over the next year or two. Fuller said that five years ago, perhaps $5 million was spent on the initial Sandia work by the U.S. DOE.

"In 2013, I estimate that over $500 million will have been spent on test and commercial systems for waste heat, solar, direct fossil fuel, and nuclear applications," said Fuller.

For example, Toshiba Corporation, The Shaw Group and Exelon Corporation are collaborating to develop Net Power's gas-fired power generation technology with a target of zero emissions. This approach uses an oxyfuel, high-pressure, supercritical CO_2 cycle, named the Allam Cycle, after lead inventor Rodney Allam. Unlike traditional carbon capture technologies, this is said to produce pipeline-ready CO_2 for sequestration or use in enhanced oil recovery (EOR) without reducing plant efficiency or increasing costs.

Power is generated using a transpiration-cooled combustor with circulating fluid CO_2. The CO_2 can be introduced into the combustor along with a fuel and an oxidant for combustion. A high-pressure, high-temperature fluid stream is then produced which comprises the circulating fluid and combustion products. The fluid stream can be introduced into a turbine, with a portion of it recycled by passing it through a heat exchanger to heat the circulating fluid prior to introduction into the combustor. Alternatively, it can produce CO_2 at pipeline pressure for sequestration. Natural gas or coal-derived gases, liquid hydrocarbons, and coal, lignite or petcoke could be employed.

Project development and systems engineering will be done by Net Power, while Shaw will provide engineering, procurement and construction services, and Exelon takes care of site selection, permitting and commissioning. Toshiba will design, test and manufacture a combustor and turbine for the natural gas plant.

The system produces a supercritical CO_2 stream to drive a turbine generator. This eliminates NOx by burning a mixture of natural gas with oxygen instead of nitrogen-rich air. In addition, it separates and collects pressurized CO_2 without adding on a carbon capture system. Toshiba envisions a high temperature and high pressure turbine and combustor. Construction is expected to begin in late 2014 or early 2015 on a 25MW natural gas plant. A 250 MW full-scale natural gas commercial plant is expected by 2017

Another commercial player is Echogen Power Systems. It has been developing a power generation cycle for waste heat recovery using supercritical CO_2 as the working fluid. The company said it has applications as broad as bottom cycling in gas turbines, industrial waste heat recovery, solar thermal, geothermal, and hybrid alternatives to the internal combustion engine (Figure 5).

A waste heat exchanger is installed into a smokestack, boiler or turbine exhaust duct, hot process gas or liquid line, or even into a solar thermal concentrator in order to transfer heat energy to the S-CO_2 working fluid which then passes through a turboexpander. Enthalpy gain from heating is converted into mechanical energy to produce electricity. Residual heat is recycled. Expanded S-CO_2 is cooled at the recuperator and condensed to liquid by a condensing medium which can be water or air.

The company has engineered two systems to date. A 200 kW to 300 kW system (designated EPS5) utilizes a turbo-alternator while a 6 MW to 8 MW unit known as EPS100 has a turbine generator.

According to Timothy Held, Chief Technology Officer at Echogen, EPS5 has completed initial checkout testing, and is beginning endurance testing this quarter. A commercial version of this machine should be available within 12 to 18 months. EPS100 is undergoing factory testing, which should be complete in the next few months. Although the unit is a prototype, it has been designed and built to commercial standards, and so should be available for commercial service in 2013.

"In the EPS5, a high speed permanent magnet generator is directly coupled to the turbine, while for the EPS100, a separate turbine drives a conventional synchronous generator through a gearbox," said Held. "Because the EPS100 power turbine is a separate unit, two different options for the turbine are being offered, one a high-speed, single-stage radial turbine, the other an API-compliant lower-speed axial turbine."

He said these machines could be used for industrial waste heat (steel mills, cement plants, glass furnaces and refineries), as well as for gas turbine and reciprocating engine exhaust, generally in the 450 to 1,200+°F exhaust temperature range. In addition, Echogen is working with Lawrence Berkeley National Laboratory for geothermal applications at lower temperatures. And it has generated interest in shipboard applications for exhaust heat recovery, as shown by the award of a U.S. Navy SBIR program to Echogen for design studies of such a system.

Held considers that S-CO_2 systems have the potential to expand waste and exhaust heat recovery applications into broader markets than today's steam and organic Rankine

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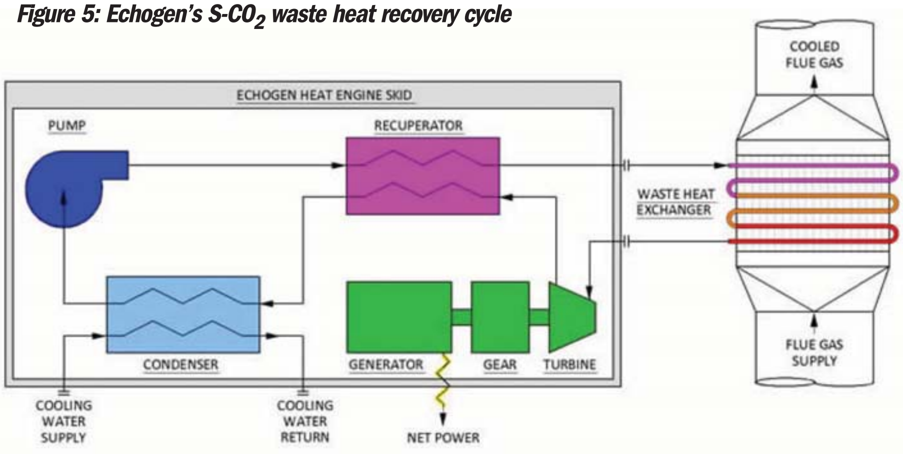
Figure 5: Echogen's S-CO_2 waste heat recovery cycle



cycles through a combination of high efficiency, low cost, and small footprint. "We project between 30% and 35% lower installed costs and a 50% reduction in footprint versus steam," said Held.

An equity stake in Echogen is held by Dresser-Rand. It is working with Echogen to move forward its S-CO_2 systems.

"Dresser-Rand will develop, engineer and manufacture the turbomachinery within the system including an S-CO_2 turboexpander," said Thomas Logan, Director, Product Management for Environmental Solutions, Dresser-Rand.

Combined cycle applications

He added that Echogen's S-CO_2 power cycle is designed to maximize power generation in gas turbine combined cycle power plant (CCPP) applications. No modifications are required to the gas turbine to accept the S-CO_2 power cycle, other than typical accommodations for an exhaust heat recovery system and controls interface.

A heat exchanger located in the waste heat stream results in gas-side pressure drops in the range of 1.0 to 7.0 inches of water column. In some cases, an induced draft fan is added to the exhaust system if the existing system is unable to overcome the waste heat exchanger pressure drop.

The first EPS100 is currently undergoing engineering testing at Dresser-Rand's Olean, NY facility and is expected to be deployed to a U.S. customer site by the end of 2013. Logan believes the technology has the potential to further boost CCPP efficiencies beyond the 60+% range over time.

"Continued development of S-CO_2 systems for the larger size and higher temperatures of industrial gas turbines will result in higher overall efficiency," said Logan.

Pratt & Whitney Rocketdyne (PWR) is another organization investing heavily in S-CO_2. Gregory Johnson of PWR was involved in a recent design study done on behalf of Argonne National Laboratories to figure out the specifics of a 1,000 MW nuclear system which would include a supercritical CO_2 cycle coupled to a large sodium-cooled liquid metal nuclear reactor (LMR). It would have an inlet temperature of 333°C and a 488°C outlet temperature. "Effective ways of coupling an S-CO_2 cycle to LMR are being investigated," said Johnson.

PWR has considered several possible configurations including 2 x 500 MW and 4 x 250 MW turbines. In the end, the preferred design is a single 1,000 MW turbine, largely driven by turbine costs and plant footprint. A split-shaft arrangement has been recommended with one turbine driving a generator and the other driving compressors.

With a single shaft, a substantial amount of additional piping would be required and efficiency would be lower. With a split-shaft design, on the other hand, fewer compressor stages and less piping would be needed as well as smaller turbines and greater efficiencies. Cost, though, would be higher.

One interesting application of S-CO_2 is in carbon capture and storage (CCS). The oxy combustion process could use S-CO_2 in a topping cycle, and steam for bottoming. The cost of CO_2 sequestration, therefore, could be recouped by efficiency gains from the S-CO_2 cycle. "This S-CO_2 cycle holds great promise for impressive efficiency gains and brings down capital costs for modern power plants," said Johnson (Figure 6).

Heat exchanger limits

This work is pushing the limits of current heat exchanger technology. As a result, Sandia is engaged in working out failure modes for heat exchangers and has several corrosion studies ongoing, as well as work on bearings and seals that can deal with these pressure and temperature extremes.

Fleming thinks that the limiting factor of this technology is going to be the heat exchangers. "Heat exchangers are going to be huge in the next couple years." said Fleming. "Development of a small, modular and low-cost heat exchanger that can keep up with worldwide demand will revolutionize the SCO_2 program."

According to Fuller, Barber-Nichols exclusively has used Heatric printed circuit heat exchangers (PCHE) at Sandia.

"PCHEs worked extremely well," said Fuller "The only improvement that would enable more S-CO_2 applications is lower cost."

Johnson, however, believes PCHEs currently have size limitations. Designers at PWR are looking at plate and sheet heat exchangers as well as double enhanced sheet and tube models.

"As the supercritical CO_2 cycle is highly recuperated, large amounts of heat transfer area are required," said Johnson. "Large, highly effective heat exchangers will need to be developed."

Reducing project costs

Heatric is touting diffusion-bonded heat exchangers (PCHEs) as a means of bringing project costs down to size by combining large heat exchange surfaces with high heat transfer coefficients. The company said these diffusion-bonded models are four-to-six times smaller than conventional shell and tube heat exchangers. They can cope with pressures beyond 600 bar (9,000 psi) and temperatures from cryogenic to 900°C (1,650°F).

Thar Energy, on the other hand, is working on compact heat exchangers which are said to be substantially better than anything that is on the market, as well as heat exchangers that are similar in performance to PCHEs but lower in pricing, according to Lalit Chordia, CEO and Founder of Thar Energy.

"We believe that high performance heat exchangers are a requirement for high efficiency, especially if the temperature of the heat source is high," said Chordia. "Every small increase in efficiency is a big step towards making a solar cycle with CO_2 competitive."

Brayton Energy manufactures both primary and secondary surface heat exchangers. However, the secondary surface provides improved compactness and strength necessary for the higher S-CO_2 pressure, said Jim Kesseli of Brayton Energy. His company offers a compact (7,000 to 10,000 m^2/m^3) wire matrix heat exchanger that has been proof pressure tested to 10,000 psig (70 MPa) without failure. This design has a welded pressure boundary and is built on a cellular architecture to create a strain-tolerant structure.

Kesseli is not convinced that PCHEs are the way to go. "Gas turbine recuperator

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experience suggests that PCHE bonded cores will succumb to fatigue cracking," he said. "The PCHE may be fine for the low temperature heat exchangers, but such rigid structures do not accommodate the thermal fatigue present in the higher temp S-CO_2 recuperator."

Renaud Le Pierres, Business Development Engineer at Heatric, disputes this claim.

"PCHEs can cope with the high pressures and temperatures required," he said. "There is no such thing as a limiter of scale out for PCHEs."

Solar CSP

On the solar front, supercritical CO_2 can potentially add value to Concentrated Solar Power (CSP) plants by being used in conjunction with nitrate salts which are pumped up the up tower and heated to a molten state.

Current research involves figuring out how to drop the salt temperature closer to 500°F at the outlet for use in waste heat recovery. For example, a cascaded CO_2 cycle could split the flow with a high temperature loop to take the salt temperature down to 750°F and a low temperature loop to take the temperature down to 550°F.

The higher temperature CO_2 would be used to drive a power turbine and the lower temperature CO_2 would drive compressors. "We are going to build a molten salt test project and we hope to drive down the cost of CSP," said Johnson.

With cost continuing to be the bugbear of many solar projects, it is understandable that much work is being done on the solar potential of S-CO_2. Echogen, for example, has recently been awarded a DOE SunShot CSP program, a collaborative national effort to make solar energy cost competitive with other forms of energy. Echogen will work with the National Renewable Energy Laboratory to develop and demonstrate a higher temperature turbine for solar applications.

Similarly, SwRI and industry collaborators General Electric, Bechtel Marine Propulsion Corporation and Thar Energy have been awarded an $8.5 million contract by the U.S. Department of Energy to develop a high-efficiency S-CO_2 hot gas turbo-expander for CSP, also part of the SunShot Initiative. GE will develop the turbomachinery, Thar the heat exchangers, SwRI the development and testing, and Bechtel the operation of the Knolls and Bettis Atomic Power Laboratories.

Klaus Brun, program director in SwRI's Mechanical Engineering Division, who will serve as project manager for the effort, explained that the highly cyclical nature of CSP plant operations means that

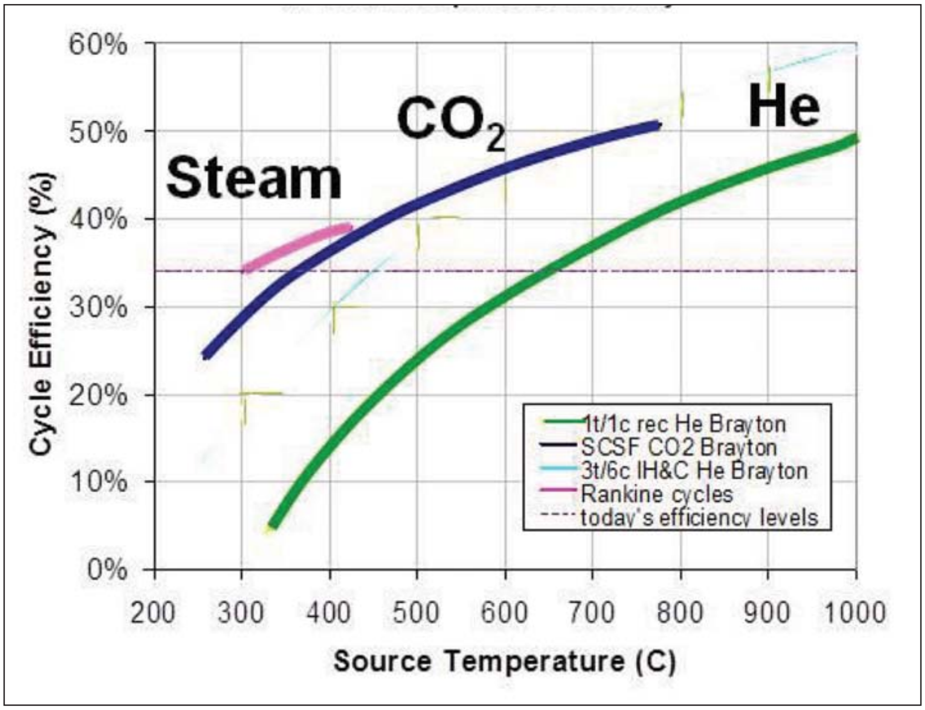

Figure 6: Cycle efficiency as a function of temperature

an S-CO_2 hot gas turbo-expander must be able to operate at high temperatures and pressures over a wide range of load conditions. At the same time, it must maintain high efficiency, handle rapid transient heat input swings and have fast start-up capabilities to optimize availability.

Further, the project is working on PCHEs to reduce manufacturing costs. The hope is that CSP power can eventually be produced at $0.06 per kilowatt hour while increasing energy conversion efficiency to greater than 50% and reducing total power block cost to below $1,200 per kilowatt installed. At the end of three years, a single- or multi-stage S-CO_2 hot gas turbo-expander, mega-watt scale prototype will be produced.

GE Global Research is currently evaluating different concepts before moving into the detailed design stage, according to Chiranjeev Kalra, Energy Systems Engineer, and project lead at GE for the S-CO_2 program.

"The power density, efficiency and low footprint of S-CO_2 makes it possible to bring down the cost of CSP to commercially competitive levels," said Kalra.

While the focus is on solar, Brun sees plenty of applications in areas such as nuclear and oxyfuel.

"The higher you go in temperature, the more difficult become your materials, cooling and so on," said Brun. "Achieving high efficiency at a low-cycle temperature is attractive. While pressures are higher, that is not so hard to deal with."

Engineering challenges certainly remain. But confidence is high. Fuller said the remaining technological barriers are being addressed and solved. He does not believe any significant roadblock currently exists on the engineering side. Held concurs, adding: "The technical barriers for the initial market introduction are low."

Larger test facilities in the 10 MW range are the next stage in S-CO_2 research and development, said Flemming. "An intermediate or prototype scale experimental loop will be needed to establish the commercial viability of S-CO_2 CBC technology prior to a full scale application."

This next stage will help resolve technological questions such as: Whether to use PCHEs or some other form of heat exchanger; whether the turbines should be radial or axial, shrouded or un-shrouded, single or multistage; and what type of compressor and how many stages.

"We have the potential to jump from power plants that operate in the 33% to 35% efficiency range to 50+%," said Fleming. "That is huge in terms of curtailing greenhouse gases (an estimated 34% drop), and for reducing electricity bills. Additionally, we will be able to bring cost-effective electricity to areas currently starved for electricity such as dry desert environments. Even when using air to cool the S-CO_2 cycle instead of water (similar to car radiator cooling), efficiencies are still good."

"We are as excited to come to work every day as were all those people working the Apollo program in the 60s," said Fleming. "We have a lot of work to do, but we're committed to seeing this technology launch." TI