NOVEL CONCEPTS FOR THE COMPRESSION OF LARGE VOLUMES OF CARBON DIOXIDE

(Note: This article was submitted to the Oil & Gas Journal in June 2007)

Dr. J. Jeffrey Moore
Ms. Marybeth Nored
Dr. Klaus Brun

Southwest Research Institute
Tel: (210) 522-5812
Email: jeff.moore@swri.org

One effort being pursued to reduce the release of carbon dioxide (CO_2) greenhouse gases to the atmosphere is sequestration of CO_2 from Integrated Gasification Combined Cycle (IGCC) and Oxy-Fuel power plants. This approach, however, requires significant compression power to boost the pressure to typical pipeline levels. The penalty can be as high as 8% to 12% for a typical IGCC plant. For a project funded by the National Energy Technology Laboratory (NETL) within the Department of Energy (DOE) and with co-funding provided by Dresser-Rand, Southwest Research Institute (SwRI) has investigated novel methods to minimize this penalty through novel compression concepts.

For gaseous compression, the project seeks to develop improved methods to compress CO_2 while removing the heat of compression internal to the compressor. The high-pressure ratio compression of CO_2 results in significant heat of compression. Because less energy is required to boost the pressure of a cool gas, both upstream and inter-stage cooling are desirable. This project has determined the optimum compressor configuration and has developed technology for internal heat removal. Other concepts that liquefy the CO_2 and boost pressure through cryogenic pumping have been explored as well.

This project is divided into 3 phases. Phase I, to develop the most promising concepts that meet the efficiency goals and integrate them into the IGCC environment, has been completed. Phase II involves detail design of the optimum solution and prototype development testing. Phase III will provide a full-scale compression solution to an existing or proposed IGCC plant.

For an example 400 MW IGCC plant, a typical CO_2 mass flow rate of 600,000 to 700,000 lbm/hr is delivered from the shift reactors and separation process from the synthesis gas. Figure 1 plots the required inlet volume flow for a given inlet pressure. The plot shows the strong sensitivity to inlet pressure on the inlet volume flow rate. If, for example, this CO_2 stream comes from combustion flue gas at atmospheric pressure, then a volume flow rate of more than 100,000 actual cubic feet per minute (ACFM) is required, while the final volume flow is only 1,000 ACFM. This is a 100 times reduction in volume flow and adds to the challenge of designing the compression system.

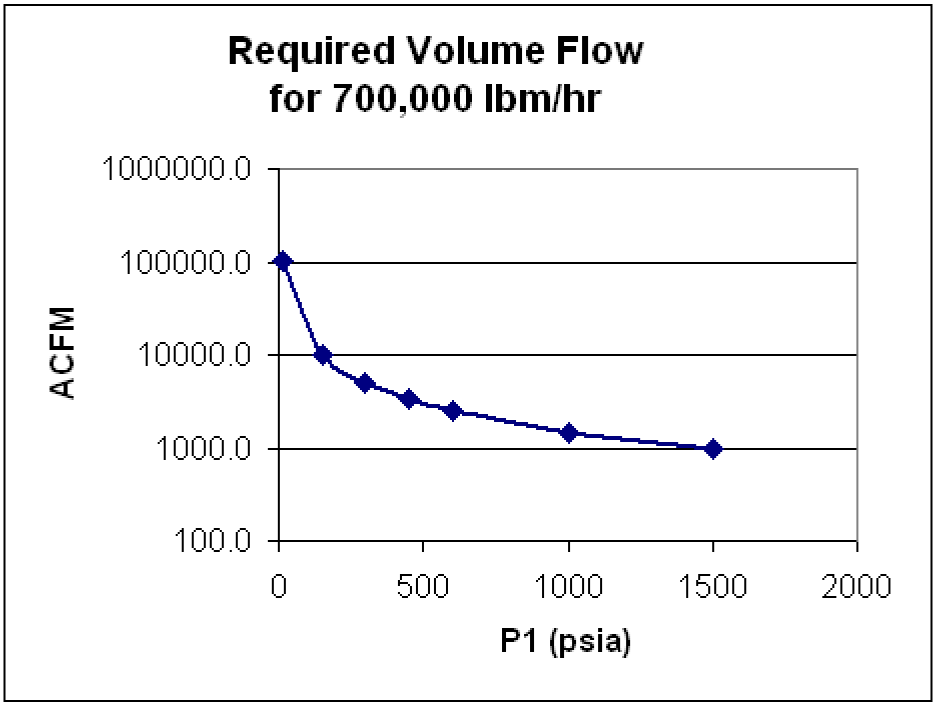

Figure 1. Volume Flow for Given Inlet Pressure

Table 1 lists the CO_2 streams of a sample 700 MW IGCC plant using a Selexol separation process. The expected discharge pressure for pipeline transmission was assumed to be 2,215 PSIA at 70°F, which is a supercritical state. The higher pressure streams provide additional volume flow that helps offset most of the large volume reduction that naturally occurs when compressing CO_2 at a high pressure ratio.

Table 1. CO_2 Streams from Selexol Separation Process

CO_2 Gas Streams	LP	MP	HP 1	HP 2
Pressure (psia)	21.9	160.0	250.0	299.0
Temperature (°F)	51.0	68.0	90.0	75.0
Density (lbm/ft^3)	0.177	1.3	1.87	2.088
Flow Rate (acfm)	33,257	2,158	3,374	1,073

The initial analysis of horsepower was conducted for a conventional approach to compressing the CO_2, using multiple stages of centrifugal compression. The low-pressure stream is compressed and blended with the medium pressure stream (which enters the compressor as a side stream). The discharge from the low-pressure (LP) compressor is blended with the two higher pressure streams to compress the carbon dioxide to its final delivery pressure of 2,215 PSIA in the high pressure (HP) body. The compressor train consists of two parallel trains with a low pressure (LP) and a high-pressure (HP) compressor driven by either a steam turbine or electric motor. Because each compressor is a back-to-back design, inter-cooling is used with each body as well as for the flow exiting the LP compressor totaling three inter-cooling steps. This process is shown schematically on a pressure-enthalpy diagram in Figure 2. The compression and inter-cooling steps are also shown. Option A provides a baseline to compare to alternative compression technologies. A second option (B) with lower inter-cooling temperatures is also shown.

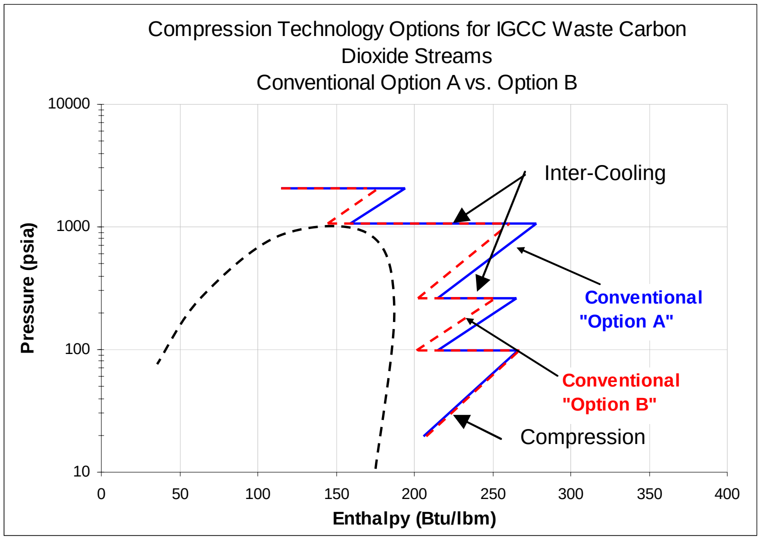

Figure 2. Comparison of Thermodynamic Paths for Baseline Case

Because less energy is required to compress a cool gas, the concept of isothermal compression is explored next. In Option C, the inlet-cooling concept is applied to each stage, using the same inter-stage pressures as Options A and B. An ideal isothermal compression process was analyzed in Option C.1 for an isothermal compression temperature of 70°F. To gauge the effect of the choice of isothermal temperature (and the required cooling power), Option C.2 was analyzed as an isothermal compression with a constant temperature of 100°F. In reality, an isothermal compression process is difficult to achieve. A typical compression process uses an increasing number of finer steps with inter-stage cooling in between each compression stage, so the actual compression process begins to approach isothermal compression. To analyze the practical realization of the isothermal process, Option C.3 uses many small compression steps with inter-stage cooling between each stage to achieve a semi-isothermal process. An illustration of the thermodynamic path taken by Options C.1 and C.3 is shown in Figure 3 to illustrate the semi-isothermal process. Figure 4 plots the compression power versus the number of inter-cooling steps and demonstrates that isothermal compression can be achieved if inter-cooling is used between each stage for the 17 total stages in the baseline selection.

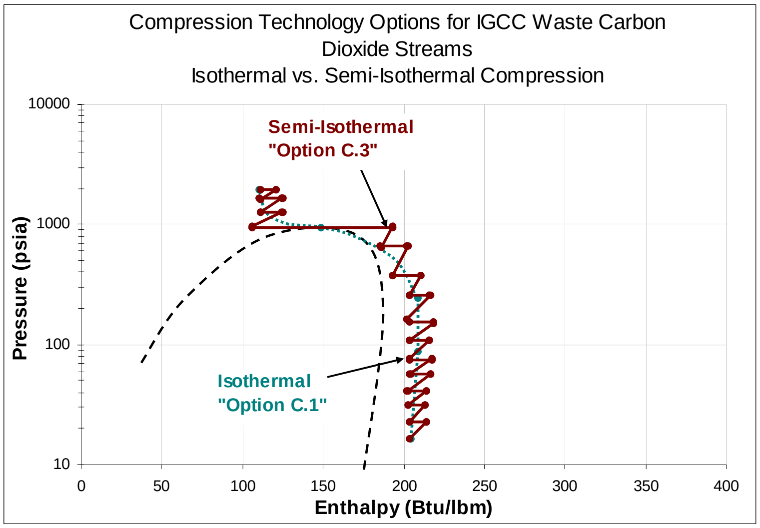

Figure 3. Comparison of Isothermal and Semi-Isothermal Compression Paths

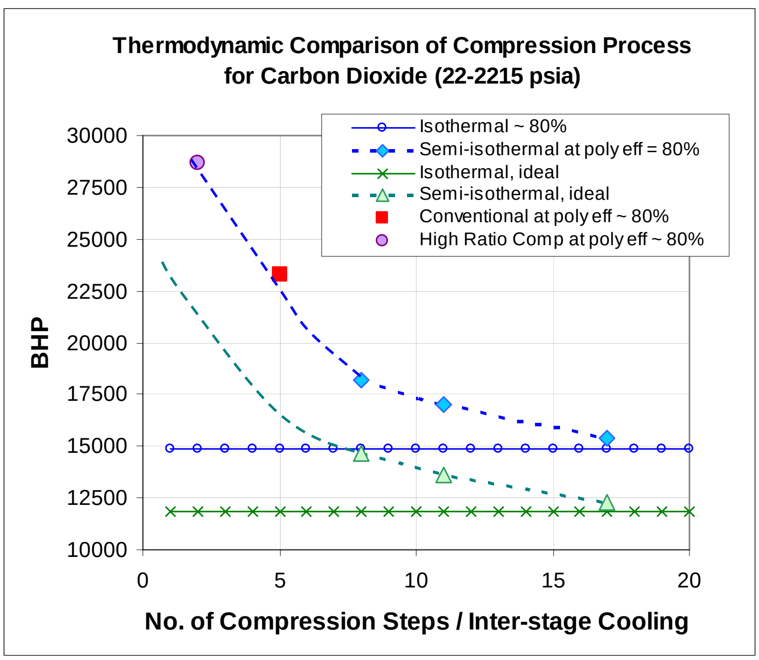

Figure 4. Brake Horsepower vs. Number of Intercooling Steps

Option D utilizes a high-ratio compression process, where extremely high-pressure ratios (up to 10:1) are assumed. The process allows the gas to be compressed in only two stages between 22 and 2,215 PSIA. However, only one cooling step is performed in between the two stages. Without the added cooling between smaller stages of compression, Option D requires significantly more horsepower than Option A. Also, high-ratio stages typically possess limited flow range, which may require cycle during part-load power plant operation.

The final option (Option E) pumps the carbon dioxide in a liquid state. To achieve cryogenic temperatures without forming solid carbon dioxide, it is necessary to compress the low and medium pressure streams to 250 PSIA. These can be joined with the high-pressure stream to undergo a refrigeration process. Normal air cooling can be used to reduce the temperature of the carbon dioxide from 255°F to 100°F or lower. Refrigeration units (typically an ammonia absorption cycle) must be used to reduce the temperature to -25°F because of the significant heat transfer required to overcome the latent heat in the gas. At -25°F and 250 PSIA, the carbon dioxide will be 100% liquid and can be pumped at a relatively low power to 2,215 PSIA. Figure 5 illustrates Option E and the reduction in temperature required to clear the gas-liquid dome.

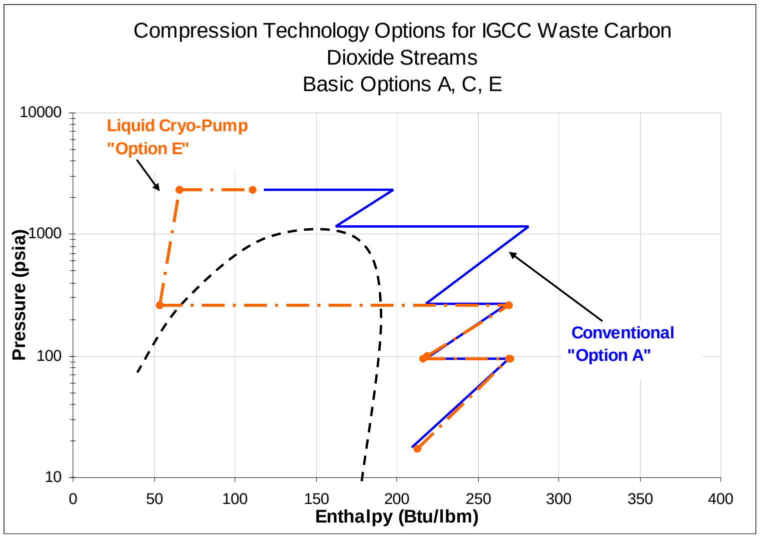

Figure 5. Comparison of Option E for Liquid Cryogenic Pump to Centrifugal Compression in Option A

Table 2 summarizes these compression calculations listing the power required for each thermodynamic process. The Option A conventional compression technology requires a total horsepower of 23,251 BHP. As the results show, the amount of horsepower required by each compression option varies significantly according to the thermodynamic path. Option B provides a small improvement in compression power but requires that cold nitrogen be delivered from the air separation units. While this provides some savings to the CO_2 compression, it will reduce the efficiency of the air separation units and thus was discounted.

The Option C concepts show that near isothermal conditions can be achieved and result in significant power savings over the baseline case. Semi-isothermal compression can be achieved by an integral geared centrifugal compressor with intercoolers between each stage. While this is a commercially viable approach today, these machines introduce greater size and more complexity than the two-body, in-line barrel compressor described in Option A.

Because of the high molecular weight of CO_2, very high pressure ratios are possible in a single stage resulting in a compact compression solution. However, Option D shows this approach results in significantly greater power requirements especially if no inter-cooling is used.

Finally, Option E.1 utilizes part compression followed by liquefaction and pumping. The pump requires only 1,400 BHP, but the refrigeration system requires almost 8,000 BHP. Nevertheless, significant power savings can be achieved with this approach. Option E.2 combines semi-isothermal compression with liquefaction and results in a 35% reduction in compression power. Obviously capital expenditure will be greater because of the additional refrigeration system, but some of this cost will be offset by the elimination of two coolers and a lower cost of the pump compared to the HP compressor.

Table 2. Summary of Compression Technology Options – Power and Cooling Requirements

Option	Compression Technology	Power Requirements	% Diff from Option A	Cooling Technology
A	Conventional Dresser-Rand Centrifugal 10-stage Compression	23,251 BHP	0.0%	Air-cool streams between separate stages
B	Conventional Dresser-Rand Centrifugal 10-stage Compression with additional cooling	21,522 BHP	-7.4%	Air-cool streams between separate stages using ASU cool N2 stream
C.1	Isothermal compression at 70 degF and 80% efficiency	14,840 BHP	-36.2%	Tc = 70 degF inlet temp throughout
C.4	Semi-isothermal compression at 70 degF, Pressure Ratio ~ 1.55	17,025 BHP (Required Cooling Power TBD)	-26.8%	Tc = 70degF in between each stage.
C.7	Semi-isothermal compression at 100 degF, Pressure Ratio ~ 1.55	17,979 BHP (Required Cooling Power TBD)	-22.7%	Tc = 100degF in between each stage.
D.3	High ratio compression at 90% efficiency - no inter-stage cooling	34,192 BHP	47.1%	Air cool at 2215 psia only
D.4	High ratio compression at 90% efficiency - intercooling on final compression stage	24,730 BHP	6.4%	Air cool at 220 and 2215 psia
E.1	Centrifugal compression to 250 psia, Liquid cryo-pump from 250-2215 psia	16,198 BHP (Includes 7,814 BHP for Refrigeration) [1]	-30.3%	Air cool up to 250 psia, Refrigeration to reduce CO2 to -25degF to liquify
E.2	Centrifugal compression to 250 psia with semi-isothermal cooling at 100 degF, Liquid cryo-pump from 250-2215 psia	15,145 BHP (Includes 7,814 BHP for Refrigeration) [1]	-34.9%	Air cool up to 250 psia between centrifugal stages, Refrigeration to reduce CO2 to -25degF to liquify

Because of the environmental pressures to reduce green house gas emissions, the U.S. government and utilities are developing technologies to separate CO_2 both pre- and post-combustion. However, the total penalty for CO_2 sequestration because of compression power requirements is on the order of 10% of a power plant's output. The additional capital and operational expenses can increase the cost of electricity between 20 and 80%. This power and cost requirement is significant and is deterring many power producers from implementing carbon capture projects. Reducing this power requirement will improve overall plant efficiencies and encourage sequestration of CO_2 on both existing and future power plants. The results of this study indicate that a 25% reduction in compression power requirements is possible with pure compression using an isothermal process. A second approach that partially liquefies the CO_2 can achieve as much as a 30% reduction. A third option combines the two approaches and can achieve more than a 35% reduction compared to currently available technology. These concepts will be further refined and tested in Phase 2 of this project, currently under way.