APPENDIX B: CARBON DIOXIDE CAPTURE TECHNOLOGY SHEETS

ADVANCED COMPRESSION

THERMAL INTEGRATION OF CO_2 COMPRESSION PROCESSES WITH COAL-FIRED POWER PLANTS EQUIPPED WITH CARBON CAPTURE

Primary Project Goals

Lehigh University is developing systems analysis models to study the benefits of improved thermal integration for coal-fired power plants equipped with post- or oxy-combustion carbon dioxide (CO_2) capture systems.

Technical Goals

- Gather technical and performance information from compressor manufacturers and the technical literature in order to calculate compressor power requirements, performance of interstage heat transfer, and interstage pressure changes.
- Develop and validate ASPEN Plus models of coal-fired power plants with solvent-based post-combustion CO_2 capture to simulate the effects of different thermal integration options on power plant efficiency and net power output.
- Develop and validate ASPEN Plus models of oxy-combustion coal power plants to simulate the effects of different thermal integration options on power plant efficiency and net power output.

Technical Content

Coal-based power plants equipped for CO_2 capture require a compression system to increase the pressure of the CO_2 to the level needed for geological storage [approximately 2,200 pounds per square inch absolute (psia)]. In addition to its relatively high capital cost, the CO_2 compression system requires a significant amount of auxiliary power for operation. The technology options available for CO_2 compression include:

- A multistage in-line centrifugal compressor with interstage and post-compression cooling.
- A multistage integrally geared centrifugal compressor with interstage cooling.
- A multistage supersonic shockwave compressor with interstage and post-compression cooling.
- A compression process involving gas phase compression to approximately 200 psia, cryogenic cooling through the two-phase region, and increase in pressure of the liquid CO_2 to the final pressure using a liquid cryogenic pump.

For some of these technology options, there is the potential for utilization of waste heat from the CO_2 compressors within the power plant. This project uses first-principle engineering analyses and computer simulations to determine the increase in power output and improvement in net unit heat rate which could occur by thermal integration of the CO_2 compression process with the CO_2 capture system, boiler, and turbine cycle. The study includes gathering information on compressor internal geometry and compressor stage efficiencies. The aerodynamic conditions and flow

Technology Maturity:

Systems analysis models

Project Focus:

Thermal Integration of CO_2 Compression Processes

Participant:

Lehigh University

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FE0002146

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Partners:

None

Performance Period:

10/1/09 – 6/29/12

geometry change from the low-pressure to high-pressure end of the compressor, very likely resulting in significant variations in isentropic stage efficiency from inlet to outlet. Correct values for isentropic stage efficiency are needed in order to obtain realistic values of compressor power and CO_2 exit temperature for each stage. In addition, fluid flow and heat transfer analyses will be performed to estimate CO_2 pressure drop in the intercoolers and the exit temperature of the cooling fluid as a function of coolant flow rate. While the literature suggests that most CO_2 compressors are air-cooled, analyses will be performed to determine the feasibility of using liquid-cooled heat exchangers for interstage cooling.

Once the analyses of the compressors are complete, the results will be linked to models of the power plant for analysis of various thermal integration options. The compressor and power plant simulations will be performed using the ASPEN Plus software. Each of the following cases will be analyzed using bituminous, Powder River Basin (PRB), and lignite coals:

- Pulverized coal-fired boiler with post-combustion solvent-based capture systems using both amine and ammonia scrubbers.
- Oxy-combustion pulverized coal boiler.

The thermal integration options which will be considered include pre-drying of low-rank coals, regeneration of CO_2 solvent, and boiler feedwater preheating. Table 1 presents the matrix of analyses which will be performed.

Table 1: Systems Analysis Matrix for CO_2 Compression Heat Integration

Use of Recovered Heat From CO_2 Compressor			
Integration Method	Pre-Dry Low Rank Coal	Regenerate CO_2 Solvent	Preheat Boiler Feedwater
Post-Combustion Solvent-Based CO_2 Capture			
Bituminous	No	Yes	Yes
PRB	Yes	Yes	Yes
Lignite	Yes	Yes	Yes
Oxy-Combustion			
Bituminous	No	No	Yes
PRB	Yes	No	Yes
Lignite	Yes	No	Yes

Technology Advantages

- Determine the best way to utilize waste heat from CO_2 compression.
- Improve power plant efficiency and increase the net power output.
- Reduce capital and operating cost for CO_2 capture and compression systems.

R&D Challenges

Implementation of the thermal integration opportunities as cost-effective technology options.

Results To Date/Accomplishments

- Obtained compressor design and performance information from CO_2 compressor vendors.
- Compared analysis algorithms to vendor data and verified analytical results.
- Initiated analysis of heat transfer and pressure drops for the pre-compression and interstage coolers.
- Developed ASPEN Plus models to analyze the effects of thermal integration on post-combustion capture and oxy-combustion systems.

Next Steps

- Complete analyses of thermal integration options for post-combustion capture system.
- Complete analyses of thermal integration options for oxy-combustion system.
- Complete analyses of pre-compression and interstage coolers.

Available Reports/Technical Papers/Presentations

No reports, technical papers, or presentations are yet available.

RAMGEN SUPERSONIC SHOCK WAVE COMPRESSION AND ENGINE TECHNOLOGY

Primary Project Goals

Ramgen Power Systems is designing and developing a unique compressor technology based upon aerospace shock wave compression theory for use as a carbon dioxide (CO_2) compressor. A shock wave-based gas turbine engine is also being developed.

Technical Goals

Phase I:

- Complete testing of a high-pressure ratio (10:1) air compressor rotor for the Ram 2 program.
- Demonstrate the feasibility of high-pressure shock wave compression.
- Develop and detail a viable commercialization path.

Phase II:

- Perform critical success factors risk reduction validation and test program to identify and reduce technical risk areas.
- Complete general assessment, preliminary, and final design of a demonstration CO_2 supersonic shock compressor approximately 13,000 hp in size.

Technical Content

Shock Wave CO_2 Compressor

Ramgen Power Systems is developing a supersonic shock wave compression technology, similar in concept to an aircraft's ramjet engine, for use in a stationary compressor. Ramgen's compressor design, known as a Rampressor, features a rotating disk that operates at high peripheral speeds to generate shock waves that compress the CO_2. Compared to conventional compressor technologies, shock compression offers several potential advantages: high compression efficiency; high, single-stage compression ratios; opportunity for waste heat recovery; and low capital cost. For example, Ramgen's shock compression has the potential to develop compression ratios from 2.0 to 15.0 per stage with an associated adiabatic efficiency of 85–90%. For CO_2 applications, Ramgen anticipates using a nominal, two-stage 100:1 compression ratio, featuring a matched pair of 10:1 compression stages with an intercooler located between the stages. Prototype testing completed in 2007 achieved a 7.8:1 compression ratio.

When shock waves pass through a gas they cause a localized compression. Figure 1 shows that the rotating rotor rim has small, shallow angles which, when rotating at high speeds, will produce supersonic shock waves both prior to and post-peak. These shock waves, modeled in the 3-D Euler Computational Fluid Dynamics (CFD) image shown, are first oblique, then normal. Additionally, strakes (ridges) are incorporated into the design of the rotor to form sidewalls. The strakes are utilized as shock compression ducts, as well as to separate high-pressure discharge from low-pressure suction. The combination of shocks and strakes result in a compressed fluid delivered from a stationary discharge duct with compression efficiencies comparable to conventional industrial turbo-compressors, but with much higher single-stage pressure ratios and therefore higher quality heat of compression that combine to deliver significant installed and operational cost savings versus existing turbo-compressors.

Technology Maturity:

Pilot, 1,680 tonnes/day CO_2

Project Focus:

Shock Wave Compression

Participant:

Ramgen Power Systems, LLC

Project Number:

FE0000493
NT42651

NETL Project Manager:

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Partners:

Dresser-Rand

Performance Period:

5/10/06 – 12/31/13

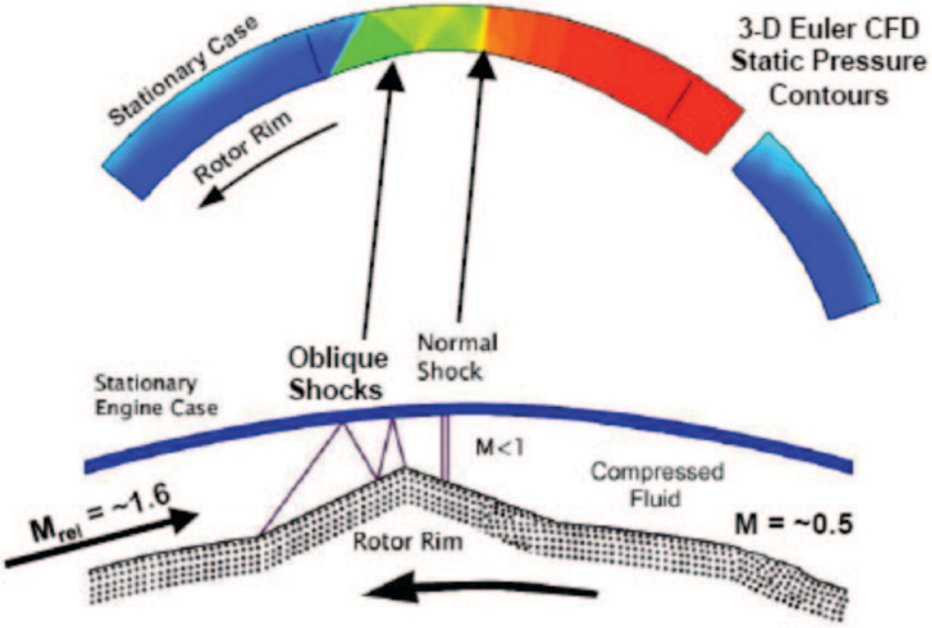

Figure 1: Schematic of Rotor Rim and Engine Case and 3-D Euler CFD Image Depicting Shock Wave Behavior

Two stages of compression are used with an intercooler located between the stages to optimize the efficiency of the compression process. Figure 2 shows the energy required as shaft work and the thermal energy lost to the cooling stream for a 200-MW coal plant with 90% CO_2 capture. The numbers found in the figure represent a stage in the process; each stage is driven independently through an external gearbox.

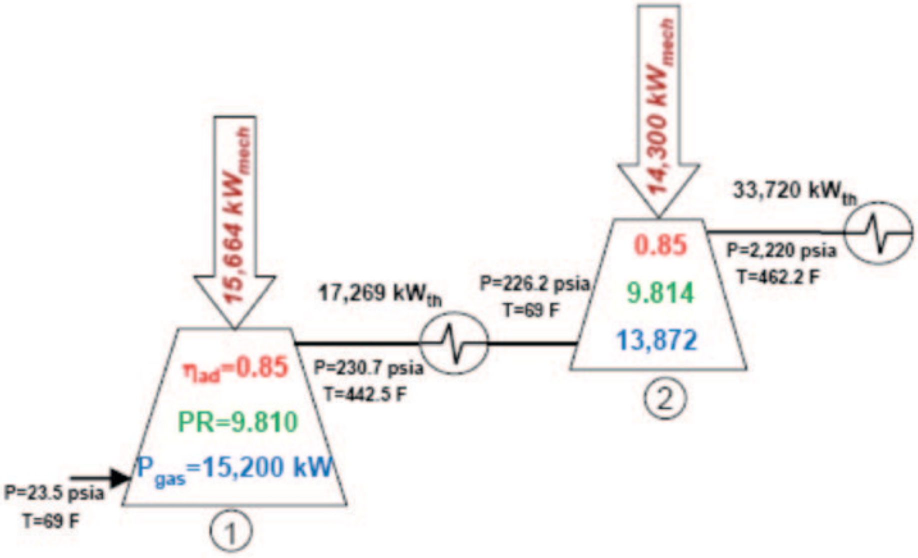

Figure 2: Series Process Schematic

As seen in Figure 2, the total shaft power is 29,964 kW_{mech}, which corresponds to a heat of compression of 50,989 kWth. Approximately 28,986 kWth of the heat of compression lost is recoverable down to 93 °C (200 °F).

Shock Wave Gas Turbine Engine

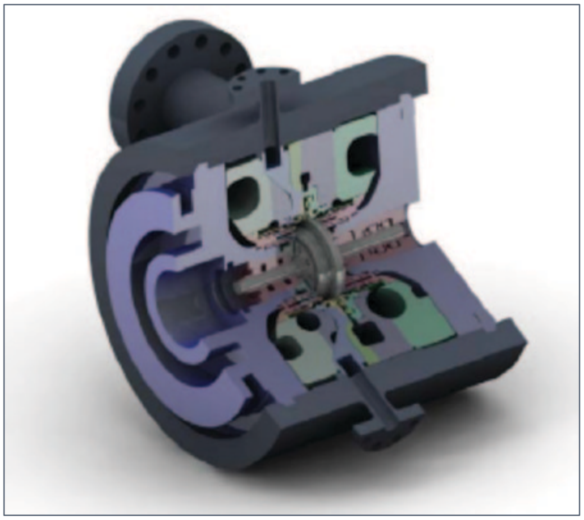

Figure 3: Cross Sectional Model of a 1/10th Scale Single Stage Supersonic Shock Wave Compressor

Ramgen is also developing a unique shock wave-based gas turbine engine that is expected to significantly improve energy efficiency. The Ramgen Integrated Supersonic Component Engine (ISCE) consolidates the compressor, combustor, and turbine of a conventional gas turbine into a single wheel that operates based on the same Brayton thermodynamic cycle as a conventional gas turbine; however, the mechanical implementation of the process is quite different. One important advantage is that because the compression, combustion, and expansion processes are all integrated into a single constant speed rotor, there is no physical acceleration of the rotating components required as the system transitions from idle to full power. The output torque and power are modulated from the full-speed, no load condition to the full-speed, full power condition by adjusting the fuel flow. As a result, the system can transition from idle to full power as quickly as the fuel flow can be adjusted. Testing has demonstrated a transition from combustor heat release levels consistent with a power variation from idle (pilot fuel only) to full power (full fuel/air premix) in periods as short as 150–200 mili-seconds (ms). The ISCE will have the ability to load follow from idle to full power in time scales as short as a few hundred ms compared with a response rate of 7–10 seconds for most intermediate sized gas turbine electric power generating systems.

The initial proof of concept Ramgen engine used an un-shrouded rotor configuration mounted on a single high-speed shaft driving a generator/starter motor through a speed reducing gearbox. The ISCE system will incorporate a fully shrouded flowpath power-wheel configuration. The power wheel now proposed will be directly supported by a magnetic bearing system and will incorporate permanent magnets into the inner diameter of the rotor. This rotor mounted magnet system will rotate around a central stator winding to form an integrated high-speed permanent magnet motor/starter system on the inner hub of the power wheel. This configuration will eliminate the need for a speed-reducing gearbox and the discrete separate motor/generator. This consolidation will result in a significantly more compact, lightweight, low-cost generation system compared to any other conventional turbo-generator system. This integrated power-wheel system is illustrated in Figure 4 and shows the engine feature of a propulsive flowpath that is fully shrouded and formed by a series of nested rim segments supported by a metal-matrix or polyimide composite outside diameter support ring.

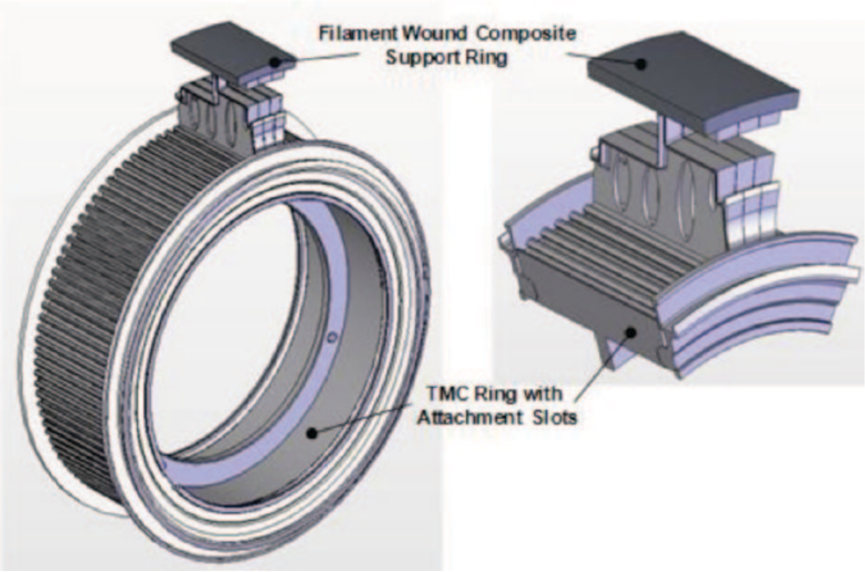

Figure 4: Integrated Power Wheel

Technology Advantages

- Competitive operating efficiency and reduced installed capital cost (approximately 50%) over multi-stage bladed turbo compressors.
- High-stage discharge temperature enables cost-effective recovery of heat of compression.
    - Improves carbon capture and sequestration (CCS) efficiency.
    - Reduces power plant de-rate.

R&D Challenges

- Complicated shock wave aerodynamics on the flowpath requires intensive computing capabilities and model development.
- High rotational speeds and the resulting stresses can result in expensive rotor manufacturing techniques.
- High-pressure ratio compressors yield high rotor thrust loads on bearings and structure.

Results To Date/Accomplishments

- Finalized the CO_2 compressor rotor and static hardware geometry.
- Completed the preliminary conceptual design of the CO_2 compressor.
- Completed flowpath validation test conceptual design review.
- Completed CO_2 compressor demonstration unit feasibility study.
- Prepared a detailed systems analysis of the CO_2 compression technology.
- Prepared a rigorous comparative economic analysis based on the systems analysis of the CO_2 compressor.
- Achieved breakthrough rotor pressure ratio of approximately 7.9:1 in air.
- Demonstrated tip speeds up to ~2,200 ft/s and M_{rels} up to ~2.7.
- Successfully modeled full flowpath 3-D viscous CFD.
- Matched performance prediction/design tools to test.
- Obtained benign surge characteristics.
- Gathered data for preliminary compressor maps.
- Developed and demonstrated bearing designs suitable for product application.
- Completed CO_2 compressor stage configuration simulations.
- Completed CO_2 compressor preliminary design review.

Next Steps

- Improve understanding of the supersonic aerodynamics needed to achieve product performance levels in the CO_2 compressor.
- Continue to develop high-speed performance computing capability at Oak Ridge National Laboratory.
- Finalize design of the rotor and all other rig components and systems.
- Fabricate and retrofit the inlet guide vanes and diffuser.
- Install and test 13,000 hp CO_2 compressor.
- Complete ISCE preliminary design review.
- Test ISCE subcomponents.

Available Reports/Technical Papers/Presentations

General project information is available on DOE/NETL website at: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/co-2compression/supersonic.html

"CO_2 Compression Using Supersonic Shock Wave Technology," Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, Pittsburgh, PA, September 2010, http://www.netl.doe.gov/publications/proceedings/10/co2capture/index.html

"CO_2 Compression Using Supersonic Shock Wave Technology," Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, Pittsburgh, PA, May 2009, http://www.netl.doe.gov/technologies/coalpower/ewr/co2/co2compression/supersonic.html

"Ramgen Power Systems Low-Cost, High-Efficiency CO_2 Compressor," Seventh Annual Conference on Carbon Capture and Sequestration, May 2008, http://www.netl.doe.gov/technologies/coalpower/ewr/co2/co2compression/supersonic.html

NOVEL CONCEPTS FOR THE COMPRESSION OF LARGE VOLUMES OF CO_2

Primary Project Goals

Southwest Research Institute (SwRI) is developing two novel compression technology concepts to reduce carbon dioxide (CO_2) compression power requirements by 35% compared to conventional compressor designs. The first concept is a semi-isothermal compression process where the CO_2 is continually cooled using an internal cooling jacket rather than using conventional inter-stage cooling. The second concept involves the use of refrigeration to liquefy the CO_2 so that its pressure can be increased using a pump rather than a compressor. The project includes prototype testing and a full-scale demonstration of each concept.

Technical Goals

- Conduct thermodynamic and economic analysis to determine the preferred CO_2 state for compression.
- Identify and evaluate intercooling concepts.
- Develop preliminary intercooling design.
- Calculate total potential energy savings.
- Complete a comprehensive thermodynamic and cost analysis of an integrated gasification combined cycle (IGCC) plant incorporating the new compression technology.
- Design a single-stage compressor test rig based on the analyses and design studies.
- Design, fabricate, and test a multi-stage pump test rig based on the analyses and design studies.

Technical Content

In the first concept, semi-isothermal compression, the gas is continually cooled after each stage in the path through the compressor. A cooling jacket insert is used in the diaphragm of each stage to provide continuous cooling. Figure 1 shows a design for an internally cooled compressor. The flow of the CO_2 is shown in red, while the cooling liquid is shown in blue.

In the second concept, compression is achieved by a combination of partial compression, liquefaction, and pumping. The liquefaction process utilizes a refrigeration system to condense CO_2 at 250 pounds per square inch gauge (psig) and -12 °F. The liquid CO_2 is then pumped from 250 to 2,200 psig. The primary power requirements are the initial compression required to boost the CO_2 to approximately 250 pounds per square inch absolute (psia) and the refrigeration power required to liquefy the gas. The pumping power to boost the pressure to pipeline supply pressure is minimal after the CO_2 is liquefied.

SwRI examined a number of different compression options to find the ones that would consume the least amount of power. Figure 2 shows how two hypothetical compression processes can achieve the same pressure, but still consume different quantities of power. The isothermal compression, even at 60% efficiency, is preferable to isentropic compression at 100% efficiency. Figure 3 shows the pressure/enthalpy curves for six of the options examined by SwRI. Table 1

Technology Maturity:

Pilot-scale, 90 tonnes/hr

Project Focus:

Evaluation of Compression Efficiency Improvements

Participant:

Southwest Research Institute

Project Number:

NT42650

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Partners:

Dresser-Rand

Performance Period:

9/28/05 – 12/31/13

presents a description of the compression and cooling technology options and the resultant power requirements for a 400-MW IGCC power plant (~700,000 lb/hr CO_2 stream). The optimal solution combines interstage cooling and a liquefaction approach (Option E.2).

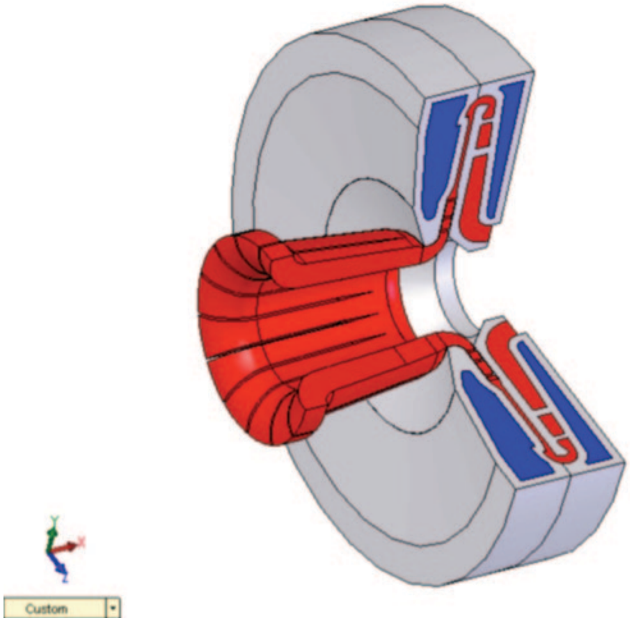

Figure 1: Design for an Internally Cooled Compressor

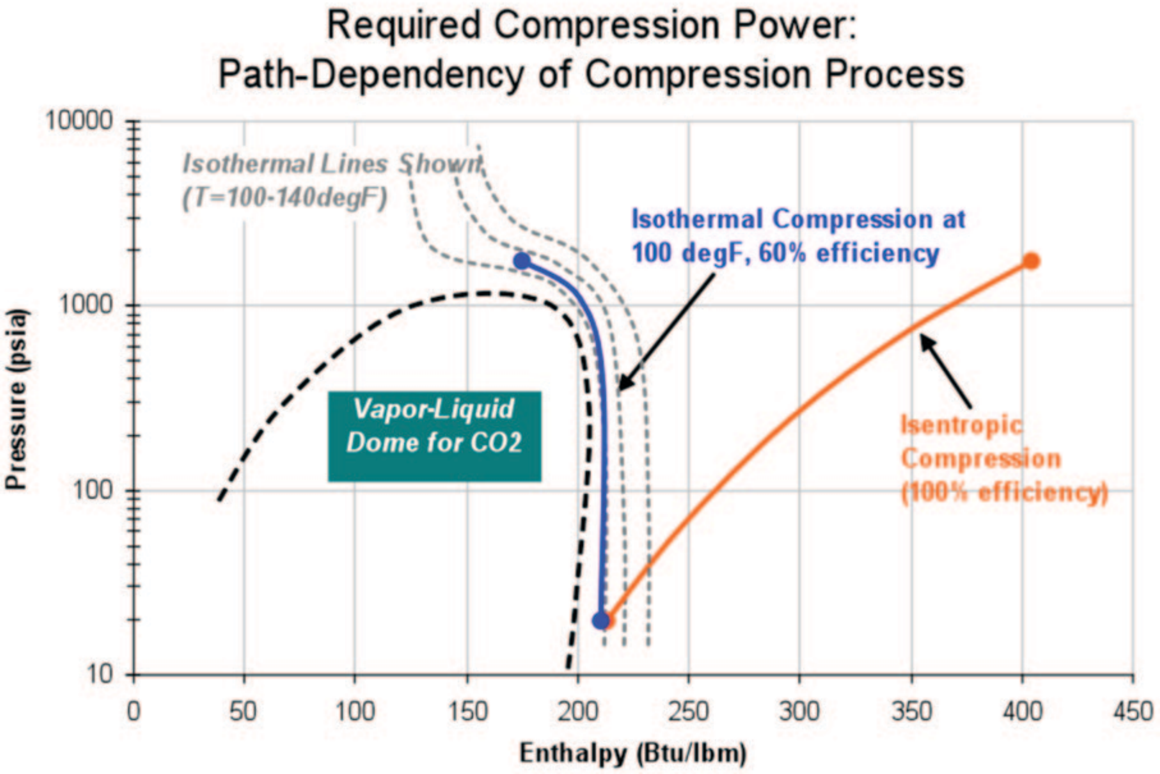

Figure 2: The Path Dependency of Compression Power

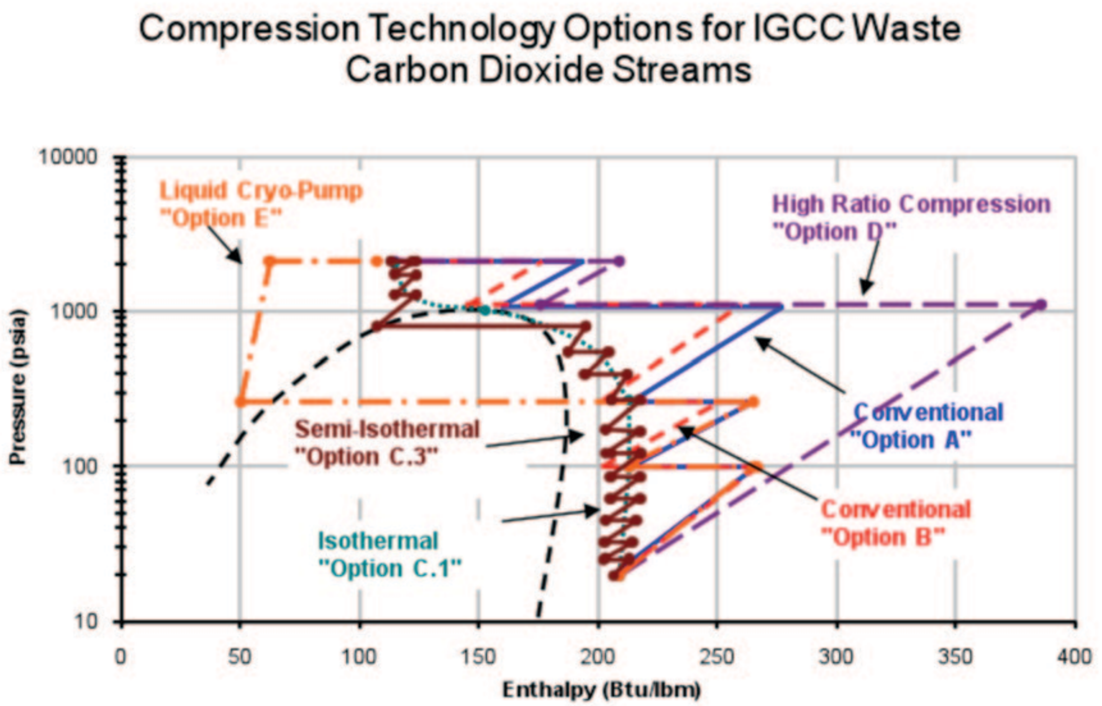

Figure 3: Required Compression Power for the Investigated Technology Options

Table 1: Comparison of Compression Technologies

Option	Compression Technology	Power Requirements	% Difference from Option A	Cooling Technology
A	Conventional Dresser-Rand Centrifugal 10-stage Compression	23,251 BHP	0.00%	Air-cool streams between separate stages
B	Conventional Dresser-Rand Centrifugal 10-stage Compression with additional cooling	21,522 BHP	-7.44%	Air-cool streams between separate stages using ASU cool N_2 stream
C.1	Isothermal compression at 70 °F and 80% efficiency	14,840 BHP	-36.17%	Tc = 70 °F inlet temp throughout
C.4	Semi-isothermal compression at 70 °F, pressure ratio ~1.55	17,025 BHP (required cooling power TBD)	-26.78%	Tc = 70 °F in between each stage.
C.7	Semi-isothermal compression at 100 °F, pressure Ratio ~1.55	17,979 BHP (required cooling power TBD)	-22.67%	Tc = 100 °F in between each stage.
D.3	High ratio compression at 90% efficiency—no inter-stage cooling	34,192 BHP	47.06%	Air cool at 2,215 psia only
D.4	High ratio compression at 90% efficiency - intercooling on final compression stage	24,730 BHP	6.36%	Air cool at 220 and 2,215 psia
E.1	Centrifugal compression to 250 psia, Liquid cryo-pump from 250 to 2,215 psia	16,198 BHP (includes 7,814 BHP for refrigeration)	-30.33%	Air cool up to 250 psia, refrigeration to reduce CO_2 to -25 °F to liquify
E.2	Centrifugal compression to 250 psia with semi-isothermal cooling at 100 degF, Liquid cryo-pump from 250 to 2,215 psia	15,145 BHP (includes 7,814 BHP for refrigeration)	-34.86%	Air cool up to 250 psia between centrifugal stages, refrigeration to reduce CO_2 to -25 °F to liquify

Figure 4: Existing Liquid CO_2 Pump Loop Constructed at SwRI

The Option E.2 compression concepts were tested in Phase 2 of the project, which included construction of a dedicated liquid CO_2 flow loop to qualify an industrial turbo-pump. Also, a cooled diaphragm was tested in a compressor test rig that verified successful performance in a single-stage test. Figure 4 shows a photograph of the liquid CO_2 pump loop including the 12-stage vertical pump that was tested. Performance and mechanical testing was performed for a range of speeds, flows, and pressures. The pump met the design conditions with a discharge pressure in excess of 2,200 psig and showed good mechanical behavior. Figure 5 shows the performance map that was measured indicating good correlation to factory measurements using liquid nitrogen.

Figure 6 shows a photograph of the internally cooled compressor diaphragm, which routes cooling fluid through the diaphragm to remove the heat of compression. This prototype was installed into a closed-loop compressor test facility at SwRI and tested for a range of speeds, flows, pressures, and cooling fluid conditions. The testing agreed well with computational fluid dynamics (CFD) predictions for the heat transfer characteristics. Figure 7 shows a comparison between measured and predicted heat exchanger effectiveness for the diaphragm, which shows good agreement. Unlike external heat exchangers, no additional pressure drop occurs between stages. Implementation of the cooled diaphragm technology into a multi-stage application can reduce the power requirements of the compressor by 20% compared to adiabatic compression.

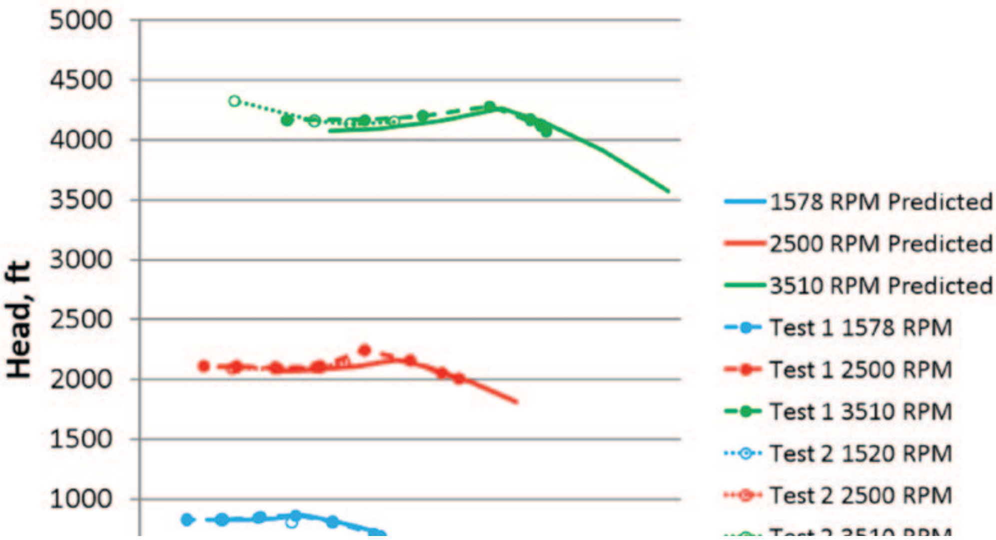

Figure 5: Pump Performance Plot (Head vs. Flow)

Figure 6: Internally Cooled Compressor Diaphragm

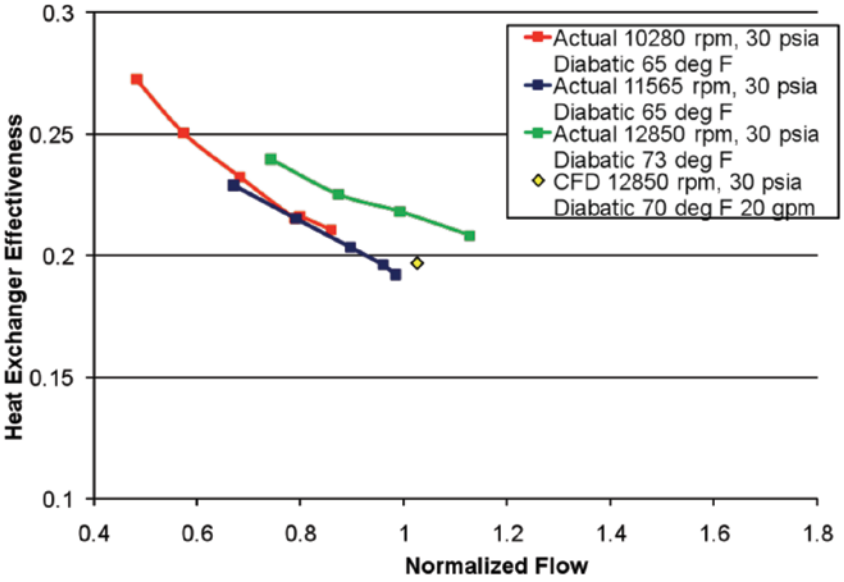

Figure 7: Heat Transfer Effectiveness of CFD and Test Results

Technology Advantages

- New compression process could use up to 35% less power combining semi-isothermal compression, liquefaction, and liquid pumping.
- Applicable to all types of power plants.
- Could result in significant capital savings compared to an integrally geared compressor.
- Pump operating costs will be lower than high-pressure compressor operating costs.

R&D Challenges

- There will be a wide range of CO_2 output from the power plant based on required electrical output.
- CO_2 compression technology must have high reliability.
- IGCC plants contain multiple CO_2 streams at different pressures.

Results To Date/Accomplishments

- Completed a thermodynamic and economic analysis to determine the preferred CO_2 state for compression. The optimal solution combines interstage cooling and a liquefaction approach (Option E.2).
- Designed, constructed, and tested pilot-scale prototype using a liquid CO_2 pumping loop.
    - Pump performed well matching the measured performance during factory testing on liquid nitrogen.
    - Achieved discharge pressure goals.
    - Liquid CO_2 introduced no mechanical issues for the pump.
    - Vibration levels were reasonable.
    - A sub-synchronous vibration occurred at minimum flow point, but only at very low flow rates.
- Designed, constructed, and tested pilot-scale prototype using a closed-loop CO_2 compressor with internal cooling.
    - Heat transfer effectiveness matched CFD predictions.
    - Up to 55% of the heat of compression was removed during testing with cooled diaphragm technology with no additional pressure drop.

Next Steps

In Phase 3 of this project, a full-scale CO_2 compression and pumping system will be engineered and installed at a power plant. This work will include:

- Detailed design and fabrication of the CO_2 compressor.
- Measurement of the CO_2 compressor performance.
- Testing to assess the actual field efficiency.
- Conduct long-term performance studies.

Final test results will not be available until the December 2013 project completion date.

Available Reports/Technical Papers/Presentations

General project information is available on DOE/NETL website at: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/co2compression/novelconcepts.html

"Novel Concepts for the Compression of Large Volumes of CO_2," Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, Pittsburgh, PA, September 2010. http://www.netl.doe.gov/publications/proceedings/10/co2capture/index.html

"Novel Concepts for the Compression of Large Volumes of CO_2 - Phase II," Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, Pittsburgh, PA, March 2009.

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