Ramgen's Novel CO_2 Compressor

> *The CO_2 compressor power required for a pulverized coal power plant is 12 percent of the plant rating.*

CO_2 compressors represent a large fraction of the enormous capital and operating cost penalties of any CCS system. The CO_2 compressor power required for a pulverized coal power plant is approximately 8-12% of the plant rating, depending on conditions. A 1,000-MW PC plant would require 120 MW, or 160,000 hp, at an estimated $160 million for today's state-of-the-art, integrally geared compressor equipment alone.

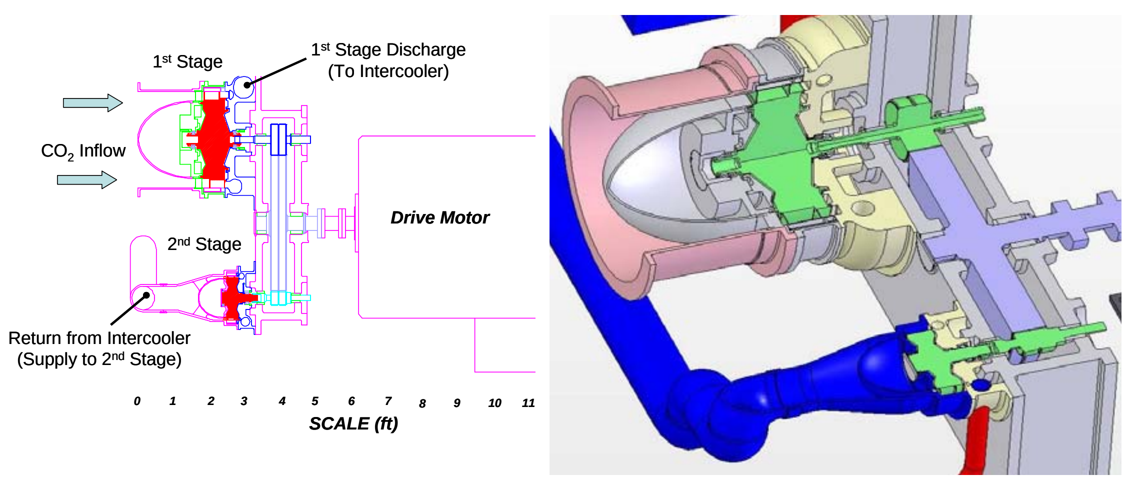
The CO_2 compressor power required for an IGCC power plant is approximately 5% of the plant rating. A 600-MW PC plant would require 30 MW, or 40,000 hp, at an estimated $40 million for just the compressor equipment alone.

Both of these values are based on current estimates of the "state-of-the-art" integrally geared turbo compressor at nominal discharge pressure of 1,600 psia, and do not include installation costs at an estimated 35 percent increment. The costs also represent a claimed 60 percent savings over two or three casing, inline process centrifugal compressors.

Ramgen's shock compression technology represents a significant advancement in the state of the art for all compressor applications, and specifically for CO_2 compression. The principal advantage of Ramgen's shock compression is that it can achieve exceptionally high compression efficiency at very high single-stage compression ratios, resulting in a product simplicity and size that will lower both manufacturing and operating costs.

The novel Ramgen technology concept addresses the two greatest objectives identified by the Department of Energy for the Capture and Storage of CO_2 – lower costs and better efficiency.

Figure 1 Ramgen's Super-Sonic Shock Wave CO_2 Compressor



Ramgen Power Systems, Inc. received a 4-year $11.0 million DOE grant to begin the development of a CO_2 compressor capable of developing the required 100:1 pressure ratio in two stages of compression.

Ramgen based its original design concept on a two-stage, integrally geared compressor, with a common driver, following the pattern of the conventional designs, but with two stages instead of eight. Figure 1 shows a drawing of one such candidate configuration, along with a dimensional scale to indicate its approximate size for a 10,000 hp unit. The final specifications of the system will be defined in Phase II as a deliverable of the program.

The reason that existing CO_2 compressor designs are so expensive is, in part, because the overall pressure ratio is 100:1, and, in part, because CO_2 requires stainless steel construction in the presence of water vapor. But by far the most significant impact on cost is an aerodynamic design practice that limits the design pressure ratio per stage on heavier gases such as CO_2.

Standard turbomachinery design practice is to limit the inlet flow Mach number to less than 0.90 at the inducer blade tip to avoid generating shock waves. The Mach number itself is a function of molecular weight and therefore the effect is more pronounced on the heavier-than-air CO_2. This inducer blade tip speed limit results in a pressure ratio per stage limits of approximately 1.8 to 2.0:1 on CO_2. At these stage pressure ratios, eight stages of compression are typically required to reach an overall pressure ratio of 100:1.

This issue is further complicated by the need to intercool the CO_2 between each compression stage. The heat of compression associated with these very low stage pressure ratios is approximately 200°F, which, as an inlet to the next stage, is too hot to achieve good efficiency, but lacks the thermal driving force for cost-effective heat exchanger selection. This heat is also of insufficient quality to be of practical use elsewhere in the process. The only option is to reject virtually all the compressor electrical input power through cooling towers or heat exchangers, themselves a significant capital and installation expense.

Intercooler selection is made even more difficult by the need for low-pressure drop designs and the requirement to use low heat transfer effectiveness 304 corrosion-resistant, stainless steel construction. Air cooled heat exchangers, often required in arid climates, exacerbate the problem with their generally lower approach temperatures and require substantial fan horsepower, often overlooked in the compressor power evaluation.

Ramgen, on the other hand, designs its rotors to create and manage shock structures and can realize the full effect of their ability to generate substantial pressure ratios, efficiently. The proposed Ramgen CO_2 compressor concept would achieve the required 100:1 pressure ratio in two stages of compression, each rated at 10:1 (10 x 10 = 100). This configuration would feature a conventional intercooler between the first and second stages as well as an aftercooler, if required by the application.

Ramgen intends to offer its compressors at approximately 35-40% of the price of the current integrally geared, state-of-the-art designs.

In addition to the obvious cost advantages, and as a direct result of the Rampressor being able to achieve single-stage compression ratios of 10:1, stage discharge temperatures are estimated to range between 450-500°F, depending on inlet gas and cooling water temperatures. This offers the potential for significant waste heat recovery, without compromising compressor performance. The combined compressor and heat recovery creates an even more impressive energy efficiency advantage by recovering 70-80% of the electrical input energy in the form of useful heat. Potential uses for the available heat are to regenerate amine solutions or pre-heat boiler feedwater.

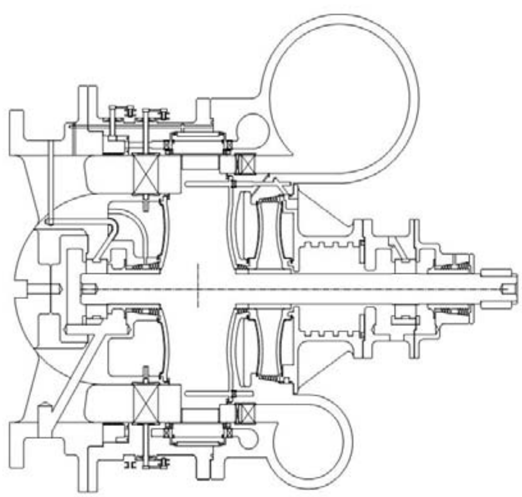
The overall comparisons are shown in Table 1 below.

Table 1 Comparison of Ramgen CO_2 Compressor to Conventional Machines

SUMMARY OF RAMGEN COMPRESSOR VS. EXISTING OFFERINGS			
	Ramgen	**Competitor Offering**	**Competitor Offering**
Characteristics			
Technology	Shock wave	Integrally Geared Turbo	Inline Process Turbo
Size (ft.)	6'x12'x8'	18'x12'x18'	25'x10'x10'
Compression Ratio per Stage	10:1	1.8:1	1.6:1
Estimated Physical Volume	576	3888	5000
Estimated Weight	70,560	476,280	612,500
lbm/hr	150,000	150,000	150,000
icfm	21,411	21,411	21,411
Number of Compression Stages	2	8	12
Intercoolers	1	7	2
Casings	1	1	3
kW	7,333	7,157	8,312
Input HP	9,830	9,598	11,147
Bhp/100	45.9	46.2	52.1
Isothermal Efficiency	66%	64%	57%
Approx. Avg stage/Casing Discharge Temp. (^oF)	470	210	380
Max Thermal Recovery Temp. (^oF)	250	250	250
% Recoverable	72%	0%	50%
Heat Recovery-Btu/hr	18,015,000	0	14,180,000
Economics			
Cost per Compression Ratio	$425/hp	$1,000/hp	$1,650/hp
Capital Cost	$4.3 million	$10.0 million	$18.0 million
Installation Cost	$1.1 million	$3.5 million	$6.3 million
Installation Cost % of Capital Cost	25%	35%	35%
Total Cost	$5.4 million	$13.5 million	$24.3 million
Source: Ramgen Power Systems			

Figure 2 – MAN Turbo 10-stage 200:1 CO_2 Compressor

Ramgen's Discrete-Drive Single-Stage Configuration
The Ramgen concept is so interesting to capture system CC(C)&S developers that we are in continuous contact with most of them. Their preferred compressor configuration appears to be a discrete-drive, single-stage compressor as indicated in the figure below:



Ramgen Discrete Drive S-1

This discrete-drive approach allows each stage to be matched to its specific process flow, including side-streams, and the inherent variable speed capability of these drive systems provides operation flexibility that the developers see as very desirable.

This single-stage discrete drive approach substantially reduces Ramgen's development cost and time. This schedule acceleration and design simplification will also allow Ramgen to submit proposals to participate in a number of the emerging opportunities to supply field demo units.

Ramgen intends to leverage high-speed motor development to the greatest extent possible by matching our rotor speeds and power requirements to existing high-speed motor designs and developments. Direct-drive steam turbine configurations would also offer the same degree of operational flexibility, and in addition to providing another opportunity for heat recovery. This product simplification with the use of existing driver systems substantially reduces development cost and risk.

Successful Ram 2 Test

The company has just completed a definitive aero test program where it demonstrated world-record level performance of a single-stage rotor, validating our advanced Computational Flow Dynamics (CFD) analysis and design tools, and proving a flow path directly traceable to the intended CO_2 compressor. The "as-built" rotor was predicted to produce a pressure ratio of 8.10:1, and the test resulted in a measured value of 7.92:1.

The DOE has reviewed these test results and has authorized Phase II work to begin on a CO_2 specific design, suitable for pilot-scale field demonstration.

The design speed of the CO_2 compressor rotor is sufficiently low as to allow consideration of a shrouded rotor design concept intended to simplify the tip clearance mechanism and the associated tip leakage effects.

Cost Estimates Confirmed by Third Party Review

Within the past three months, Ramgen received a detailed analysis from Manufacturing Resources, Inc. that confirmed the costing assumptions used in the business plan were extremely conservative. Their analysis underscored that approximately 80% of the parts and components necessary for the CO_2 compressor are already available in competitive markets. The move to a discrete drive design decreases development costs.

Ramgen Development Plan

Ramgen intends to invest in it own Center of Excellence Development & Test Facility to accelerate its Phase II efforts. The facility will include a closed loop CO_2 test capability and concentrate on validating mechanical, performance and operational issues on CO_2, prior to the field demo.

At the same time, Ramgen will be working with CC&S System developers to maximize the use of heat of compression in their respective processes. To date the CC&S developers have been designing their processes without much insight on compressor cost and performance. Most are now beginning to realize that a cost effective CO_2 compressor is key to their success and Ramgen is supporting their efforts to lower cost and improve efficiency. High-pressure ratio per stage is the key enabling capability necessary to achieving this goal.