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of the
Workshop on Future Large CO2 Compression Systems

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Prepared By

Ronald H. Wolk
Wolk Integrated Technical Services
San Jose, CA

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List of Abbreviations

3D	three dimensional
A	amperes
AC	Alternating Current
acfm	actual cubic feet per minute
API	American Petroleum Institute
Bar	metric unit of pressure, approximately 14.5 psi
Bara	bar, absolute
bcf	billion cubic feet
C	Centigrade
CCS	Carbon Capture and Sequestration
CTE	Coefficient of Thermal Expansion
ERDC-CERL	US Army Engineer Research and Development Center, Construction Engineering Research Lab
EPRI	Electric Power Research Institute
d	day
DC	Direct Current
DMOSFET	Double Diffused (or Implanted) Metal-Oxide-Semiconductor Field Effect Transistor
DOD	Department of Defense
DOE	Department of Energy
EOR	
EOS	Equation of State
F	Fahrenheit
FC	Fuel Cell
GW	Gigawatt
Gt	Giga-tonnes
GTO	Gate Turn-Off Thyristor
HANS	HANS equation of state
HF	High Frequency
Hz	Hertz
hr	hour
HVDC	High Voltage Direct Current
HV	High Voltage
IEA	International Energy Agency
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
kA	kilo-amperes
kHz	kilohertz
km	kilometer
kV	kilovolt
kVA	kilovolt ampere
kW	kilowatt
kWh	kilowatt hour
lbm/hr	pound moles/hour

LCI	Line Commutated Inverter
LMTD	Log Mean Temperature Difference
LNG	Liquefied Natural Gas
MEA	Monoethanolamine
MERGE	Model for Evaluating the Regional and Global Effects of GHG Reduction Policies
M/G	Motor/Generator
MM	million
MMSCFD	million standard cubic feet per day
MSCF	thousand standard cubic feet
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
mt	metric tonnes
mt/yr	metric tonnes per year
MVA	Megavolt Ampere
MW	Megawatt electric
MWt	Megawatt thermal
NIST	National Institute of Standards and Technology
Nm3	Normal cubic meters
PCS	Power Conditioning System
psia	pounds per square inch absolute
PVT	Pressure Volume Temperature
ppm	parts per million
R&D	Research and Development
RKS	Redlich-Kwong-Soave equation of state
rpm	revolutions per minute
SwRI	Southwest Research Institute
tpd	tons/day
V	volts
VLE	Vapor Liquid Equilibria

1. Summary

A Workshop on Future Large CO_2 Compression Systems was held on March 30-31, 2009 at NIST headquarters in Gaithersburg, MD. Such systems could be utilized as part of the equipment needed to transport CO_2 captured at fossil fuel power plants by pipeline to permanent sequestration sites and/or for sequestration well injection. Seventy-seven people who are active in this field participated. The Organizing Committee for the Workshop consisted of Dr. Allen Hefner of NIST, Dr. Robert Steele of EPRI, Dr. Peter Rozelle of DOE and Ronald H. Wolk of Wolk Integrated Technical Services.

The objective of this Workshop was to identify and prioritize R&D projects that could support development of more efficient and lower cost CO_2 compression systems. Reducing the total cost of Carbon Capture and Sequestration is a major goal of R&D programs sponsored by organizations including US DOE, IEA, EPRI, MERGE and others. The capital cost of compression equipment and the associated cost for compression energy are major components of this total cost.

Twenty technical presentations were given to familiarize Workshop participants with a broad spectrum of multiple aspects of the technologies involved including:

- Future Market Drivers for CO_2 Compression Equipment
- Characteristics of Large Power Plants Equipped for CO_2 Capture and Compression
- Oil and Gas Industry Experience with CO_2 Capture, Compressors and Pipelines
- Compressor Vendor Perspective on Changes in Compression Cycle Machinery
- Electric Drive Compressor Potential for Improvement in Capitol Cost, Power Requirements, Availability, and Safety
- Advanced Compressor Machinery Future R&D Needs
- Advanced Electric Drive Compressor Future R&D Needs

The presentations are available at www.nist.gov/eeel/high_megawatt/2009_workshop.cfm

The key points that can be summarized from these presentations are that:

- Existing commercial CO_2 pipelines in the United States, with a total length of about 5650 km (3500 miles), operate safely
- These pipelines are utilized primarily to deliver about 68,000 mt/day (75,000 tons/day) of pressurized CO_2, recovered from both natural reservoirs and from natural gas purification and chemical plants to existing Enhanced Oil Recovery projects.
- A typical 550 MW coal-fired power plant will produce about 13,500 mt/day (15,000 tons/day) of CO_2. A large number of coal-fired power plants of this size are likely to be built between now and 2030 to meet the increased demand for power in the US. According to the EIA *AEO2009* reference case, total electricity generation from coal-fired power plants will increase from 1906 billion kWh in 2009 to 2236 billion kWh in 2030. The current capacity of coal fired generating plants in the US is about 311,000 MW.

- The accuracy of the Equations of State used to predict the properties of the CO_2 recovered from the flue gas produced by coal-fired power plants, which includes a wide variety of contaminants, needs to be improved to reduce typical design margins used by compressor vendors.
- Reciprocating and centrifugal compressors are available from a variety of vendors to meet the pressure and volumetric flow requirements of all applications. The largest machines pressurize about 18,000 mt/day (20,000 tons/day) to 27,000 mt/day (30,000 tons/day) of CO_2 to the pressures required for pipeline transportation or sequestration well injection.
- Power required for compression could be reduced if CO_2 was first compressed to an intermediate pressure, then cooled and liquefied, and that liquid is then pumped to the higher pressure level required for pipeline injection.
- Improved materials are needed to allow higher speed rotor operation and corrosion resistance of rotors and stators.
- Competitively priced commercially available power conditioning components and modules are needed that will allow systems to operate at >10 kV and switch at >10 kHz
- SiC-based power conditioning and control components to replace existing Si-based components can lead to higher efficiency electric drive systems.

After digesting the information presented, the Workshop participants suggested a total of 33 R&D projects in seven categories. Thirty-seven of the Workshop attendees then participated in a Prioritization Exercise that allocated 3700 votes (100 by each of those participants) among the seven categories of R&D activities and 33 specific R&D projects.

The results of the Prioritization Exercise are presented in Tables 1 and 2. Table 1 lists the rank order by total votes of the seven Categories. Table 2 lists the top 10 projects, out of a total of 33, by rank order of total votes.

Table 1. Rank Order of R&D Categories

R&D Categories	Total Votes
1. Properties of CO2 and Co-constituents	914
2. Integration of CO2 Capture and Compression	726
3. Compression Systems Machinery and Components	690
4. Electric Drive Machinery	545
5. Pipeline Issues	456
6. Drive Electronics and Components	326
7. Impacts of Legislation on CCS	43

Table 2. Rank Order of Top 10 R&D Projects

R&D Project	Total Votes
1. Perform more gas properties measurements of CO_2 mixtures	435
2. Improve Equations of State	401
3. Optimize integration of a CO_2 capture/compression system together with the power plant	280
4. Comparison and evaluation of compression-liquefaction and pumping options and configurations	204
5. Higher voltage, higher power, and speed electric motors and drives	165
6. Install test coupons in existing CO_2 pipelines to obtain corrosion data, then develop CO_2 product specifications	150
7. Determine optimal electric motor and drive types, speeds, and needed voltages, etc., for CO_2 compressors	143
8. Establish allowable levels of contaminants in CO_2 pipelines and/or compressors	120
9. Compressor heat exchanger data for power plant applications including supercritical fluids	117
10. Integrate utilization of waste heat to improve cycle efficiency	113

2. Overview of Technical Presentations

This section of the report organizes a fraction of the total information presented at the Workshop into brief summaries. Readers are strongly encouraged to review the actual presentation materials for those topics about which they need additional information.

A. Sources of CO_2 in the US

CO_2 is recovered commercially from a variety of sources including natural sealed reservoirs typically referred to as domes, and industrial plants. High purity (>95%) CO_2 gas streams are available from processing plants that purify raw natural gas to meet standards for pipeline transmission, and from chemical plants that gasify coal or produce hydrogen, ammonia, and other fertilizers, and potentially from future gasified coal power plants. These operations are the preferred man-made sources of CO_2 because the gas from those plants is available at high pressure. Other sources of CO_2 are available at lower pressures at high purity (from fermentation plants producing ethanol) and at low purity (from pulverized coal power plants and cement plants). The locations of various commercially utilized sources of CO_2 are listed below and are also shown in Figure 2.1 (Kubek)

- Natural CO_2 Reservoirs
    - Bravo Dome (TX)
    - Jackson Dome (MS)
    - McElmo Dome (CO)
    - Sheep Mountain Dome (CO)
- Natural Gas Purification Plants
    - LaBarge Gas Plant (WY)
    - Mitchell Gas Plant (TX)
    - Puckett Gas Plant (TX)
    - Terrell Gas Plant (TX)
- Solid Fuel Gasification Plant
    - Great Plains Coal Gasification Plant (ND) – fueled with North Dakota lignite (2.7 million tons CO_2 per year)
    - Coffeeville Resources Plant (KS) – fueled with Coffeeville refinery petroleum coke
- Industrial Chemical Plants
    - Ammonia Plant (OK)

Low purity CO_2 containing streams are produced by coal-fired power plants (12-15%), cement plants (12-15%), and natural gas fired gas turbine/combined cycle power plants (3-4%). These are not used as sources for large scale CO_2 recovery. (Schoff)

Much of the CO_2 that is separated in natural gas purification systems is not utilized commercially but is disposed of by venting to the atmosphere, or if contaminated with H_2S, is injected into saline aquifers through deep injection wells. Over 50 acid gas (CO_2 + H_2S) injection projects for acid gas disposal are currently operating in North America. In most cases the acid gases consist primarily of H_2S but all streams contain CO_2. Injection rates range from < 0.0268 MM Nm^3 (<1 MMSCFD) to 0.48 MM Nm^3 (18 MMSCFD) in Canada. The ExxonMobil LaBarge Gas Plant in Wyoming injects about 2.4 MM Nm^3 (90 MMSCFD). Major process components after the Acid Gas Removal plant are either compression with integrated partial dehydration or compression and standard dehydration. Various conceptual projects are in the design stages in the Middle East for acid gas injection rates that will exceed 10.7 MM Nm^3 /day (400 MMSCFD). (Maddocks)

Existing acid gas injection plants typically use reciprocating compressors. Larger volume conceptual projects, for larger volume applications in the Middle East, are being designed with centrifugal compressors. Injection pressures can range from 34.5 bar (500 psi) to over 207 bar (3000 psi) depending upon the depth and permeability of the formation. Depleted reservoirs or deep aquifers are typically utilized. These “relatively” small projects can be designed and operated safely with existing technology. (Maddocks)

Figure 2.1 Location of CO_2 Sources and Pipelines in the US

B. CO_2 Capture Technology

CO_2 is typically captured from a process plant gas stream by contacting the stream with an appropriate solvent. The choice of solvent depends primarily on the pressure of that gas, its CO_2

content, and the levels and types of contaminants contained in that gas. Low pressure (near atmospheric pressure) gas streams are typically treated with amine-based solvents that remove the CO_2 by chemical reaction. High pressure gas streams (>3.6 bar (50 psi)) are typically treated with solvents that capture CO_2 by physical absorption. Solvent regeneration to break the chemical bonds between the amine and CO_2 is done by the use of heat, typically recovered from other plant process streams. CO_2 is typically removed from the physical solvents by pressure reduction.

There are three relatively low capacity plants currently operating in the US that use monoethanolamine (MEA) solvent to capture CO_2 for local uses including freezing chickens, carbonating soda pop, and manufacturing baking soda, at a cost of ~$140/ton CO_2. The total amount of CO_2 recovered in these plants is about 270 MT/day (300 tons/day). This is equivalent to the emissions from a very small (~15 MW) power plant.

Coal gasification plants that produce hydrogen, ammonia, and other fertilizers typically use physical solvents to remove CO_2 and H_2S from product gases. Most of these plants are located in China and South Africa. Some plants of this type operate in the US.

Oxyfuel is a combustion process under development at a number of locations. It combusts fuel with oxygen which is diluted with captured and recycled CO_2. There are several contaminants that must be controlled to specific levels including O_2, N_2, Ar, SO_2, and H_2O, to avoid problems with the CO_2 capture system. (Schoff). The largest Oxyfuel development facility is a 50 MWt natural gas fired demonstration plant that is being planned for installation at the Kimberlina Power Plant near Bakersfield, CA. Other test facilities include a number of smaller coal-fired facilities including the B&W 30-MWt test facility in Ohio, a 30-MWt pilot plant under construction by Vattenfall, and several operating pilot-scale (~1 MWt) test units. (Schoff, Hustad)

Other technologies for CO_2 capture are under development. Many pilot plant projects are planned and in development, including those that use chilled ammonia as a solvent. (Schoff)

One CCS demonstration now under way in the North Sea off the Norwegian coast is the Sleipner CO_2 Injection Project. It is located on a drilling platform and utilizes an amine system to capture 1 million mt/y (1.1 million/tons/y) of CO_2 that is then injected into a deep saline aquifer at 65 bar (840 psi).The objective of the project is to reduce the CO_2 content of raw natural gas from 9 % to 2.5 % to meet commercial sale specifications. The test program has been in operation since 1996 with a reliability level of 98-99%. (Miller)

The costs of CO_2 capture from natural gas fired and coal fired power plants (IGCC plants and Oxyfuel plants) followed by pressurization to 150 bar (2200 psi) as reported at the Workshop by two authors are shown in Table 2.1.

Table 2-1 Cost of CO_2 Capture

Author	**Hattenbach**	**Amick**
	$/metric ton	**$/metric ton**
Natural Gas Combined Cycle	83	
Supercritical Pulverized Coal	67-68	40
IGCC	39	20
Oxyfuel (new)	48	
Oxyfuel (retrofit)	67	
Coal to Liquids		10
Synthetic Natural Gas		8

C. CO_2 Pipelines

As shown in Figure 2.1, existing networks of pipelines move CO_2 from sources to markets. The purity of the CO_2 used for EOR is >95 %. (Hattenbach) At this time, the major markets for CO_2 are for Enhanced Oil Recovery (EOR) in the Permian Basin of Texas and New Mexico, the Gulf Coast, and the Weyburn fields in Saskatchewan, Canada. EOR operations in the Permian Basin utilize 0.043 bNm3/d (1.6 bcf/d) of CO2 to recover ~180,000 barrels per day (B/D) of incremental oil, which represents ~70 % of global CO2-EOR production. (Hustad) In the U.S., a limited number of locations in Kansas, Mississippi, Wyoming, Oklahoma, Colorado, Utah, Montana, Alaska, and Pennsylvania also utilize CO2 injection to increase oil recovery. (Hattenbach, Kuuskraa).

The first CO_2 pipeline in the US was constructed in 1974. All of these pipelines utilize the same type of carbon steel pipe that is used for natural gas pipelines. These systems operate routinely without any significant or safety issues. Corrosion of carbon steel has been successfully avoided by maintaining the water content of the CO_2 at very low levels to avoid formation of carbonic acid, which attacks carbon steel. (Kadnar)

- CO_2 pipelines are protected from damage by the following procedures:
  - 24 hour monitoring by a Control Center
  - Membership in statewide one-call networks
  - Compliance with Common Ground Alliance Best Practices
  - Patrolled by air 26 times per year
- CO_2 pipelines are protected from corrosion by:
  - Annual pipe to soil survey of pipeline
  - Five year cycle of Close Interval Surveys
  - Assessments of High Consequence Areas under Pipeline Integrity Management program (Kruuskaa)

Based on the assumed use of about 0.3 mt (0.33 tons) of CO_2 /barrel of oil produced and production of about 250,000 B/D of oil by using CO_2 injection (Kuuskraa), the total amount of CO_2 carried by all the CO_2 pipelines in the US is estimated at about 67,000 mt/day (75,000 tons/day). To put that number in perspective relative to the potential markets for CO_2 capture for

CCS purposes, a single 550 MW coal-fired power plant produces about 15,000 tons/day of CO_2. (Schoff) Currently, US emissions of CO_2 resulting from coal combustion amount to about 2100 MMT/y (2300 million tons per year) or about 5.7 million mt/day (6.3 million tons/day, equivalent to 400 coal-fired power plants, each with a capacity of 550 MW).

The costs of new CO_2 pipelines have been estimated as follows:
100 miles of 24” pipe line with a capacity of (500 MMSCFD)

• Flat Dry Land	$120,000,000
• Mountains	$204,000,000
• High Populated Urban	$250.000.000
• Offshore with a water depth of 46 m (150 ft.) – 61 m (200 ft) (Kuuskraa)	$1,680,000,000

IEA has proposed a combination of several approaches to stabilize the CO_2 concentration in the atmosphere at 450 ppm by 2030. These include an annual reduction of CO_2 emissions by 2.3 Gt/year by means of CCS. This would imply that the future amount of captured CO_2 will be about the same as today’s natural gas production.

Twelve full-scale CCS projects are in the planning stage for Europe by 2012. These early projects will have individual pipelines. Interconnections among early projects are anticipated in 2015-2025. Looping of these pipelines is anticipated in 2025-2035 to create a CO_2 pipeline ring similar to that now exists in Texas to serve the Permian Basin EOR market. (Bratfos)

D. Delivered Cost of CO_2

CO_2 obtained from natural sources is now delivered commercially by pipeline to EOR sites at a price of about $1.25/MSCF ($24/metric ton, $22/ton). In comparison, the cost to compress and transport for 50 miles about 1.34 MM Nm^3 (50 MMSCF/d) of CO_2 recovered from high purity (>95%) man-made sources (natural gas processing plants, hydrogen production plants, etc.) will cost from $1.30 to $1.75/ MSCF or $25.50/mt ($23/ton) to $33.70/mt ($30/ton). The cost of compressing and transporting a similar amount of CO_2 recovered from low purity (<15%) sources a similar distance would range from $2.85 to $4.00/MSCF or from $55.00/mt ($50/ton) to $77.00/mt ($70/ton). Of that total, the cost of capture is much higher than that of compression. Significant reductions are needed in both capture and compression cost for man-made sources of CO_2 to compete with natural sources for EOR markets. (Hattenbach)

E. Challenges of CO_2 Transportation

The development of a national pipeline network equal in scope to the present natural gas pipeline network is a challenging task. An alternate approach is to focus on regional sequestration sites, and be proactive about siting issues so that new plants will be near sequestration sites. The use of CO_2 for EOR is mature and the liability issues have been resolved. DOE cost goals for CO_2

sequestration are very aggressive relative to currently estimated costs of capture and transportation. (Hattenbach)

For non-EOR sequestration to be commercially attractive, US industry needs visibility on:

- Value of emission reduction credit
- Regulations – Federal and State
    - Early action might be penalized
    - Economic - benefit or cost?
- Pore space ownership
- Liability issues
- Cost for capture and compression of man-made CO_2 needs to be decreased (Hattenbach)

There are a number of concerns related to large scale CO_2 transmission by pipeline:

- **Root causes**
    - Emergency blowdown of large dense phase inventories
    - Accidental denting
    - CO_2 corrosion leaks in case of accidental intake of water
    - Material compatibility (elastomers, polymers)
    - Ductile fracture of pipeline ("un-zipping")
- **Consequences**
    - Dispersion of concentrated CO_2
    - Dispersion of toxic impurities
    - Pipeline damage/downtime

(Bratfos)

F. Properties of CO_2 and Co-constituents Near the CO_2 Critical Point

One of the conclusions reached by participants of the Workshop was that the use of currently available versions of the Equations of State (EOS) to predict the properties of supercritical CO_2 which is contaminated with other compounds (i.e. A, N_2, O_2, CO, NH_3, H_2S,) at conditions near the critical point are not reliable enough for precise compression system designs. Several of the presentations commented on this issue as follows.

"GE has used the BWRS (Benedict-Webb-Rubin-Starling) EOS for the last 30 years: up to 300 bar on regular basis and up to 540 bar with CO_2 + HC gas mixture in specific cases .... also in the supercritical region. BWRS above 480 bar requires careful verification of literature data and is not suitable for liquid-vapor equilibrium calculations**.** Many existing CO_2 EOS are optimized for pure CO_2 but not for mixtures. To allow for regions not adequately covered by current EOS, GE is introducing a new thermodynamic model to improve predictability." (Minotti)

"Better understanding of Phase behavior and confidence in EOS predictions" is needed."(Maddocks)

"Equations of state near critical point… theories vary at high pressure also with co-constituents". (Miller)

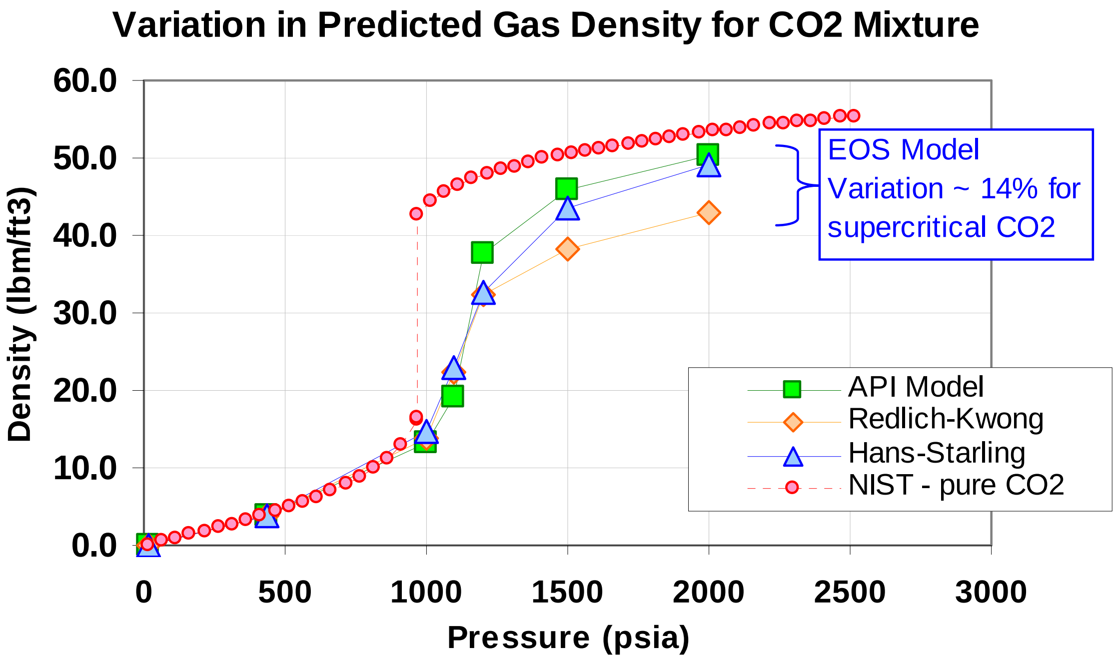
"Compressibility is an issue at high pressure to stay away from liquid phase." (Kisor)

"Equation of state models for CO_2 based mixtures have not been fully developed or validated. Large differences (19% variation) exist in gas properties predicted by standard equation of state models (API, RKS, HANS) and pure CO_2 correlation models from 1000-2000 psia. EOS fall short on density and speed of sound especially with NIST supertrack program – is it applicable? "The needed actions are to perform more gas properties measurements of CO_2 mixtures and refine equation of state near critical point and with mixtures." (Moore)

"Equations of state are not good enough when we have water condensing out. Small amounts of impurities in CO_2 change the location of the supercritical line. Better [pressure, volume, temperature] PVT data are needed on mixtures of CO_2 and other gases." (Hustad)

As a result of the deficiencies in the available data, larger margins than may be necessary are used by designers and manufacturers in their products. Better EOS have the potential to be used to lower equipment costs. As one illustration of the differences, Figure 2-2 (Moore) shows the variation in predicted density of CO_2 obtained with various prediction methodologies.

Figure 2-2



G. Compression Systems Machinery

1. Existing Compression System Machinery

Most of the large scale industrial experience with CO_2 compression has been with CO_2+H_2S re-injection, fertilizer and hydrogen manufacturing, and CO_2 pipelines. (Miller, Minotti, and Kisor) Reliability experience ranks centrifugal compressors highest, followed by integrally geared, and then reciprocating units. (Minotti) GE has recently utilized supercritical compression (6 stages) to reach liquefaction conditions, followed by centrifugal pumping to enable pumping the supercritical fluid to the final required pressure. (Minotti) Integrally geared machines achieve near-isothermal compression, which saves energy, but those machines have many more moving parts compared to reciprocating and centrifugal compressors. MAN Turbo compressors are used to pressurize CO_2 at the Great Plains Coal Gasification plant in Beulah, ND for transmission by pipeline to the Weyburn oil fields in Saskatchewan, Canada a distance of more than 325 km. (200 miles).

CO_2 compression requires a significant amount of energy to achieve a final pressure of 103 bara (1,500 psia) to 152 bara (2,200 psia) for pipeline transport or re-injection. For a typical 400 MW coal-fired plant, the typical CO_2 flow rate is 120 mt/hr (132 tons/hr) to 140 mt/hr (154 tons/hr). The type of compressor selected is highly dependent on the starting pressure, which is approximately 1.3 bar (20 psia) to 34.5 bara (500 psia) for CO_2 scrubbing of the fuel stream from an IGCC plant and approximately one bara (14.5 psia) from conventional pulverized coal power and Oxy-Fuel process power plants. Various types of compressors including ordinary and integrally geared centrifugal and reciprocating machines have been utilized to meet these compression service requirements depending on inlet and outlet pressures and volumetric flows. Reciprocating compressors are capable of achieving higher final pressures than centrifugal compressors, while centrifugal compressors can handle higher flow rates. For the large quantities of CO_2 that must be handled in CCS applications, large capacity, single compression trains offer a significant cost advantage. (Moore)

Many vendors market the compressors that could be used in CO_2 compression service for CCS projects. Dresser Rand, GE, and MAN Turbo, which are representative of vendors that produced very large compressors were invited to present information on their typical products. Participants in the Workshop included representatives of other compressor vendors and technology developers including ABB, Curtiss-Wright, Elliott, Florida Turbine Technologies, Mitsubishi Heavy Industries, Solar Turbines, Turblex, and others.

The compressor data presented by Dresser-Rand, GE and MAN Turbo is summarized in Table 2-2.

Table 2.2 – Representative Large Compressor Data

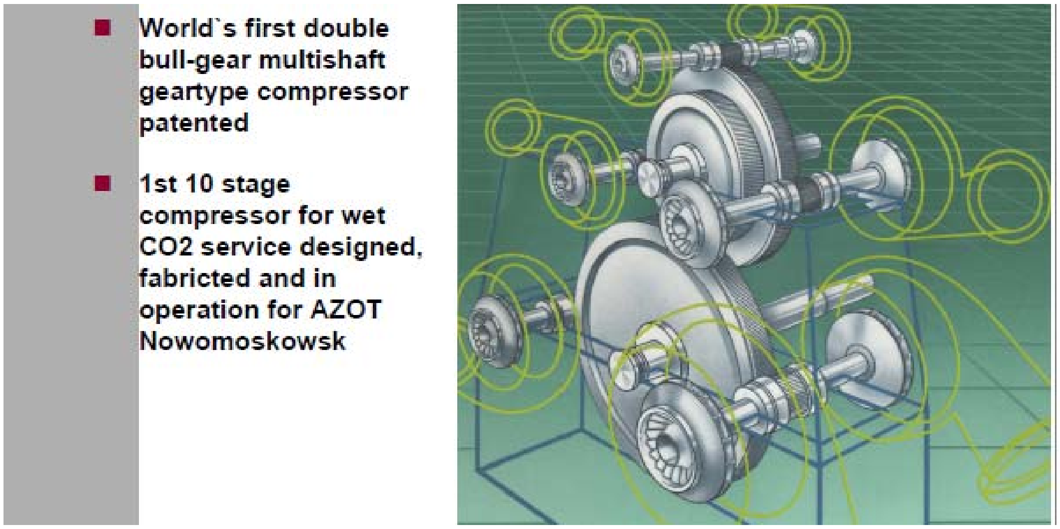
Vendor	**Dresser Rand**	**GE**	**MAN Turbo**
Reference	**Miller**	**Minotti**	**Kisor**
Compressor type	**Reciprocating, Centrifugal**	**Centrifugal**	**Integrally Geared Centrifugal**
Centrifugal Compressors in service/ total power	105/ ~300 MW total	200+/up to 18 MW for largest unit	
Maximum Discharge Pressure	Centrifugal 178 bar (2,580 psia) operating 309 bar (4,472 psia) to be delivered in late 2009	280 bara	225 bar
Maximum inlet flow	82,100 m3/hr (48,300 acfm)	300,000 Nm3/hr (176,500 acfm)	350,000 Nm3/hr (205,800 acfm)
Reciprocating Compressors in service/ total power demand	227 units/ >395MW	180+/	
Maximum Discharge Pressure	426 bara (6,213 psia)	750 bara	
Maximum inlet flow	7,300 m3/hr (4,300 acfm)	19,000 Nm3/hr (11,300 acfm)	

Design issues for CO_2 compressors include carbonic acid corrosion of carbon steel if water is present in the system. The use of stainless steel for any components in contact with wet CO_2 eliminates the problem. Similarly, the presence of water containing CO creates iron carbonyl upon contact with carbon steel. Again, the use of stainless steels solves the problem. Special O-ring materials are required to resist explosive decompression due to entrapped CO_2 within the O-rings. (Miller)

Aerodynamic challenges include very high pressure ratio and compressibility and a wide range of flow coefficient stages. Additional challenges relative to rotor dynamics are the very high density of CO_2 and destabilizing effects and predictability of compressor seal dynamic coefficients. (Minotti)

Integrally geared compressors can be optimized for each stage due to lower volume and higher pressure at each progressive stage. This attribute provides the ability to spin high pressure impellers at higher speed. It is possible to go to different speeds on each pinion and stage so that very high (50,000) rpm are possible. The polytropic efficiency of these machines is in the high eighties. As a result of the potential to form liquid phases at high pressures, the final compression stages are not intercooled, so that the temperature is always maintained above the critical point to stay in gas regions. (Kisor)

A sketch of a recent design of a MAN Turbo integrally geared compressor is shown in Figure 2-3.



- World`s first double bull-gear multishaft geartype compressor patented
- 1st 10 stage compressor for wet CO2 service designed, fabricted and in operation for AZOT Nowomoskowsk

[c1]

Figure 2.3 MAN Turbo Integrally Geared Compressor

2. R&D to Support Future Advancements in Compression Systems Machinery

Interstage Cooling/Liquefaction/Cryogenic Pumping

The high pressure ratios required in each turbine stage to ultimately reach the high total pressures required by CCS systems results in a significant amount of heat of compression. Compression systems must also be integrated with both the power production and CO_2 capture plants to optimize heat integration. DOE-supported studies by SwRI, working with Dresser-Rand, have demonstrated that an isothermal compressor combined with cryogenic pumping offers the potential to significantly reduce compression power requirements by 20-35%. The goal of this R&D program is to develop an internally cooled compressor stage and qualify a liquid CO_2 pump for CCS service

The focus of the internally cooled compressor stage program is to:

- Provide performance equivalent to an integrally geared compressor
- Achieve the high reliability of an in-line centrifugal compressor
- Reduce the overall footprint of the package
- Have less pressure drop than an external intercooler

The CO_2 liquefaction process that SwRI has identified as being very promising in terms of reducing compression requirements significantly follows the steps listed below:

- Utilizes a refrigeration system to condense CO_2 at about 17.2 bar (250 psia) and -20ºC (-36ºF).
- Liquid is then pumped from 17.2 bara (250 psia) to 153 bara (2,215 psi).
- Significantly less power is required to pump liquid compared to compressing a gas.
- The cost of the refrigeration system must be accounted for. (Moore)

GE is now using supercritical compression (4 stages) and centrifugal pumps and refrigeration at -20 ºC (-36 ºF) to reduce power requirements by about 25 % in one specific application. (Minotti)

Advanced Compressors

Ramgen is developing an advanced compressor for CCS applications with the following:

- 100:1 CO2 compressor 2-casings/2-stages/intercooled
    - No aero Mach # limit
    - 10+:1 pressure ratio; 400°F temperature rise
    - 1400 fps tip speeds; Shrouded rotor design
- Single-stage, discrete-drive
    - Single stage per drive optimizes specific speed match
- “Compressor” heat exchanger cost can be eliminated
    - Eliminate or substantially reduce cooling tower requirement
    - Eliminate or substantially reduce cooling tower make-up water
    - 3x LMTD heat exchangers with 1/3 the surface area

The claimed attributes of this approach are:

- 1/10th the physical size – facilitate space constrained retrofits
- 1/2 the installation cost
- Reduce CCS cost by 56 % from \$64 to \$28/tonne CO_2 (Baldwin)

Dresser-Rand has recently begun supporting this program. (Miller)

H. Electric Drive Machinery

1. Existing Electric Drive Machinery

The oil and gas industry is following the world-wide trend to increased electrification with a diverse range of applications for high power electric drives which require:

- High reliability/availability/maintainability
- High power
- High voltage
- High speed

- Ability to operate in harsh environments

(Zhang)

A variety of high megawatt direct electric drives are currently available for exploration, production, transport, and processing applications. However, further improvements in capabilities are needed to serve the market for remote sub-sea power located more than 100 miles off-shore in water with depths greater than 200 feet.

The relationship among speed and power rating for various segments of the electric drive market is shown in Figure 2.4.

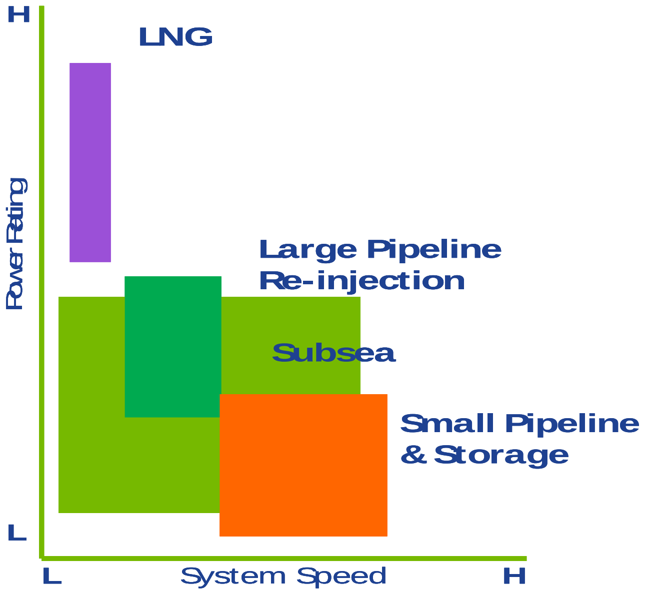


Figure 2.4 Market Segments for Large Electric Drives (Zhang)

Among the requirements for this equipment are low ripple currents and low harmonics. GE is offering an integrated high speed motor/generator to the oil and gas markets with drive power needs of up to 15 MW. High speed, high power, direct drive systems eliminate the need for a gear box, which improves reliability.

Recent achievements reported by GE include:

- Replacement of LCI with ICGT drive systems reduces torque ripple by a factor of 3
- Move to high frequency integrated M/G operating at 11,000-17,000 rpm
- 35 MW output at 100 Hz with multi-thread parallel and interleaving control system design

High efficiency synchronous motors are an important approach to minimum total lifecycle costs for drive machinery, since the cost of the electricity used represents 74 % of total lifetime cost for these systems. 4-6 pole synchronous motors offered by ABB in the range of 10-60 MW feature high efficiency, low inrush current and variable power factor. (Kullinger)

Converteam offers Variable Motor Drive Systems in two power ranges, 2-32 MW and 10-100 MW. The lower power system, which uses MV- IGBT press pack technology, can be used with high speed motors, induction motors, and synchronous motors. The higher power system, which uses LCI – Thyristor technology, can be used with both synchronous motors and high speed synchronous motors. (Moran)

2. R&D to Support Future Advancements in Electric Drive Machinery

The market requirements for electric drive machinery are focused on the needs to operate at higher power ratings with even greater reliability and efficiency than today's product offerings. The key to meeting these market demands lies in the realm of technology development that will allow commercial products to operate reliably at voltages above 10 kVA and frequencies above 10 kHz.

Drive component R&D needs include:

- Advanced stator and rotor cooling schemes
- Improved materials for high speed rotors, advanced design tools
- Advanced stator and rotor materials to handle corrosive gases
- Improved drive electronics
  - higher fundamental frequencies for high speed machines
  - improved controls and bandwidth to provide low torque ripple
- Tighter integration of compressor, motor and drive components and engineering

(Raju)

I. Drive Electronics and Components

1. Existing Drive Electronics and Components

Mechanical drives have been widely used in the past. They are available at high ratings and are independent of the requirements associated with electricity supply infrastructure. Compared to mechanical drives, electrical drives offer improved speed control, higher system efficiency, reduced maintenance, dynamic braking, the capability of short start-up time and load assumption, and elimination of the gear box that enables tight integration of drive motor with the compressor. Electrical drive challenges include the requirement of availability of on-site electricity and power ratings have to be met by both motor and frequency converter ("drive"). The integration advantages of electric drives include direct coupling of motor and compressor rotors thereby eliminating the gear box and the ability to cool motors with the flow of process gas. The power train can be levitated by magnetic bearings. As a result of these characteristics, there is the potential for substantial simplification of compression stations through the use of electric drives in place of mechanical drives.

Permanent magnet motor technology using rare-earth permanent magnet rotor poles, metallic retaining ring and magnetization after assembly, offer the benefits of robust manufacturing processes, no active rotor components, and minimal heating and thermal cycling. (Raju/Weeber)

The use of SiC based components in place of Si-based components can enhance the performance of semiconductor power devices by an order of magnitude for switching frequency and a factor of 5 for device voltage, as shown in Figure 2.5

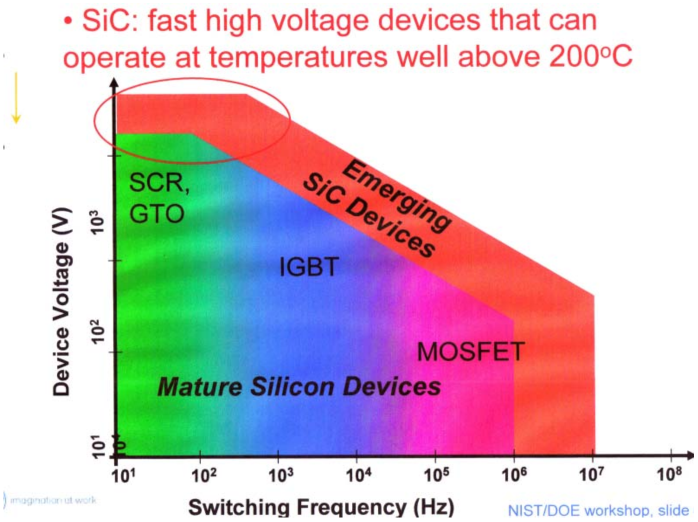


Figure 2.5 Semiconductor Power Devices (Stevanovic)

Currently, there are no commercially available SiC devices that are capable of operating at 10 kV. Robust, reliable devices scaleable to >1 kA are also needed. The challenges facing currently available power modules include thermal limitations, electrical de-rating, and wirebond reliability. New soft magnetic materials have the advantages of minimizing hysteretic losses, minimizing eddy current losses and maximizing materials utilization. (Stevanovic)

Today's commercial market for power conditioning devices, used primarily in Power Factor Correction (PFC) and solar power conversion applications, utilizes Si (silicon)-based 600-1200 V, 5 A-50 A components. Silicon Carbide (SiC) based components offer significant technical advantages relative to silicon components, which are summarized below:

- 10X Breakdown Field of Si
    - Tradeoff higher breakdown voltage
    - Lower specific on-resistance
    - Faster switching
- 3X Thermal Conductivity of Si
    - Higher current densities
- 3X Bandgap of Si
    - Low n_i ⇒ Low leakage current
    - Higher temperature operation

Today SiC based components are relatively expensive but larger production volumes and larger wafer sizes (4 inch diameter instead of 3 inch diameter) are resulting in continuous product cost reduction.

Recent field experience with SiC-based test components was reported at the Workshop by Cree. A 2.4 % increase in efficiency of a 3-phase solar inverter was achieved using Cree 1200 V SiC DMOSFETs in place of 1200 V Si IGBTs. Significant cost savings were achieved by reducing losses in power conversion efficiency. Switching losses with 3.3 kV SiC DMOSFET were more than >10X lower than with 3 kV Si IGBT at 125 °C. The 3.3 kV SiC DMOSFET is capable of 20 kHz switching operation. Early field data is showing a 10X lower failure rate than comparable silicon-based parts. (Palmour)

2. R&D to Support Future Drive Electronics and Components

Robust, reliable devices scaleable to >1 kA are needed. There are no commercially available 10 kV SiC devices. The challenges include:

- VON(T) for majority carrier devices
- Improving the yield of large MOS-gated (FET, IGBT) devices
- Gate oxide reliability, stability
- Bipolar degradation

There are no commercially available >10 kV, >1 kA modules. Design challenges include:

- Device interconnect for high currents and temperatures
- Materials CTE matching
- Fault tolerant to open/short failure
- High performance (top & bottom) device cooling

Development of new magnetic materials requires R&D to:

- Advance alloy theory and modeling to impact: saturation magnetization, anisotropy magnetostriction
- Apply advanced magnetic and structural probes to magnetic materials
- Develop new process routes to achieve desired microstructures
- Validate material performance in pilot-scale processing (Stevanovic)

To provide the needed capabilities for 10 kV devices, SiC IGBTs, GTOs and PiN Diodes are needed. This will require:

- SiC production and reliability proven at low voltages (600-1200 V) and running in high volume
- SiC MOSFETs nearing production at 1.2 kV, and 3.2 kV – 10 kV devices are proven and circuit demos show incredible performance
- For higher voltage (>10 kV), GTOs and IGBTs have been demonstrated
- SiC will enable high voltage drive trains with efficiencies and frequencies far in excess of what can be achieved in Si (Palmour)

3. Prioritization of Potential R&D Projects

Workshop participants were asked to suggest research projects for consideration by the group and subsequent prioritization. Similar suggestions were combined with one another to reduce the number of proposed projects. A total of 33 projects were suggested which were organized into seven categories.

The voting process allocated 100 total votes to each participant. Individuals could distribute their votes among as many projects as they wished, but were not allowed to award more than thirty votes to any one project. As a result of time constraints, participants were asked to submit their completed ballots by email. A total of 37 individuals participated. Employees of the sponsoring organizations (DOE, NIST, and EPRI) did not participate in the prioritization process.

Tables 3.1 presents the distribution of total votes among the seven categories. Table 3.2 lists the ten highest ranked projects. Tables 3.3 through 3.9 present the total votes for R&D projects in each of the seven categories.

The highest ranked category and highest ranked projects related to the need to have more accurate prediction methodologies available for calculating the thermodynamic properties of mixtures of CO_2 containing relatively small concentrations of contaminants totaling less than about 5 %. This category and topic were followed in priority by projects to improve integration of the capture and compression systems.

Table 3.1 Category Rank Order

Category Rank Order	**Total Votes**
1. Properties of CO_2 **and Co-constituents**	**914**
2. Integration of CO_2 **Capture and Compression**	**726**
3. Compression Systems Machinery and Components	**690**
4. Electric Drive Machinery	**545**
5. Pipeline Issues	**456**
6. Drive Electronics and Components	**326**
7. Impacts of Legislation on CCS	**43**

Table 3.2 R&D Project Rank Order

R&D Project	Total Votes
1. Perform more gas properties measurements of CO_2 mixtures	435
2. Improve Equations of State	401
3. Optimize integration of a CO_2 capture/compression systems together with the power plant	280
4. Comparison and evaluation of compression-liquefaction and pumping options and configurations	204
5. Higher voltage, higher power, and speed machines and drives.	165
6. Install test coupons in existing CO_2 pipelines to obtain corrosion data, then develop CO_2 product specifications	150
7. Determine optimal machine types, speeds, needed voltages, etc. for CO_2 compressors	143
8. Establish allowable levels of contaminants in CO_2 pipeline and/or compressors	120
9. Compressor heat exchanger data for power plant applications including supercritical fluids	117
10. Integrate utilization of waste heat to improve cycle efficiency	113

Table 3.3 Voting Distribution - Properties of CO_2 and Co-constituents

Category	Total R&D Project Votes (Rank Order)	R&D Project Descriptions
1. Properties of CO_2 and Co-constituents **Total Category Votes = 914**	435 (1)	Perform more gas properties measurements of CO_2 mixtures • Collect experimental PVT and VLE data and develop correlations for systems with 60-100 % CO_2, 0-40 % H_2S, 0-5 % Ar, and 0-5 % N_2, H_2O • Develop an understanding of the impact of Ar and N_2 and the pressure required to obtain dense phase supercritical CO_2 • Thermodynamic properties of CO_2 and ranges of impurities expected in CCS applications within vapor dome is liquid (also supercritical) • Variable speed of sound pulsation models (real gas effects) • Provide experimental data of CO_2 and co-constituents properties including $(NH_3)2$ at pressures ranging from 5-2500 psia and then develop simulation model with experimental data
	401 (2)	Improve Equations of State • Equation of State predictions at all pressures with water present at various concentrations • Establish standard equations of state usage in analysis • Refine equation of state near critical point and with mixtures from 1 psia up to 11,000 psia
	78 (21)	Define compositions/pressures for power plants, reinjection recycle, pipeline

Table 3.4 Voting Distribution - Integration of CO_2 Capture and Compression

Category	Total R&D Project Votes (Rank Order)	R&D Project Descriptions
Integration of CO_2 **Capture and Compression**	280 (3)	Optimized integration of ~~a~~ CO_2 capture/compression systems together with the power plant
Total Category Votes = 726	161 (6)	Evaluate cost/benefits for various CO_2 capture options based on various CO_2 impurity specs (10 ppm, 50 ppm, 100 ppm, 1000 ppm)
	113 (11)	Integrate utilization of waste heat to improve cycle efficiency
	91 (16)	Evaluate alternate CO_2 compressor drives (steam and gas turbines)
	81 (20)	IGCC Demonstration project with CO_2 capture to reduce risk and enhance workability

Table 3.5 Voting Distribution - Compression Systems Machinery and Components

Category	Total R&D Project Votes (Rank Order)	R&D Project Descriptions
Compression Systems Machinery and Components **Total Category Votes = 690**	204 (4)	Comparison and evaluation of compression-liquefaction and pumping options and configurations
	117 (10)	Compressor heat exchanger data for power plant applications including supercritical fluids
	99 (15)	Advanced rotating equipment clearance control and sealing technology demonstration
	91 (16)	Axial compression system demonstrator for 13 k ton/day
	90 (18)	Design very large axial compressors to provide initial stages of compression followed by conventional HP compressors
	48 (25)	Integrated back-pressure steam turbine and CO_2 compressor
	30 (28)	Document duty cycle requirements for reference plant
	11 (31)	Improve reliability of recipe EOR recycle compressors, i.e. valve reliability, lubrication

Table 3.6 Voting Distribution =- Electric Drive Machinery

Category	Total R&D Project Votes (Rank Order)	R&D Project Descriptions
Electric Drive Machinery **Total Category Votes = 545**	165 (5)	Higher voltage, higher power, and speed machines and drives.
	143 (8)	Determine optimal machine types, speeds, needed voltages, etc. for CO_2 compressors
	111 (12)	Tighter integration of compressor, motor and drive components and engineering.
	56 (23)	Improve drive electronics • higher fundamental frequencies for high speed machines, improved controls, and bandwidth to provide low torque ripple
	45 (26)	Advanced Stator and Rotor cooling schemes
	15 (28)	Improve materials for high speed rotors and advanced design tools
	10 (32)	Advanced Stator and Rotor materials to handle corrosive gases

Table 3.7 Voting Distribution - Pipeline Issues

Category	Total R&D Project Votes (Rank Order)	R&D Project Descriptions
Pipeline Issues	150 (7)	Install test coupons in existing CO_2 pipelines to obtain corrosion data, then develop CO_2 product specifications including H_2O, O_2, NH_3, TEG, Amines
Total Category Vote - 456	120 (9)	Establish allowable levels of contaminants in CO_2 pipeline and/or compressors
	111 (12)	Perform optimization of pipeline booster stations. Station spacing, liquid vs. gas, driver selection

	75 (22)	Perform further corrosion studies on the effects of moisture on pipeline corrosion

Table 3.8 Voting Distribution - Drive Electronics and Components

Category	Total R&D Project Votes (Rank Order)	R&D Project Descriptions
Drive Electronics and Components **Total Category Votes= 326**	108 (14)	Development of SiC components and inverter modules for cost effective variable speed drive and cost effective electrically driven compressors • Manufacturing and cost reduction for SiC power modules • Determine and develop optimal device type for CO_2 compression application
	88 (19)	Integration of CO_2 compression electric drive with power plant electrical system
	55 (24)	Development and demonstration of high voltage, high frequency motor drives
	45 (26)	Integration of pipeline pumping station motor drive with electrical grid
	25 (29)	High frequency transformer magnetic materials: nano-crystalline magnetic materials
	5 (33)	High voltage, high current module packaging • Better thermal performance • Better reliability

Table 3.9 Voting Distribution - Effects of Legislation on CCS

Category	Total R&D Project Votes (Rank Order)	R&D Project Descriptions
Effects of legislation on CCS **Total Category Votes = 43**	43 (27)	Determine practical effects of new legislation on CCS (after new legislation is in place)

4. List of Workshop Presentations

Phil Amick, ConocoPhillips; ***Gasification Project Outlook***

Peter Baldwin, RamGen; ***Ramgen Power Systems***

Hans Axel Bratfos, DNV; ***Risk Aspects Related to Pipeline Transmission of CO_2***

Ray Hattenbach, Blue Source LLC***; Future Market Drivers for CO_2 Compression*** *Equipment*

Carl Hustad, CO_2 Global; ***CO_2 Compression for Advanced Oxy-Fuel Cycles***

Joy Kadnar, US Department of Transportation; ***CO_2 Transportation Via Pipelines***

Kevin Kisor, MAN Turbo; ***Centrifugal Compressors for High Pressure CO_2 Applications***

Dan Kubek, Gas Processing Solutions; ***Large CO_2 Sources and Capture Systems***

Kenneth Kullinger, ABB; ***High-megawatt Electric Drive Motors***

Vello Kuuskraa, Advanced Resources International; ***Summary of Results from the EPRI Workshop on Costs of CO_2 Storage and Transportation***

Jim Maddocks, Gas Liquids Engineering; ***Gas Processing***

Harry Miller, Dresser Rand; ***Carbon Dioxide Compression***

Marco Minotti, GE; ***CO_2 Compression Capabilities***

Jeff Moore, SwRI; ***Research and Development Needs for Advanced Compression of Large Volumes of Carbon Dioxide***

Steve Moran, Converteam; ***Multi-megawatt Motor Drive Technology Electronics***

John Palmour, Cree; ***Future High-Voltage Silicon Carbide Power Devices***

Ravi Raju (for Konrad Weeber), GE Research***; Advanced Electric Machines Technology***

Ron Schoff, EPRI; ***Introduction of Large Power Plants with CO_2 Capture and Compression***

Ljubisa Stevanovic, GE Energy; ***Advanced Electronic Components for High Speed, High-megawatt Drives***

Richard Zhang, GE Oil and Gas; ***High-megawatt Electric Drive Applications in Oil and Gas***

5. Appendices

5a. Workshop Agenda

Workshop on Future Large CO2 Compression Systems

Sponsored by
DOE Office of Clean Energy Systems, EPRI, and NIST

Dates
March 30-31, 2009

March 30, 2009

- **Future Market Outlook for CO_2 Compression and Sequestration**
- **Existing Industry Experience with CO_2 Compression**
- **Approaches to Improve Cost, Efficiency, Availability, and Safety**

March 31, 2009

- **Advanced Compressor Machinery R&D Needs**
- **Advanced Electric Drive Technology R&D Needs**
- **Identify and Prioritize R&D Needed for Future CO_2 Compressors**

Time	Topics
	First Day (March 30)
8 AM	Registration and Breakfast
8:30 AM	1.0 Opening Welcome • Introduction of Participants, Opening Remarks Al Hefner, NIST; Pete Rozelle, DOE; Rob Steele, EPRI 1.1 Review of Workshop Objectives • Ron Wolk 1.2 Keynote Speakers • Future Market Drivers for CO_2 Compression Equipment; Ray Hattenbach, Blue Source LLC • Introduction of Large Power Plants with CO_2 Capture and Compression; Ron Schoff, EPRI
10:00 AM	Break
10:20 AM	2.0 Oil and Gas Industry Experience with CO_2 Compressors and Pipelines • Joy Kadnar, US Department of Transportation; CO_2 Transportation Via Pipelines • Hans Axel Bratfos, DNV; Risk Aspects Related to Pipeline Transmission of CO_2 • Dan Kubek, Gas Processing Solutions; Large CO_2 Sources and Capture Systems • Vello Kuuskraa, Advanced Resources International; Summary of

	Results from the EPRI Workshop on Costs of CO_2 Storage and Transportation 2.1 Panel Discussion • Jim Maddocks, Gas Liquids Engineering • Phil Amick, ConocoPhillips
12:15 PM	Lunch
1:15 PM	3.0 Compressor Vendor Perspective on Changes in Compression Cycle, Machinery, and CO_2 Capture System to Increase Energy Efficiency • Harry Miller, Dresser Rand; Dresser-Rand Centrifugal and Reciprocating Compressor Technology and Experience with CO_2 Compression Applications. • Kevin Kisor, MAN Turbo; Compressors for High Pressure CO_2 Applications • Marco Minotti, GE; CO_2 Compression Capabilities
3 PM	Break
3:30 PM	4.0 Electric Drive Compressor Potential for Improvement in Capitol Cost, Power Requirements, Availability, and Safety • Richard Zhang, GE Oil and Gas; High-megawatt Electric Drive Applications in Oil and Gas • Kenneth Kullinger, ABB; High-megawatt Electric Drive Motors • Steve Moran, Converteam; High-megawatt Motor Drive Electronics
5 PM	Adjourn
6:30 PM	EPRI-Hosted Workshop Dinner
	<u>Second Day (March 31)</u>
8 AM	Breakfast
8:30 AM	5.0 Review Workshop Charge to Identify and Prioritize R&D for Future CO2 Compression Systems • Ron Wolk
8:40 AM	6.0 Advanced Compressor Machinery Future R&D Needs • Jeff Moore, SwRI; Research and Development Needs for Advanced Compression of Large Volumes of Carbon Dioxide • Carl Hustad, CO_2 Global; CO_2 Compression for Advanced Oxy-Fuel Cycles • Peter Baldwin, RamGen; Ramgen Overview and Status Update
10 AM	Break
10:30 AM	7.0 Advanced Electric Drive Compressor Future R&D Needs • Ravi Raju for Konrad Weeber, GE Research; Advanced PM and Synchronous Machine Technology • Ljubisa Stevanovic, GE Energy; Advanced Electronic Components for High Speed, High-megawatt Drives • John Palmour, Cree; Future High-Voltage SiC Power Device Manufacturing Technology

Noon	**Lunch**
1 PM	**8.0 Compilation of Potential R&D Areas** **Workshop Participants, (Ron Wolk, Facilitator)** • **Capture and Compression System Modifications** • **Potential Compressor Machinery Improvements** • **Potential Electric Drive Compressor Developments** • **Potential Improvements in High Power Electronics**
2:00 PM	**R&D Prioritization Exercise** **Workshop Participants, (Ron Wolk, Facilitator)**
3:00 PM	**Adjourn**

5b. Workshop Participants

Last Name	**First Name**	**Company**	**E-mail**
Agarwal	Anant	Cree Inc.	Anant_Agarwal@cree.com
Alsup	Charles (Chuck)	DOE/NETL	calsup@netl.doe.gov
Altpeter	Paul D.	Air Products and Chemicals	altpetpd@airproducts.com
Ames	Robin	NETL - DOE	Robin.Ames@NETL.DOE.GOV
Amick	Phil	Conoco-Phillips	Phil.Amick@ConocoPhillips.com
Anderson	Malcolm	Southern California Edison	malcolm.anderson@sce.com
Baldwin	Peter	Ramgen Power Systems	pete_baldwin@ramgen.com
Beermann-Curtin	Sharon	DARPA	Sharon.Beermann-curtin@darpa.mil
Behnke	Paul W.	Bechtel	PWBEHNKE@BECHTEL.COM
Bender	William	Technology & Management Services	wbender@tms-hq.com
Biondo	Sam	DOE Headquarters	SAMUEL.BIONDO@HQ.DOE.GOV
Boal	Charles	Elliott Company	cboal@elliott-turbo.com
Bower	Richard D. (Rick)	Alter NRG Corp.	rbower@alternrg.ca
Bratfos	Hans Axel	Det Norske Veritas (DNV) Energy	hans.axel.bratfos@dnv.com
Brent	Richard	Solar Turbines	cochraham_nicole@solarturbines.com
Brostmeyer	Joseph	Florida Turbine Technologies	jbrostmeyer@fttinc.com
Brown	Barry	Florida Turbine Technologies	bbrown@fttinc.com
Bygrave	Jonathan W.	Rolls-Royce Energy Systems, Inc.	jonathan.bygrave@rolls-royce.com
Colangelo	Mike	A.O. Smith	Mike.Colangelo@AOSEPC.COM
Davis	Gary	Elliott Company	gdavis@elliott-turbo.com
Dennis	Richard	US DOE - NETL	Richard.dennis@netl.doe.gov
Ericsen	Terry	ONR	ericset@onr.navy.mil
Faller	Wolfgang	Solar Turbines, Inc.	Faller_Wolfgang@solarturbines.com
Feier	Ioan	Battelle Memorial Institute	feieri@battelle.org
Gaspar	Jeff	Converteam	jeffrey.gaspar@converteam.com
Hannon	Cesar	ALSTOM Power - Environmental Control Systems	cesar.hannon@power.alstom.com
Hattenbach	Ray P	Blue Source LLC	rhattenbach@bluesource.com
Hefner	Allen	NIST	allen.hefner@nist.gov
Hoffman	James	DOE/NETL	jhoffman@netl.doe.gov
Hood	Colleen	NIST	colleen.hood@nist.gov
Hoover	Ron	Southern California Edison	Ronald.hoover@sce.com
Hopkinson	David	DOE	david.hopkinson@hq.doe.gov
Horiba	Junichi	Mitsubishi Heavy Industries America, Inc.	junichi_horiba@mhiahq.com
Huntington	Richard	ExxonMobil Research & Engineering Co.	Richard.huntington@exxonmobil.com
Hustad	Carl-W.	CO2-Global	cwh@co2-global.com
Jones	Russell	Florida Turbine Technologies	rjones@fttinc.com
Kadnar	Joy O.	U.S Department of Transportation	Joy.kadnar@dot.gov

Kerth	Jason	Dresser-Rand	Jkerth@dresser-rand.com
Kindt	Jack T.	Air Products and Chemicals	kindtjt@airproducts.com
Kisor	Kevin W.	MAN Turbo Inc. USA	Kevin.Kisor@manturbo-us.com
Kubek	Dan	Gas Processing Solutions LLC	dan.kubek@sbcglobal.net
Kullinger	Kenneth	ABB	Kenneth.kullinger@se.abb.com
Kuuskraa	Vello A.	Advanced Resources International, Inc.	vkuuskraa@adv-res.com
Lai	Jason	Virginia Tech	laijs@vt.edu
Le	Patrick H.	US DOE/NETL	ple@netl.doe.gov
Ludwiczak	Christian	E.ON Ruhrgas AG	Christian.ludwiczak@eon-ruhrgas.com
Maddocks	Jim	Gas Liquids Engineering Ltd.	jmaddocks@gasliquids.com
Miller	Harry F.	Dresser-Rand	hmiller@dresser-rand.com
Minotti	Marco	GE Oil & Gas	Marco.minotti@ge.com
Moore	Jeff	Southwest Research Institute	jeff.moore@swri.org
Moran	Steven	Converteam Naval Systems	steven.moran@converteam-navsys.com
Muraskin	David	Alstom Power	David.j,Muraskin@power.alstom.com
Olliver	Richard A.	CH2M Hill	rolliver@ch2m.com
Omatick	Todd	Elliott Company	tomatick@elliott-turbo.com
Palmour	John	Cree, Inc.	john_palmour@cree.com
Peralta-Solorio	David	E.ON Engineering Ltd.	David/peralta-solorio@eon-engineeringuk.com
Pollard	Alicia	Elliott Company	apollard@elliott-turbo.com
Quedenfeld	Heather	U. S. DOE	heather.quedenfeld@netl.doe.gov
Raines	Tom	Alstom Power Environmental Control Systems	thomas.s.raines@power.alstom.com
Raju	Ravisekhar(Ravi)	General Electric Company	raju@crd.ge.com
Royal	John	Praxair Inc.	John_royal@praxair.com
Rozelle	Peter	DOE Headquarters	peter.rozelle@hq.doe.gov
Sadok	Richard D.	ConocoPhillips	Richard.D.Sadok@Conocophillips.com
Schoff	Ronald L.	Electric Power Research Institute	rschoff@epri.com
Shaffer	Ron	Curtiss-Wright EMD	Rshaffer2@curtisswright.com
Shelton	Walter W.	U.S. DOE / NETL/ OSAP	Walter.Shelton@NETL.DOE.GOV
Soghomonian	Dr. Zareh	BMT Syntek Technologies	zsoghomonian@bmtsyntek.com
Steele	Rob	EPRI	rsteele@epri.com
Stevanovic	Ljubisa	GE Global Research Center	stevanov@crd.ge.com
Temofonte	Peter	Turblex, a Siemens Company	peter.temofonte@siemens.com
Tipsword	Robert	Core Energy, LLC	btipsword@coreenergyllc.com
Wadas	Brian	G E Oil & Gas	brian.wadas@ge.com
Wen	Harvey	Bechtel Power Corp	hwen@bechtel.com
Wheeler	Emily	DOE	Emily.wheeler@hq.doe.gov
Williams	Ben	Ariel Corporation	bwilliams@arielcorp.com
Wolk	Ronald H.	Wolk Integrated Technical Services	ronwolk@aol.com
Worst	Jeff	Curtiss-Wright	jworst@curtisswright.com

Wung	Dr. Peter	A. O. Smith Electrical Products Company	Peter.wung@aosepc.com
Zgrabik	Larry	ABB Inc.	larry.l.zgrabik@us.abb.com
Zhang	Richard	GE Oil & Gas	zhangr@ge.com