PCOR Partnership Plains CO_2 Reduction (PCOR) Partnership
Energy & Environmental Research Center (EERC)

PRELIMINARY DESIGN OF ADVANCED COMPRESSION TECHNOLOGY

Plains CO_2 Reduction (PCOR) Partnership Phase III
Task 6 – Deliverable D47

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ABSTRACT

Research is being conducted into ways to make the compression step of carbon capture and storage (CCS) more efficient and cost-effective. Ramgen Power Systems, LLC (Ramgen), has developed a novel compression stage called the Rampressor™ that offers a step-change improvement in both areas. The Rampressor is based on supersonic shock compression theory. The efficiency of this compression process is very high because the compressor has very few aerodynamic leading edges and minimal drag. Ramgen's current development work is focused on preparing a demonstration unit sized for use in a 250-MW pulverized-coal plant. Ramgen subcontracted with the Plains CO_2 Reduction (PCOR) Partnership to perform the activities necessary for the integration of the Rampressor into a CCS demonstration project. This report describes the efforts that have been taken to move toward a smooth integration of the Rampressor into the PCOR Partnership's large-scale CCS demonstration scheduled for 2012–2013.

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ACRONYMS AND ABBREVIATIONS

°F	degrees Fahrenheit
AEP	American Electric Power
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
bhp	brake horsepower
CAD	computer-aided design
CCS	carbon capture and storage
CFD	computational fluid dynamics
CHP	combined heat and power
CO_2	carbon dioxide
COE	cost of electricity
dB	decibel
DOE	U.S. Department of Energy
EERC	Energy & Environmental Research Center
FEED	front-end engineering design
ft	feet
gpm	gallons per minute
h	hour
H_2S	hydrogen sulfide
hp	horsepower
Hz	Hertz
icfm	inlet cubic feet per minute
in.	inch
ISO	International Organization for Standardization
kBtu	thousand British thermal units
kW	kilowatts
lb	pound mass
m	meter
m^3	cubic meters
MBtu	million British thermal units
MCC	motor control center
MEA	monoethanolamine
mg	milligram
MIT	Massachusetts Institute of Technology
MW	megawatt
NIOSH	National Institute for Occupational Safety and Health
NPS	nominal pipe size
OEM	original equipment manufacturer
ORC	organic Rankine cycle
OSHA	Occupational Health and Safety Administration
pc	pulverized coal
PC	personal computer
PCOR	Plains CO_2 Reduction (Partnership)
PFD	process flow diagram

PLC	programmable logic controller
PR	pressure ratio
psia	pounds force per square inch absolute
psig	pounds force per square inch gauge
s	second
VAC	volts alternating current
VFD	variable frequency drive
μm	micrometer

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EXECUTIVE SUMMARY

When traditional methods of compression are employed during carbon capture and storage (CCS) activities, considerable cost and power are required because of the volume of the carbon dioxide (CO_2) streams. Research is being conducted into ways to make the compression step more efficient and cost-effective. Ramgen Power Systems, LLC (Ramgen), has developed a novel compression stage called the Rampressor™ that offers a step-change improvement in both efficiency and cost-effectiveness.

The Rampressor is based on supersonic shock compression theory. The principal advantage of shock compression is that it can achieve exceptionally high compression efficiency at very high compression ratios. Ramgen's technical innovation has been to apply supersonic flight inlet concepts in a stationary compressor application. The Rampressor features a rotating disk that operates at the high peripheral speeds necessary to achieve supersonic effect in a stationary environment. The rim of the disk has raised sections and cavities that mimic the effect of the centerbody and channels of a conventional ramjet inlet. Air enters through a common inlet and then passes into the annular space between the supersonically spinning disk and the outer edge of the casing. When the flow of air enters this space, the raised sections of the disk rim create a "ramming" effect, generating shock waves and air compression in a manner completely analogous to ramjet inlets on supersonic aerospace vehicles. The efficiency of this compression process is very high because the compressor has very few aerodynamic leading edges and minimal drag.

Ramgen's current development work is focused on preparing a demonstration unit sized for use in a 250-MW pulverized-coal (pc) plant. The CO_2 emission from such a plant would be approximately 2 million tons per year. Ramgen collaborated with the Plains CO_2 Reduction (PCOR) Partnership to perform activities necessary for the integration of the Rampressor into a CCS demonstration project. These activities included 1) determining the expected energy and cost savings relative to a more traditional CO_2 compressor, 2) determining which data should be

taken during a demonstration test as well as success criteria for the Rampressor in a demonstration setting, 3) identifying facility and interface issues that may arise when the Rampressor is integrated into a coal-fired power plant, 4) using the information gleaned during performance of these activities to develop the conceptual configuration of a demonstration unit and to formulate the requirements for all of the demonstration unit's subsystems, and 5) developing a procurement plan that will ensure the Rampressor's availability for the PCOR Partnership Phase III integrated CCS demonstration.

As part of the work effort under the PCOR Partnership subcontract, Ramgen developed a cost model based upon simplified U.S. Department of Energy (DOE) and Massachusetts Institute of Technology (MIT) calculations for cost of electricity (COE) (Ramezan and others, 2007; Ansolabehere and others, 2007). The model was validated through comparison of the cost increases calculated by the model with the results of several pc studies with and without CCS capability. Ramgen then enhanced the model to differentiate the financial penalty of CCS between the contribution from capture and compression and that from capital and operating costs. The model indicates that compression contributes one-third of the cost increase and capture contributes the other two-thirds. The Ramgen model indicates that capital costs make up roughly 40%–43% of the increase in COE, while operating costs make up 57%–60% of the increase in COE.

The model also shows that the COE increase could be reduced by 18% if MANTurbo CO_2 compressors (such as are employed at the Great Plains Synfuels Plant in Beulah, North Dakota) were replaced by Ramgen's Rampressor technology. When the Rampressor was combined with an advanced capture technology, the COE increase was reduced to 31%. These results indicate that advanced compression is required to achieve DOE's targets for minimizing the COE, even when advanced capture technologies are employed. Stated in terms of capital savings, one 554-MW pc plant CO_2 compressor installation using Ramgen's Rampressor technology instead of conventional technology would save approximately $150 million, or about 18% of the capital cost of the complete CCS system.

Ramgen identified the data that must be collected during demonstration at a coal-fired power plant to verify that Ramgen's advanced compression technology can be successfully applied and that it is more effective than existing CO_2 compression techniques. These data are in the areas of aerodynamic performance, mechanical robustness, and compressor operational control. A successful demonstration will show that the Rampressor meets all of the criteria. In addition, the demonstration will gather data that can be used to determine the actual cost of compression as part of a CCS scenario.

Issues that should be considered when interfacing the Rampressor with a pc plant include footprint size; electrical, air, and water needs and hookups; how the usable heat from the interstage and discharge cooling will be recovered, what equipment will be required, and how it will hook into the power plant systems; and tolerance to impurities contained in the CO_2 stream from a pc plant.

The PCOR Partnership demonstration of CCS from a pc plant may begin in 2012, and it is important that the Rampressor demonstration unit be fabricated, shaken down, and installed in the 2012–2013 timeframe. Ramgen entered into a partnership with Dresser-Rand, a U.S.-based compressor manufacturer, during the last quarter of 2008. The collaboration with Dresser-Rand will result in significant benefits in terms of financial support and technical expertise. The collaboration has allowed the planned size of the demonstration unit to be increased from 3000 hp to 13,000 hp, reducing the time to commercial introduction by an estimated 2 years. In addition, the larger size will eliminate scaling questions and enable factual determinations of impact on plant costs, both capital and operational. The larger size aligns well with the needs of utilities planning CCS demonstrations because CO_2 capture from a 250-MW pc plant would require a single 13,000-hp CO_2 compressor.

The Rampressor will be tested at Dresser-Rand's test facility in Olean, New York. Dresser-Rand's test facility is one of the most flexible and sophisticated gas-testing facilities in the world. This test facility will allow the initial evaluation of the demonstration unit to be performed with far greater control than in a field demonstration scenario. A procurement plan has been developed that ensures that the Rampressor will be ready for testing and, ultimately, the field demonstration by the 2012–2013 timeframe.

The Rampressor offers a step-change improvement in CO_2 compression efficiency and cost-effectiveness. All preparations that can be made at this time have been made in order to ensure smooth integration of the Rampressor into the PCOR Partnership large-scale CCS demonstration.

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INTRODUCTION

Deployment of carbon capture and storage (CCS) as a means of limiting carbon dioxide (CO_2) emissions depends not only upon the technical ability to capture, compress, transport, and sequester the CO_2 but also on the ability to perform these steps cost-effectively. Pipeline transportation is a well-known, widely used approach for moving large amounts of fluids from one location to another. Injection of CO_2 into secure geologic formations has been performed for more than 30 years by the oil and gas industry during tertiary oil recovery operations. Considerable research effort and funding is currently being used to develop cost-effective, efficient methods of capturing CO_2 from mixed-gas streams. Compression is often the "forgotten" piece of the puzzle because compression of gases is a common unit operation in many industries. However, when traditional methods of compression are employed during CCS activities, considerable cost and power are required because of the volume of the CO_2 streams. Research is being conducted into ways to make the compression step more efficient and cost-effective. Ramgen Power Systems, LLC (Ramgen), has developed a novel compression stage called the Rampressor™ that offers a step-change improvement in both efficiency and cost-effectiveness.

THE RAMPRESSOR

Shock Compression Theory

The Rampressor is based on supersonic shock compression theory. Since the sound barrier was broken in the late 1940s, ramjet engines have been widely used as a means to propel aerospace vehicles at supersonic speeds. The underlying supersonic shock theories and aerodynamic technologies are very well understood and fully characterized. Ramgen has applied ramjet engine concepts to a stationary "shock" compressor. The principal advantage of shock compression is that it can achieve exceptionally high compression efficiency at very high compression ratios. Ramjet engines feature the same discrete compression, combustion and expansion sections that are used in conventional, subsonic jet engines to create the thrust used to propel the aircraft. The significant difference in ramjet engines is that the compressor section does not rotate and the turbine section is, therefore, eliminated. At supersonic velocities, air enters the engine and flows around a fixed obstructing body in the center of the engine duct, "ramming" the airflow into channels between the centerbody and the engine's sidewall. Inside these channels, the airflow is almost instantaneously slowed to subsonic speeds, creating "shock waves." These shock waves are associated with a dramatic increase in pressure or, in other words, "shock compression." As with conventional subsonic turbine engines, fuel is then added and the hot, pressurized exhaust gas expands through a nozzle to create forward thrust, as shown in Figure 1.

Ramjets are simple, with no moving parts, but the aircraft has to be moving at supersonic speeds to initiate the shock necessary for effective operation. As a result, all ramjet experience has been in the context of supersonic planes and missiles.

Advanced Compressor Design

Ramgen's technical innovation has been to apply ramjet engine concepts in a stationary compressor application. The Rampressor features a rotating disk that operates at the high peripheral speeds necessary to achieve supersonic effect in a stationary environment. The rim of the disk has raised sections and cavities that mimic the effect of the centerbody and channels of a conventional ramjet inlet. Air enters through a common inlet and then passes into the annular space between the supersonically spinning disk and the outer edge of the casing. When the flow of air enters this space, the raised sections of the disk rim create a "ramming" effect, generating shock waves and air compression in a manner completely analogous to ramjet inlets on supersonic aerospace vehicles. Figure 2 illustrates the similarities between the profiles of both a supersonic F-15 fighter jet engine inlet and the Rampressor rotor. The efficiency of this compression process is very high because the compressor has very few aerodynamic leading edges and minimal drag.

The strength of the shock wave and, therefore, the amount of compression increase exponentially with the relative Mach number. For example, in air at Mach 1.6, a compression ratio of 3.5:1 is achieved, while at Mach 2.4, it is approximately 15:1. A higher Mach number is

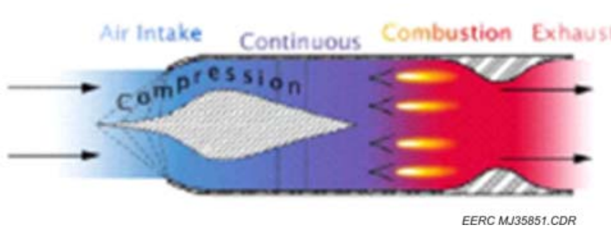

Figure 1. Cross-sectional view of a ramjet engine (courtesy of Ramgen Power Systems, LLC).

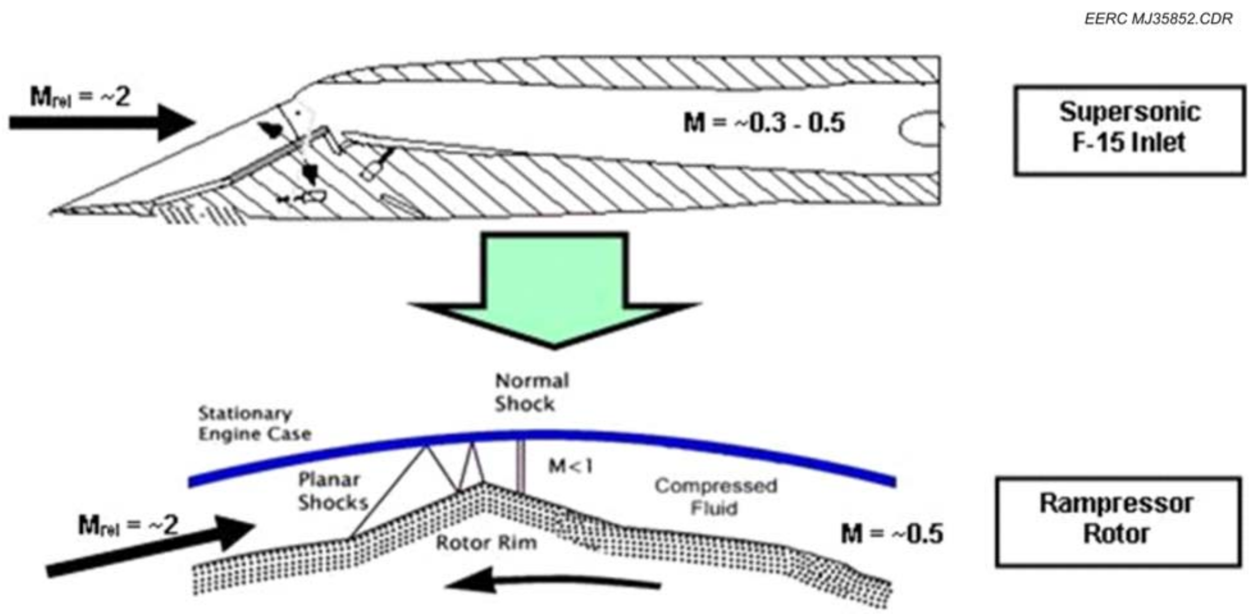

Figure 2. Profiles of an F-15 jet engine inlet and a Rampressor rotor (courtesy of Ramgen Power Systems, LLC).

achieved by spinning the disc faster. Similarly, the heavier the gas, the lower the rotor speed required to achieve a given Mach number.

Ramgen's current development work is focused on preparing a demonstration unit sized for use in a 250-MW pulverized-coal (pc) plant. The CO_2 emission from such a plant would be approximately 2 million tons per year. Current nominal specifications of the demonstration unit include the following:

- Capacity = 86 lb/s
- Gas composition has not been determined.
- Inlet pressure = 220 psia
- Inlet temperature = 100°F
- Discharge pressure = 2200 psia
- Power = 13,000 bhp

Dimensions

- Length = 12 ft (with drive motor)
- Width = 4.5 ft
- Height = 5.0 ft

Motor options

- Direct-drive, variable-speed motor
- Steam turbine
- Induction motor with gearbox

The Rampressor rotor, shown in Figure 3, includes three supersonic compression inlet flow paths on the disk rim. The disk chambers, or "strakes," are angled so that the compressed gas is "augured" via rotation into a collector. The compression process is inherently oil-free, requiring no oil for lubrication and/or sealing. Figure 4 is an animated, slow-motion view of the operation of the Rampressor.

Application of the Rampressor to CO_2 Capture

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. 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 while meeting the needs of any capture system pressure and flow requirements. Typical capture system pressure ratio (PR) requirements range from 10:1 in a single-rotor stage unit to 100:1 in two single-stage units. For example, advanced monoethanolamine (MEA) scrubbing requires a 100:1 PR, while a Selexol™ system can require two or three different PR stages. The Alstom chilled ammonia system requires a PR of less than 10:1. The Powerspan aqueous ammonia system can utilize either a 10:1 or a 100:1 PR system.

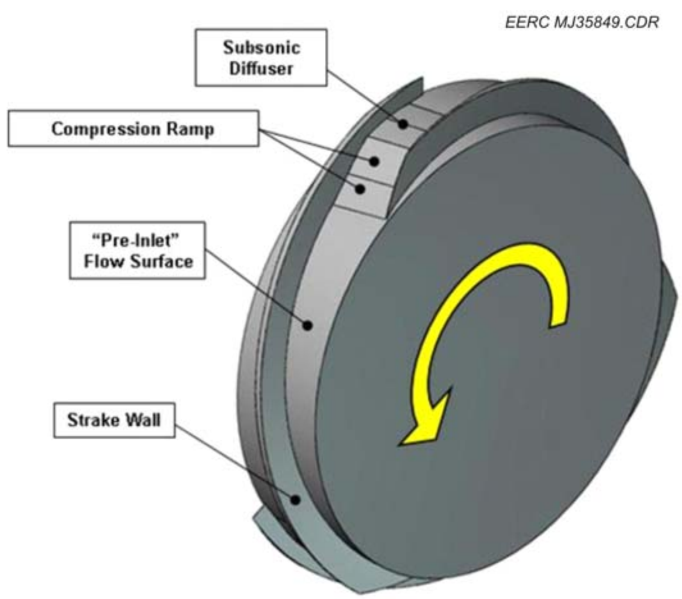

Figure 3. Rampressor rotor disk (courtesy of Ramgen Power Systems, LLC).

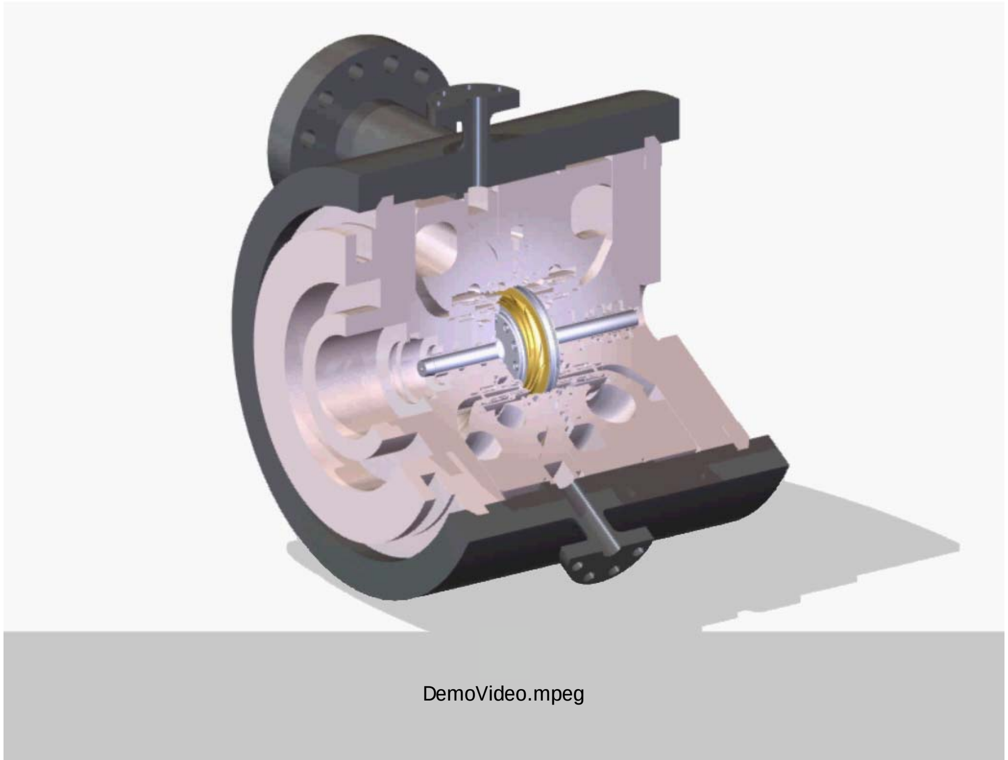

Figure 4. Animated media clip showing slow-motion operation of the Rampressor (courtesy of Ramgen Power Systems, LLC) (Double-click on the picture to begin the animation; 6 seconds into the clip, it zooms in on the rotor. The animation requires the newest Adobe Reader [which can be downloaded from www.adobe.com] and Quick Time player. If your computer does not have the Quick Time player, a popup window will direct you to the Web site for downloading, after which this document must be reopened to view the animation.)

Conventional centrifugal and axial compressor design practice typically limits the inlet Mach number to 0.90 to prevent disruptive shock effects from occurring within the blade flow path. Mach number is inversely proportional to molecular weight. In practice, this limits the achievable PR per stage of compression in a state-of-the-art turbomachinery compressor to approximately 1.8:1. Consequently, a conventional "high performance," integrally geared centrifugal compressor processing CO_2 to the specified PR of 10:1 will likely require four stages of compression (1.8×1.8×1.8×1.8), with an intercooler between stages one and two, two and three, and three and four. An aftercooler may also be needed. These intercoolers would discharge their heat to the atmosphere because the gas temperature increase per stage would only be about 90°F and thus could not be used elsewhere. Compression from 14.7 to 1470 psi (100:1) would require eight stages of compression as well as stainless steel intercoolers between each stage and, possibly, an aftercooler.

The Rampressor's rotors were designed to create, manage, and use these shock structures to efficiently generate substantial PRs. The Rampressor is designed to achieve the required PR in one or two stages of compression, each rated at 10:1 (10×10 = 100). Instead of warming the gas by 90°F, each stage of compression would warm it nearly 400°F. Rather than wasting 100% of the heat created by compression, using a Rampressor would permit recapture and use of 70%–80% of the heat produced to offset the parasitic heat loads required by some capture technologies or to produce steam.

Testing conducted in May 2007 on the Rampressor 2 produced a world record PR for a single-stage axial compressor of ~7.9:1. Development efforts are under way to increase this to the desired 10:1 ratio.

APPLYING THE RAMPRESSOR TO CCS

Given that the Ramgen advanced compression technology is novel, innovative, and appears to offer substantial improvement over existing CO_2 compression technology, the logical next step is to evaluate its effectiveness at a pc-fired power plant during an integrated CCS demonstration. Ramgen subcontracted with the Plains CO_2 Reduction (PCOR) Partnership to perform activities necessary for the integration of the Rampressor into a CCS demonstration project. These activities included 1) determining the expected energy and cost savings relative to a more traditional CO_2 compressor, 2) determining which data should be taken during a demonstration test as well as success criteria for the Rampressor in a demonstration setting, 3) identifying facility and interface issues that may arise when the Rampressor is integrated into a coal-fired power plant, 4) using the information gleaned during performance of these activities to develop the conceptual configuration of a demonstration unit and to formulate the requirements for all of the demonstration unit’s subsystems, and 5) developing a procurement plan that will ensure the Rampressor’s availability for the PCOR Partnership Phase III integrated CCS demonstration.

Energy and Cost Model Development

As part of the work effort under the PCOR Partnership subcontract, Ramgen developed a cost model based upon simplified U.S. Department of Energy (DOE) and Massachusetts Institute of Technology (MIT) calculations for cost of electricity (COE) (Ramezan and others, 2007; Ansolabehere and others, 2007). The model was validated through comparison of the cost increases calculated by the model with the results of several pc studies with and without CCS capability. Ramgen then enhanced the model to differentiate the financial penalty of CCS between the contribution from capture and compression and that from capital and operating costs. The model indicates that compression contributes one-third of the cost increase and capture contributes the other two-thirds. Operating costs and efficiency are widely believed to drive COE more than capital outlay. The Ramgen model shows that this is not the case, indicating that capital costs make up roughly 40%–43% of the increase in COE, while operating costs make up 57%–60% of the increase in COE.

The Ramgen model closely duplicates the results published in the 2007 DOE report for the Alstom/American Electric Power (AEP) retrofit plant study (Ramezan and others, 2007) as well as the 2007 MIT comparisons of various plant and CCS scenarios (Ansolabehere and others, 2007). Figure 5 compares the Ramgen model results with those of the DOE and MIT reports. In

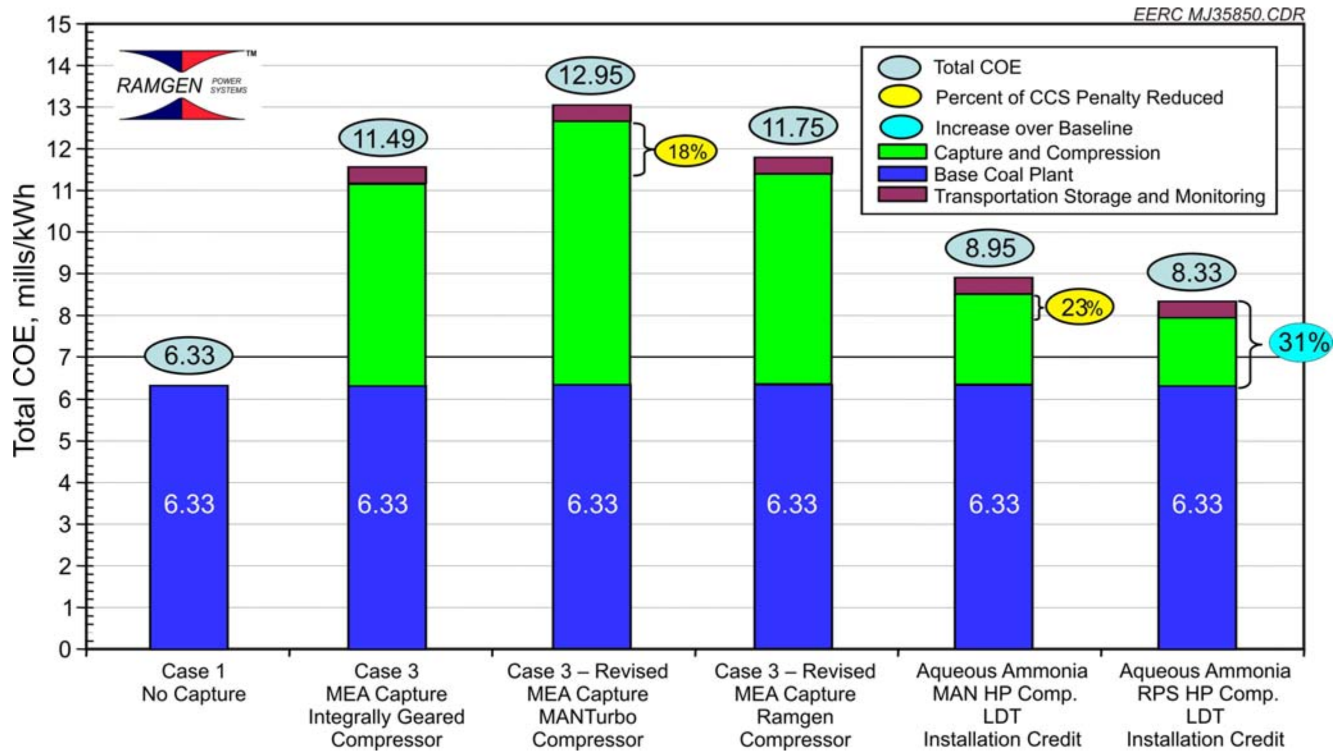

Figure 5. Ramgen model results showing COE increases for various scenarios (courtesy of Ramgen Power Systems, LLC).

the figure, Case 1 is a baseline COE for a pc power plant without CCS. Case 3 is a DOE-documented configuration of the same baseline coal plant with CCS. Ramgen has studied the analysis and found input assumptions that yield a compressor power consumption and cost impact that is too low, a view shared by both Dresser-Rand and AEP. Therefore, Ramgen calculated a revised Case 3 that is based on an analysis of available industrial compressors. The model shows that the revised Case 3 CCS COE increase would be reduced by 18% if MANTurbo CO_2 compressors (such as are employed at the Great Plains Synfuels Plant in Beulah, North Dakota) were replaced by Ramgen CO_2 compressors.

After establishing a revised Case 3 CCS baseline with and without Ramgen CO_2 compressors, a number of CCS configurations were analyzed. The goal was to identify a configuration that would increase the COE by 35% or less in order to achieve DOE's goal for combustion-based power plants. For gasification-based power plants, the DOE goal is a COE increase of no more than 10%. When combined with advanced capture technology, utilizing an integrated MANTurbo installation resulted in an increase in COE of 41%. When the Rampressor was combined with an advanced capture technology, the COE increase was reduced to 31%. These results indicate that advanced compression is required to achieve DOE's targets for minimizing the COE, even when advanced capture technologies are employed. Stated in terms of capital savings, one 554-MW pc plant CO_2 compressor installation using Ramgen's Rampressor technology instead of conventional technology would save approximately $150 million, or about 18% of the capital cost of the complete CCS system.

A two-stage, 100:1 PR Rampressor product is compared to theorized conventional integrally geared and in-line process compressor configurations in Table 1.

Table 1. Comparison of the Rampressor to Conventional CO_2 Compressors

Parameter	Rampressor	Integrally Geared Turbocompressor	In-Line Process Turbocompressor
lb/h	150,000	150,000	150,000
icfm	21,411	21,411	21,411
Stages	2	8	12
Intercoolers	1	7	2
Casings	1	1	3
kW	7,333	7,382	8,312
hp	9,830	9,899	11,147
bhp/100	45.9	46.2	52.1
Isothermal Efficiency	65.8%	64.0%	56.9%
Approximate Average Stage/Casing Discharge Temperature, °F	470	210	380
Maximum Thermal Recovery Temperature, °F	250	250	250
kW Equivalent of Heat	5263	554	4172
% of Heat That Is Recoverable	71.8%	7.5%	50.2%
Shaft Power kW – Heat Recovery kW	2070	6828	4141

Demonstration Test Data Requirements and Success Criteria

Ramgen identified the data that must be collected during demonstration at a coal-fired power plant to verify that Ramgen's advanced compression technology can be successfully applied and that it is more effective than existing CO_2 compression techniques.

Specific parameters that will be measured during a demonstration include the following:

- Aerodynamic performance
- PR capability
  - The maximum PR achievable by the rotor will be measured and compared to computational fluid dynamics (CFD) predictions.
  - The minimum PR before surge will be measured and compared to CFD predictions.
- Compressor efficiency characteristics
  - The highest aerodynamic efficiency achievable by the rotor will be measured and compared to CFD predictions.
  - The compressor will be operated through a range of PRs and corrected mass flows to establish a performance map.
  - Mechanical losses (windage, bearings, gearbox, leakage, etc.) will be determined and compared to predictions.
- Mechanical robustness
  - The rotor, bearing, and seals will be inspected to ensure that wear is within the expected limits.
  - The acoustic signature will be measured using industry-standard methods and compared to predictions and Occupational Safety and Health Administration requirements.
  - The rotordynamic characteristics will be measured and compared to predictions and American Petroleum Institute (API) requirements.
- Compressor operational control
- Start-up
  - The power draw required during acceleration to design speed will be measured.

- The start-up procedure and ability to control speed and critical operating parameters during acceleration and back pressurization will be demonstrated.
- The time required from initiation of the start-up process to steady-state, on-design operation will be measured.

- On-point control
  - The ability to maintain the Rampressor back pressure within specified limits will be demonstrated.
  - The ability to control the mass flow within specified limits will be demonstrated.
  - The ability to break into a process that is prepressurized to 2200 psia (i.e., bringing a compressor online to an already pressurized pipeline) will be demonstrated.
  - The power required during design point operation will be measured.
  - The compressor discharge temperature will be measured and compared to the predicted heat recovery opportunity.
- Off-design control
  - The ability to reduce corrected mass flow to predicted levels (i.e., turndown) will be demonstrated.
  - The controllability near the surge region via pressure rise to surge will be demonstrated.
- Shutdown
  - The shutdown procedure and controllability will be demonstrated.
  - The time required from initiation of shutdown to zero speed will be measured.

A successful demonstration will show that the Rampressor meets all of these criteria. In addition, the demonstration will gather data that can be used to determine the actual cost of compression as part of a CCS scenario.

Interfacing the Rampressor with a pc Power Plant

Issues that should be considered when interfacing the Rampressor with a pc plant include footprint size; electrical, air, and water needs and hookups; how the usable heat from the interstage cooling will be recovered, what equipment will be required, and how it will hook into the power plant systems; and tolerance to impurities contained in the CO_2 stream from a pc plant.

Rampressor Footprint

The Rampressor skid is estimated to be 30 ft long, 15 ft wide, and 15 ft tall and is shown in Figure 6. It will weigh approximately 200,000 lb when loaded with all equipment. Appropriately sized pads for the Rampressor and auxiliary systems (which will be dictated by the specific facility configuration) must be available and able to support the loads associated with the equipment. The control room will require 110-VAC power and must be large enough for both the remote control system and operators. For optimum efficiency, this equipment should be located near the CO_2 separation system control center within the power plant.

Electrical, Air, and Water Requirements of the Rampressor

The power plant will have to supply the following for demonstration of a single-stage, high-pressure Rampressor:

- CO_2 stream at approximately 220 psia and 100°F; if the separation technology utilized results in a suction pressure significantly lower than 220 psia, additional compression should be considered.

- Overpressure control with noise suppression based on facility operating requirements.

- Bleed system piping with a 0–17.5-lb/s starting bleed.

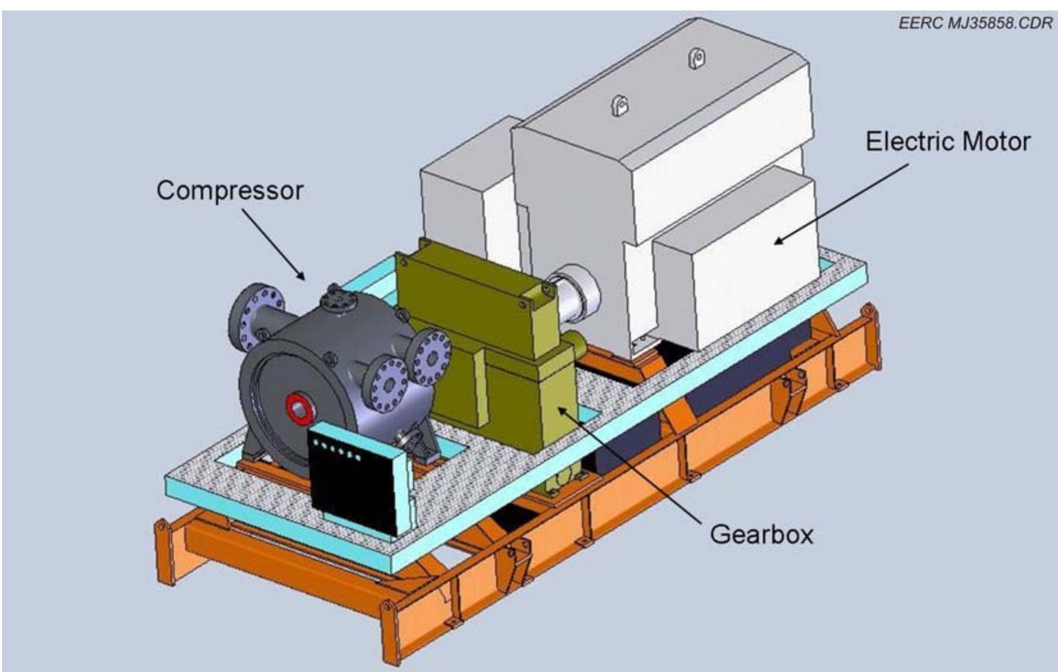

Figure 6. Ramgen CAD (computer-aided design) model showing conceptual Rampressor skid layout (courtesy of Ramgen Power Systems, LLC).

- Shop air at 0.25 lb/sec.

Oil-free instrument air at 0.5 lb/s, with a −40°F dew point and a 10-μm filter.

- High-voltage switchgear and cabling for electric drive system (10 MW, 6600 VAC, and 60 Hz).
- Steam supply system as per power plant-supplied turbine, if selected instead of electric drive.
- 480-V motor control center (MCC) and cabling for auxiliary systems.
- Cooling water and flanges for the core CO_2 bypass cooler (4500 gpm, 12-in. nominal pipe size [NPS]), injection discharge cooler (500 gpm, 4-in. NPS), oil cooler (150 gpm, 2-in. NPS), and main exhaust flow cooler (both water flow and flange are use-dependent); water must be supplied at a temperature of no more than 85°F with a maximum temperature rise of 30°F.

Heat Recovery System

Because one of the features of the Rampressor is the usable heat produced in the interstage heat exchanger and aftercooler, integrating the heat recovery system into the power plant will be crucial. Usable heat available from a 100:1, two-stage Ramgen CO_2 compressor is shown in Figure 7. With a 100°F recovery temperature (compressor inlet temperature), 153% of the combined shaft work is available as heat. Most industrial applications will not allow heat recovery to this level; 250°F is more reasonable. The heat recovered is still substantial under these conditions, however.

There are multiple opportunities to utilize the compressor discharge heat, depending on plant configuration and local needs. Heat recovery can be used to reduce the amount of steam diverted from the power plant steam cycle for absorbent regeneration. Diverted steam reduces the available plant output power, so reducing steam requirements results in increased plant output. Put another way, it reduces the plant's derating. Recovered heat could also be introduced directly into the plant steam cycle via boiler feed water heating, improving the plant's overall efficiency.

Heat can also be used for combined heat and power applications (CHP) or to generate electricity directly via Organic Rankine Cycle (ORC) applications. A well-designed ORC could generate electricity equivalent to nearly 30% of the shaft input power for the two-stage configuration described in Figure 7, significantly reducing the compressor impact on plant output. Another opportunity for heat integration would involve the use of absorption chillers, which utilize a heat source to provide cooling.

EERC MJ35855.CDR

	Low-Pressure Stage 22–220 psia	High-Pressure Stage 220–2200 psia
Compressor Shaft Input Work	90.6 Btu/lb_m	87.0 Btu/lb_m
Discharge Temperature	489°F	509°F
Lower Recovery Temperature	100°F	100°F
Recovered Heat	92.4 Btu/lb_m	178.8 Btu/lb_m
Recovered Heat/Compression Work	102%	205%

- Heat available in the HP hot discharge CO_2 is more than double the compressor shaft work.
- 153% of the combined LP + HP shaft work is available as heat in the discharge CO_2.

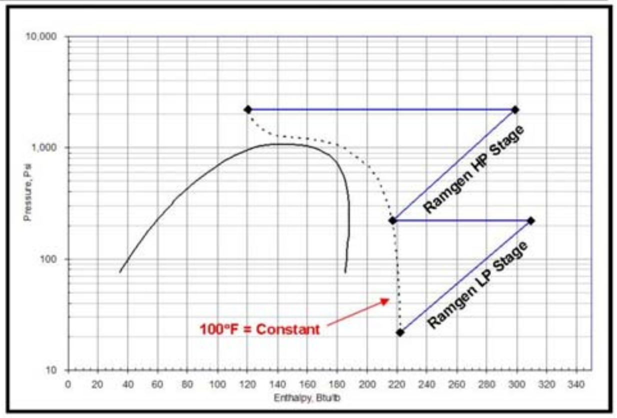

Figure 7. Usable heat available from a 100:1, two-stage Rampressor (courtesy of Ramgen Power Systems, LLC).

As CO_2 separation systems mature with increased efficiency and reduced parasitic power, Ramgen compressor heat recovery will play an even larger role in improving overall CCS efficiency.

Impurities in the CO_2 Stream

All CO_2 compressors face issues of corrosion caused by the CO_2 in the presence of free water. Affected areas include inter- and after-coolers as well as inlet transition pieces. The Ramgen compressor utilizes titanium rotor and standard materials as well as design techniques typically used to resist these effects.

The flue gas is typically passed through a series of wet scrubbers that reduce both the chemical contaminants and particulate matter. Even after the flue gas passes through all of the pollution control devices and the CO_2 capture equipment, the CO_2 stream from a pc power plant may contain trace amounts of HCl, SO_3, SO_2, NO_2, NO, and mercury. Since the mole fraction of these impurities is small, their impact on supersonic aerodynamics is correspondingly small, and there will be negligible effect on compressor performance.

Of greater importance is that these impurities will reach their individual supercritical condition at different pressures during the compression process and can cause two-phase flows to develop in the compressor flowpath. Two-phase flows can cause physical damage to compressor hardware, and great care must be exercised when using interstage cooling near these supercritical regions, shown in red in Figure 8. It is important to note that the Ramgen two-stage compression process, shown in blue, avoids this region entirely.

Demonstration Unit Conceptual Configuration and Subsystem Requirements

A process flow diagram showing the Rampressor demonstration unit is presented in Figure 9. Requirements for the various subsystems and additional supporting technical data are included in the Appendix A.

Procurement Plan and Time Line for Demonstration Planning

The PCOR Partnership demonstration of CCS from a pc plant will likely begin in 2012, and it is important that the Rampressor demonstration unit be fabricated, shaken down, and installed in the 2012–2013 timeframe. Ramgen entered into a partnership with Dresser-Rand, a U.S.-based compressor manufacturer, during the last quarter of 2008. The collaboration with Dresser-Rand will result in significant benefits in terms of financial support and technical expertise. Ramgen has incorporated two significant enhancements into the development plan of the CO_2 Rampressor based on these benefits. One such enhancement is the increase in the planned size of the demonstration unit from 3000 hp to 13,000 hp. This will reduce the time to commercial introduction by an estimated 2 years. Moving to a notional 13,000-hp compressor will provide the option to test advanced compression at the scale needed to support a demonstration project in the 2012–2015 timeframe. The larger size will eliminate scaling

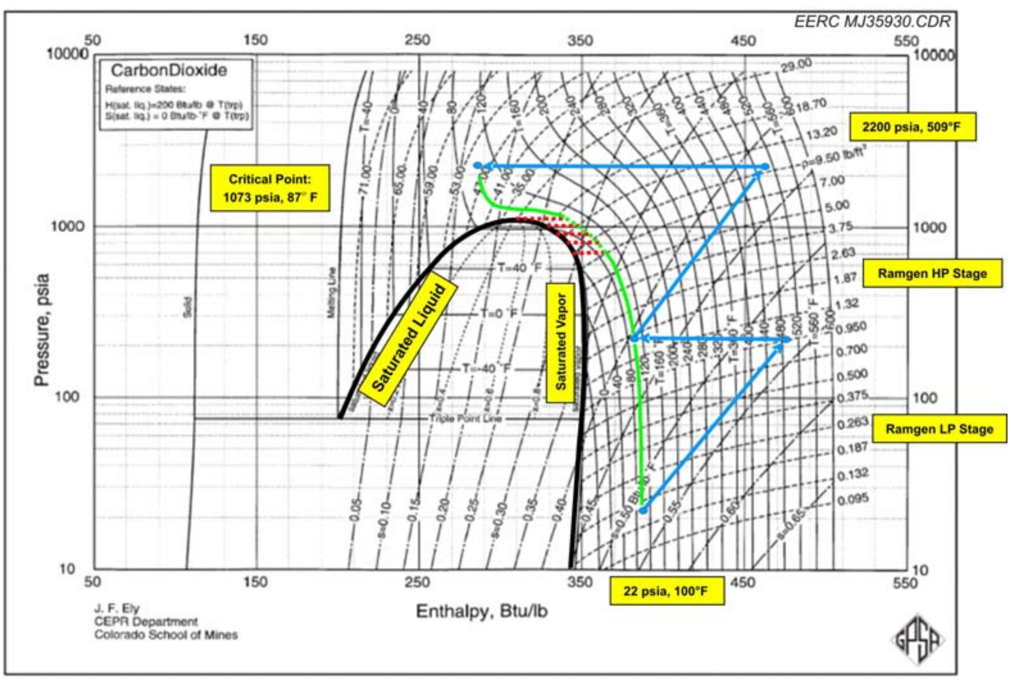

Figure 8. Pressure–enthalpy diagram for CO_2. The Ramgen two-stage compression process is shown in blue (courtesy of Ramgen Power Systems, LLC).

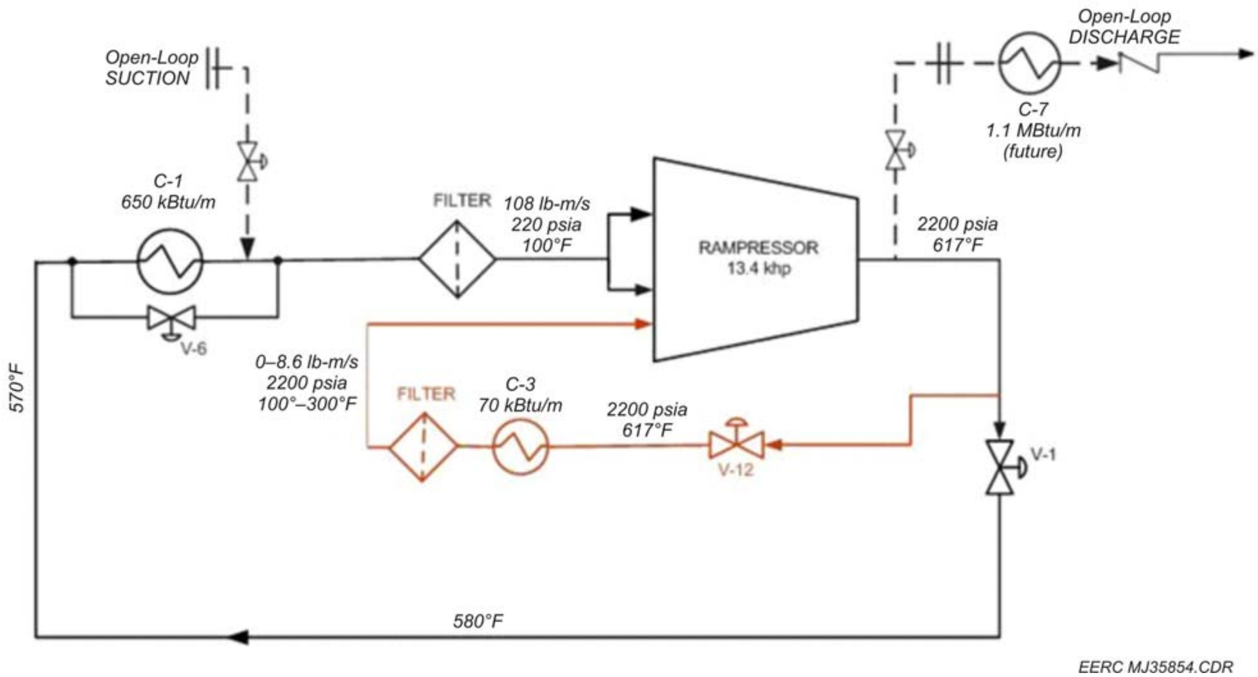

Figure 9. Process flow diagram for the Rampressor demonstration unit (courtesy of Ramgen Power Systems, LLC).

questions and enable factual determinations of impact on plant costs, both capital and operational. Additionally, the larger size aligns well with the needs of utilities planning CCS demonstrations because CO_2 capture from a 250-MW pc plant would require a single 13,000-hp CO_2 compressor. Ramgen had extensive discussions with utilities planning CCS demonstrations over the past year, and several stated their need for an advanced CO_2 compressor in the 13,000-hp size range as quickly as possible and preferably in the 2012–2013 timeframe.

The high-level time line for the planning and incorporation of a CO_2 Rampressor into a pc plant is depicted in Figure 10.

Product Definition and Front-End Engineering Design (FEED) Study

Ramgen actively supports ongoing FEED studies to evaluate potential applications of its demonstration unit. The application definition process includes the following basic performance and sizing parameters:

- Gas composition, including moisture content
- Mass flow
- Inlet pressure
- Inlet temperature
- Discharge pressure
- Cooling media and temperature

Often forgotten is the need to define the following:

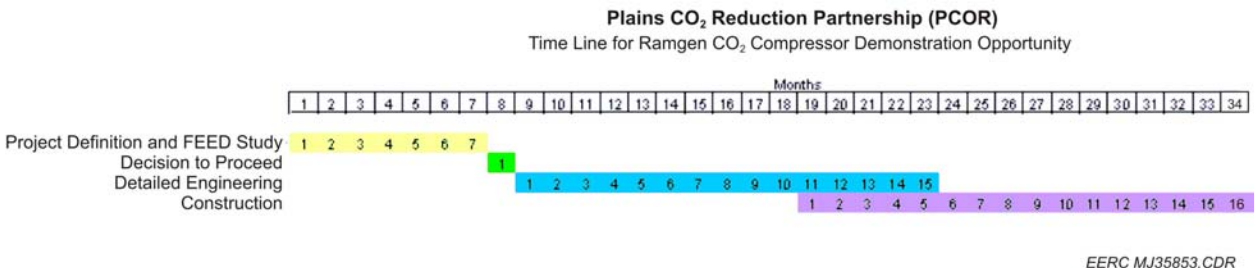

Figure 10. High-level time line for the incorporation of a CO_2 Rampressor.

- Air
- Water-cooled
- Process-cooled
  - Interstage assumptions
- Pressure drop
- Design practice
- Estimated $\Delta P = \frac{P_2^{0.7}}{10}$; not to exceed 5 psi
- Intercooler/heat exchanger approach temperature or cold-temperature difference (CTD)
- 15°F CTD normal approach temperature
  - Mechanical losses
- Compressor
- Gearbox
  - Sparing philosophy (i.e., 2 × 50% + 1)

In addition, CCS-specific issues include the following:

- Capture system flash levels and control requirements
  - Pressure
  - Mass flow additions
- Water knockout
  - Process location (i.e., pressure)
  - Method – glycol/molecular sieve/PSA
- CO_2 compressor inlet pressure
- Heat integration
- Materials of construction
  - Heat exchangers
  - Piping
- Discharge pressure

Ramgen evaluates and screens all of these parameters for prospective application of the high-pressure demonstration size as part of any FEED activity. The FEED activity supports longer-lead-time and commercial-scale projects at the same time. Ramgen will work with the customer during this study phase to define the specific application conditions and alignment with the planned Ramgen product sizes.

Decision to Proceed

Upon FEED completion and receipt of necessary permitting, a commitment to purchase and supply a Rampressor demonstration unit can be made. Commercial-scale projects continue on their own time line.

Detailed Engineering

During this phase, both the Rampressor selection and selected options and features related to plant integration of heat recovery will be designed.

Construction

This phase will include compressor production by a commercial original equipment manufacturer (OEM) (i.e., Dresser-Rand), checkout, and installation in the plant facility. Exact production time lines will depend on several factors and will be specified and committed at the end of the FEED study.

Another enhancement as a result of Ramgen's partnership with Dresser-Rand is the intent to test the CO_2 Rampressor in Dresser-Rand's test facility in Olean, New York, prior to the field demonstration. Dresser-Rand's test facility is one of the most flexible and sophisticated gas-testing facilities in the world. This test facility will allow the demonstration unit to be evaluated with far greater control than in a field demonstration scenario. The Dresser-Rand test facility will eliminate the risk of disruptions due to the plant itself, the carbon capture process and equipment, and the storage availability. It will also enable demonstration on a variety of CO_2 gas mixtures that can be created in the facility. The addition of Dresser-Rand's test facility reduces the risks associated with shaking down the CO_2 compressor in the field for the first time on CO_2. Ramgen plans to install and test the PCOR Partnership demonstration unit at Dresser-Rand's facility in Olean, New York.

A procurement plan for the Rampressor demonstration at Dresser-Rand has been developed that ensures that the Rampressor will be ready for testing and, ultimately, the field demonstration by the 2012–2013 timeframe. Vendors have been identified that can provide or fabricate all of the major components. The plan is summarized in Table 2.

Ramgen is in the process of material qualification testing for the potential use of other materials in addition to titanium in the fabrication of the rotor.

Table 2. Rampressor Procurement Plan

Major Component	Lead Time, months
Motor	9.5
Variable Frequency Drives	6.5
Gearbox	7.5
High-Speed Coupling	10
Rotor Titanium and Machining	14
Pressure Case Material and Machining	6
Bearings	7
Seals	6

CONCLUSION

The Ramgen advanced compression technology, the Rampressor, offers a step-change improvement in CO_2 compression efficiency and cost-effectiveness. A 13,000-hp unit will be ready for field testing during the PCOR Partnership's large-scale CCS demonstration slated to begin about 2012–2013. All preparations that can be made at this time have been made in order to ensure smooth integration of the Rampressor into the demonstration.

Basin Electric Power Cooperative, our presumed Phase III CO_2 provider, has experienced significant delays in designing capture facilities. Should these delays continue, it may be necessary to identify alternate sources of CO_2. However, we are confident that with some additional engineering and design, the Ramgen system will be able to be integrated into the Phase III demonstration.

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APPENDIX A

SUPPORTING TECHNICAL DATA

Table A–1. Process Flow Diagram Valve Requirements

Item	Application	Method of Operation	Failure Mode	Class	Preliminary Style	Max. Pressure, psig	Max. Metal Temp., °F
V-1	Discharge back pressure	Positioner[a]	NO[b]	1500	Globe	2680	650
V-2	Discharge back pressure	Positioner	NO	1500	Globe	2680	650
V-3	Injection thermostat	E controller[c]	NC[d]	1500	Globe	2680	650
V-4	Wheel space regulator	E controller	NO	300	Globe	530	200
V-5	Injection relief	E controller	NO	1500	Globe	2680	650
V-6	Core loop thermostat	E controller	NC	300	Globe	530	650
V-7	Suction regulator	E controller	NO	300	Globe	530	300
V-8	Liquid tank regulator	Modulating[e]	–[f]	300	Globe	600	200
V-9	Inject comp. suction regulator	Modulating	NC	1500	Globe	2680	650
V-10	Dump valve	On/off	NO	300	Ball	530	650
V-11	Makeup CO_2 regulator	Modulating	NC	300	Globe	600	200
V-12	Aux. inject supply	E controller	NC	1500	Globe	2680	650
V-13	CO_2 vapor tank relief	ASME[g] relief	Relief	300	Relief	600	200
V-14	CO_2 liquid tank vapor relief	ASME relief	Relief	300	Relief	350	-80
V-15	Blue/orange zone relief	ASME relief	Relief	300	Relief	530	200
V-16	Red zone relief	ASME relief	Relief	1500	Relief	2680	650
V-17	Starting bleed valve	On/off	NC	300	Ball	530	650
V-18	Steady bleed/leakage	E controller	NO	300	Globe	530	650
V-19	Leakage check	Check	NC	300	Check	530	650

[a] “Positioner” indicates that the valve is operated by a positioner which receives a proportional signal from the programmable logic controller (PLC).
[b] Fail open.
[c] E controller” indicates that the valve is operated by an electronic closed loop controller with set point remotely adjusted by the PLC.
[d] Fail closed.
[e] “Modulating” indicates that the valve is operated by an electronic or mechanical closed loop controller with manual set point.
[f] Not applicable since manually controlled.
[g] American Society of Mechanical Engineers.

Table A–2. Heat Exchangers

Item	Application	Preliminary Heat Load	Cooling water, gpm	Water Flanges, inch NPS
C-1	Core CO_2 bypass cooler	750 kBtu/m	4500	12
C-3	Injection discharge cooler	70 kBtu/m	500	4
C-5	Main exhaust flow cooler	1.2 MBtu/m	Use-dependent	Use-dependent
C-6	Oil cooler	20 kBtu/m	150	2

Table A–3. Gas Conditions

Gas Constituents	Value or Range
CO_2 Concentration	Maximum = 100%, minimum = 98.5%
Oxygen Concentration	Maximum = 15 ppm, minimum = 10 ppm
Nitrogen Concentration	Maximum = 25 ppm, minimum = 10 ppm
Ammonia Concentration	Maximum = 75 ppm, minimum = 30 ppm
H_2S Concentration	None
Other Gases	None
Particulate Size and Concentration	25-µm maximum size; 1 mg/m^3
Suction Pressure Operational Range	220 psig to 230 psig
Nominal Operational Suction	220 psig
Nominal Discharge Pressure	2200 psig
Nominal Discharge Temperature	517°F
Suction Temperature	100°F
Mass Flow Rate	391,152 lb/hr, turndown 30%

Table A–4. Compressor Interfaces

Suction Interface	
Flange Size	12-in. (quantity two)
Flange Class	300-lb stainless steel
Discharge Interface	
Flange Size	12-in. (quantity one)
Flange Class	1500-lb stainless steel
Bleed Interface	
Flange Size	10-in. (quantity two)
Flange Class	300-lb stainless steel

Table A–5. Controls and Instrumentation

All-weather electrical enclosures and connectors are expected.
Control system will be PLC-based with a personal computer (PC) operator station.
Control system communication between control room and Rampressor PLC will be by Ethernet (or per power plant preference).
The PLC will control all dedicated subsystems as well as the Rampressor. This includes the oil system, injection valves, leakage recompression, and seal support system.
Control system monitors system health (pressures, temperatures, vibration). Operator will be notified if any parameter approaches its limit.
Control system will detect when the unit is not running and will automatically attempt to restart.
Control station will have audible and visible alarms to allow operator to monitor multiple stations.

Table A–6. Electrical Interfaces

Electrical Supply – High Voltage	
13,000-hp motor on Variable Frequency Drives	6600 V, 3-phase, 10 MW
Location	One connection at each motor/controller
Electrical Supply – Medium Voltage	
Various Motors and Pumps	480 V, 3-phase, 175 kW
Oil Heater	480 V, 3-phase, under 10 kW
Two Required	110 V, single-phase, under 5 kW
Location	One connection at Ramgen skid
Electrical Supply – Uninterruptible Power Supply Requirements	
Drive Supply	
Oil Pump Systems	

Table A–7. Cooling Systems

Cooling Water	Normal cooling tower temperatures
Capacity	See Table A-2, Heat Exchangers
Pressure	50 psig (2)
Maximum Supply Temperature	85°F
Open- or Closed-Loop	Power plant choice
Maximum Temperature Rise	30°F
Chemical Additives	No glycol or toxics
Interface	Class 150 (2)

Table A–8. Lubrications Systems

Lubricant Grade	International Organization for Standardization Grade 32 synthetic oil
Supplier	Mobil SHC 824 or power plant preference

Table A–9. General Requirements – Personnel Safety

- All equipment hazards shall be marked with warning signs and/or equipped with guards.
- All automated equipment shall include lockouts, emergency stops, alarms, and other safety features as included in Occupational Safety and Health Administration guidelines.
- All vented CO_2 will be directed away from confined spaces and mixed with air to prevent concentrations over 3% CO_2 by volume (10-min exposure is allowable under National Institute for Occupational Safety and Health). Concentrations below 1% are preferred.
- There are no legal restrictions on the amount of CO_2 released. Decisions on discharge shall be based on the cost of capture and recycling vs. the cost of venting to the atmosphere.
- Oxygen-monitoring equipment for employee safety will be the responsibility of the power plant.
- Ramgen will take reasonable precautions to limit noise, but noise levels in excess of 100 dB are expected within 10 ft of machinery, so hearing protection will be required.
- Equipment shall include lifting points for crane or forklift as required for installation and maintenance.
- Block valves are present for facility process interface; no hot taps required.