PUMPING & COMPRESSION OF CO2 – A TUTORIAL
RON ADAMS - SULZER PUMPS
HARRY MILLER - DRESSER-RAND
Contents – Pumping of CO2

• CO$_2$ Value Chain and Scrubbing Methods

• Is it a Pump or Compressor application ??

• Super Critical CO$_2$ Pump Applications
  – Experiences, Thermodynamics, Rotor Construction, Mechanical Seals

• Recent CO2 Pump application pictures

• Harry Miller will then cover CO2 compression

• Final Exam
**CO₂ Emissions: Sources**

**Fossil fuels** = dominant form of energy utilized in the world (86%) and account for 75% of current anthropogenic CO₂ emissions

CO₂ emissions have probably doubled in last 40 years

**Total emissions** from fossil fuel consumption

24,000 MtCO₂ per year (in 2001)

**Large stationary sources**

(> 0.1 Mt CO₂ per year)

<table>
<thead>
<tr>
<th>Source</th>
<th>MtCO₂ yr⁻¹</th>
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<tbody>
<tr>
<td><strong>Fossil fuels</strong></td>
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<tr>
<td>Power</td>
<td>10,539</td>
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<td>Cement production</td>
<td>932</td>
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<td>Refineries</td>
<td>798</td>
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<td>Iron and steel industry</td>
<td>646</td>
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<tr>
<td>Petrochemical industry</td>
<td>379</td>
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<tr>
<td>Oil and gas processing</td>
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<tr>
<td>Other sources</td>
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<tr>
<td><strong>Biomass</strong></td>
<td></td>
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<tr>
<td>Bioethanol and bioenergy</td>
<td>91</td>
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<tr>
<td><strong>Total</strong></td>
<td>13,466</td>
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</table>

anthropogenic = derived from human activities

Source: IPCC, 2005
Getting Green is Expensive…

- It takes lots and lots of energy to capture CO2 from stacks at power plants, cement kilns, refineries, etc.
- It takes more energy to pipeline CO2 to the point of injection.
- Some people want to just pump it deep under ground or into the ocean bottom and let it sit there.
- A few oil fields lend themselves to tertiary recovery using CO2 as a miscible flood to break more oil loose from the sands.
- CO2 has a surface tension a power of 10 less than propane and a viscosity that is a tiny fraction of the viscosity of water. It penetrates tiny pores or cracks and mixes readily with oils.

Non-metallic Pigs that have been in CO2 pipelines grow to enormous size when removed. Orings can explode when decompressed.
CO₂ Value Chain

**Capture**
- Pre-combustion
- Post-combustion
- Oxyfuel

**Compression / Liquefaction**
- Supercritical fluid or vapor (> 74 bar)
- Last stage after compressor

**Transport**
- Booster pumps for ambient ground temperature

**Injection**
- Pressure needed depends on storage location
  - *Pressure gradient:*
  - ~80 bar/km of depth

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**CO₂ Capture**

**Pressure Boosting**

**Pipelines & Oil Production or CO₂ sequestration**
**CO₂ Capture options**

**Post-Combustion**
- Commercially available in medium scale.
- At present, most expensive, but winner!

**Oxyfuel**
- Most competitive / preferred technology for coal.
- Needs development

**Pre-Combustion**
- Might be competitive.
- IGCC without capture in 5 demo plants
Note 50 MW of compression in cryogenic gas plant on frontend for 190+120 = 310MW electric output. Power to run the Acid Gas Removal Plant power on backend, is not included.
Cost of Plant and kWh estimates for CO2 scrubbing

- Following 2 slides from this presentation

Email: Jared.Ciferno@netl.doe.gov
Phone: 412-386-5862

NETL Energy Analysis Link:
www.netl.doe.gov/energy-analyses

Model Links:
Power Systems Financial Model (PSFM):
Integrated Environmental Control Model (IECM):
www.netl.doe.gov/energy-analyses/technology/html
CO2 Capture – Power Plant Capital Cost increase

Average Total Plant Cost Comparison

Post Combustion CO2 scrubbing could increase plant cost by 75%

Total Plant Capital Cost includes contingencies and engineering fees

Note: Preliminary results as of May 2006.
Final report release Date: May 2007
CO2 Capture – Power Cost Increase

Post Combustion CO2 scrubbing could increase $/kwh by 72%
History: Gas Scrubbing in the Oil Patch

Removing H2S and CO2 from natural gas, has been around a long, long time. Randall (now CBI), Ortloff (now UOP), Ventech, Howe Baker (now CBI), Petrofac, Pritchard (now B&V) were all players in that business. Diagram below from UOP paper.

Feed gas enters absorber at pipeline pressure – for effective contact of amine and feed gas.

![Diagram of Conventional Amine Unit Flow Scheme](image)
Membrane Separation in CO2 Recovery Plants

- Effluent (Oil, Gas, produced water and contaminants) from producing wells or lines enters plant. Liquids are separated out in separators.
- Water vapor, Hydrogen, Helium and CO2 are allowed to pass through membrane.
- dP across membrane is high so it takes energy, and thus is not a likely candidate for scrubbing stack gases.

**Figure 5**: Spiral-Wound Membrane Element
Cryogenic air separation plant

-315 deg. F

-193.2°C
1.33 bara
Cryogenic Gas Plants & Air Separation

- Gas Treating is removal of hydrocarbon liquids and contaminants from natural gas.
- Cold Box separation of butane, propane, ethane, nitrogen is accomplished by cooling the gas to near cryogenic temperatures where the lower vapor pressure components liquefy. Air separation is a similar process.
- Typical pump services are deethanizer, demethanizer and liquid CO2. CO2 & Ethane vapor pressure at -50C (-60 F) is only 6 to 8 Bar (90 to 120 psi). Ethane vapor pressure could be > 150 Bar (600 psia) at 25 deg. C (77 F)
- Pure gas seals with Nitrogen purge won't work at cold temperature because injected gas will get into pump and disrupt NPSHa.
- Once the fluid gets to nearly critical pressure (and typically higher temperature), then a horizontal pump may be used with gas seals.
Post-combustion: CO2 Stack Gas Scrubbing

Solvent circulation

**Absorber**
- $T \sim 40-50°C (105-120°F)$
- $P_{abs} \sim 1$ bar (15 psi)

**Stripper**
- $T \sim 120°C (250°F)$
- $P_{abs} \sim 2$ bar (30 psi)

**Pump: Absorber → Stripper**
- About 15 m (50 feet) of head

**Pump: Stripper → Absorber**
- About 30 m (100 feet) of head

CO2 off the stripper is still warm and low pressure = compressor

Head ~ 15 m
~ 50 Ft
Post-combustion: Pumps requirements

**ANSI B73.1, ISO 5199**

**Single Stage**

500 MW coal power plant (2-3 columns)

CO₂ emission ~2.5 Mt CO₂/year

≈ MEA flow rate: 3 200 m³/h (14 000 GPM)

Possible Pumps: 2 or 3 plus a spare

**Materials:**

CO₂ + Water = Carbonic Acid

300 series SS
## CO₂ Value Chain

<table>
<thead>
<tr>
<th>Capture</th>
<th>Compression / Liquefaction</th>
<th>Transport</th>
<th>Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-combustion</td>
<td>Supercritical fluid or vapor &gt; 74 bara (1080 psia) Last stage after compressor</td>
<td>Booster pumps</td>
<td>Pressure needed depends on storage location</td>
</tr>
<tr>
<td>Post combustion</td>
<td></td>
<td></td>
<td><em>Pressure gradient:</em> ~80 bar/km (1900 psi / mile) of depth</td>
</tr>
<tr>
<td>Oxyfuel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Still at low pressure &amp; ambient temp = compressor</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CO₂ Capture**: Pressure Boosting

- Compression / Liquefaction:
  - Supercritical fluid or vapor
  - > 74 bara (1080 psia)
  - Last stage after compressor

- Transport:
  - Booster pumps

- Injection:
  - Pressure needed depends on storage location

*Pressure gradient*: ~80 bar/km (1900 psi / mile) of depth
Sublimation of an element or compound is a transition from the solid to gas phase with no intermediate liquid stage.
Compression to Supercritical Fluid

injection pressure – 200 to 300 Bar, 2900 to 4500 psia

critical pressure, 75 Bar, 1080 psia

critical temperature, 31 deg. C (88 deg F)

Sublimation of an element or compound is a transition from the solid to gas phase with no intermediate liquid stage.
Pressure – Enthalpy Diagrams

Pressure - Enthalpy Diagrams provide graphical evidence of equation of state values.

3 states: Solid, Liquid, Vapor

For CO2, Colder = more dense

Really cold = dry ice

Warm = vapor (gas)

2 phase dome is demonstration of boiling when heat is added to liquid

Pressures (P)

Dry Ice = Solid

More Dense

Supercritical Fluid

Critical Pressure

Less Dense

Liquid

Vapor

less heat << Colder

Enthalpy (H)

>> more heat Warmer
CO2 Pipelines typically run at supercritical pressure to increase density. That allows a smaller diameter pipeline for same mass flow = lower installed cost.

It also helps keep the line from surging and reduces chance of hydraulic shock.
Constant entropy lines are nearly flat to right of dome

That means there is much temperature rise with little change in pressure

Before the next stage, the gas is intercooled

2\textsuperscript{nd} stage adds more dP and dT

More intercooling

Another stage, intercooling

The compressors at DGC use 8 intercooled stages
Aftercooling and pipeline size

The CO₂ may be aftercooled to reduce its volume.

Temperature is limited by the temperature of the cooling medium (air, water, etc) and the heat exchange effectiveness.

Final CO₂ temperature is seldom lower than 6 deg. C (11 deg F) warmer than the air or water temperature on a particular day.
Supercritical CO₂ Pump Applications

• Super Critical CO₂ Applications
  – Experiences,
  – Thermodynamics,
  – Rotor Construction,
  – Mechanical Seals
Super Critical CO$_2$ Pumping Applications

Once we have scrubbed the CO2 out of the stack gas or other source, we then compress it to pipeline pressures – typically between 100 and 150 Bar (1440 and 1900 psi).

CO2 has very little viscosity and thus is non-lubricating.

Warm CO2 is compressible – more m3/h (GPM) will go into the pump than will come out. Mass flow rate stays the same.

When we compress CO2, it get warmer if we start at ambient temperatures.

That leads us to focus on our

- Experience with CO2
- Understanding of performance on CO2 (Thermodynamics)
- Experience with non-lubricating hydrocarbons
- Pump Rotor construction
- Bearing systems
- Mechanical seals
CO₂ – Early Days in West Texas

- Water floods had been in place for many years and the oil production was declining.
- The first trial CO₂ floods were a few trailers of CO₂ at 0F and 300 psia (-18C and 20 Bara) on an pile of dirt (to make enough NPSH). The CO₂ flowed from the trailers into triplex or quintiplex recip pumps and was injected into the wells.
- Sealing the plungers was a learning curve since the CO₂ flashed and formed dry ice crystals abrading the plunger packing.
- Tandem stuffing boxes with automatic transmission fluid in the secondary packing enhanced plunger packing life.
- The CO₂ bubbled out through the transmission fluid and packing life improved to acceptable months between repair.

In late 1970's and early 1980's CO₂ became the hot topic as oil companies tried to extend the life of the Permian Basin in West Texas (because it helped fund the state university system including TAMU!!)
CO₂ for well fracturing – 1980's

- Each CO₂ trailer had a small vane type pump to pump the liquid CO₂ out of the trailer to refill tanks. They were limited on flow and pressure differential.
- Early trials using single stage centrifugal booster pumps didn't work well because the seals would fail from the dry ice crystals.
- In about 1982, we installed a set of dual lip seals outboard of a single primary seal and filled the cavity between with brake fluid. The CO₂ bubbled out thru the brake fluid. That allowed us to run centrifugal pumps on CO₂ trailers and in larger booster pumping trailers to supply 15 to 20 well fracturing pumping units.
CO₂ – Well Fracturing – 1980's

- It was common to pump 1400 tons of CO₂ into the well with Hydrochloric acid in less than 4 hours – and the frac pressure was over 800 Bar (> 13000 psi).
- Several days before the frac job, a steady stream of trailers brought in the CO₂ and transferred it to large temporary onsite storage tanks.
- The onsite CO₂ storage tanks at -18C (0 F) and 20 Bar (300 psia) saturation point provided suction to the boosters which boosted to about 27 Bar (400 psia). The recip frac pumps made the rest of the dP. Commonly, there were over 15,000 hp (11 MW) in diesel engines running simultaneously around 1 wellhead.
- By the end of the day, the site was clear of people and equipment.

We wore our shirt collars up, not because we were cool, but because the dry ice flakes burned our necks during pump cool-down venting.
CO₂ – Thermodynamics: Pressure Enthalpy diagram

For constant entropy pressure rise, from Ts/Ps, follow constant Entropy line to discharge pressure.
Read density and temperature

Example: Ts/Ps 90°F, 1250 psia / 43 lbm/ft³ to 2500 psia: 47 lbm/ft³, 123°F
(32°C, 86 Bar, 690 kg/m³, to 172 Bar, 50°C, 754 kg/m³)

In the early days, we had to use P-H diagrams and draw lines on them parallel to constant entropy lines.
Equations of State went nuts around critical temperature & pressure.
CO₂ Applications – Thermodynamics

- We start with Ts and Ps from customer. For estimating, we divide the dP by about 4 or 5 and add that increment to Ps.
- We use recognized software for equations of state.
- We assume constant entropy pressure rise to Pd.
- We then average sp.gr. and sp. heat. Sp.Gr. is used to calculate head. Sp. Heat is used to calc dT due to pump inefficiency.

<table>
<thead>
<tr>
<th>Temperature (deg. F)</th>
<th>Pressure (psia)</th>
<th>Density (lbm/ft³)</th>
<th>Enthalpy (Btu/lbm)</th>
<th>Entropy (Btu/lbm-R)</th>
<th>Cv (Btu/lbm-R)</th>
<th>Cp (Btu/lbm-R)</th>
<th>Sound Speed (ft/s)</th>
<th>Comp. Factor</th>
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<td>0.21478</td>
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</tbody>
</table>

A bit more nitrogen or hydrogen in the gas stream will measurably affect discharge temperature and density.
CO₂ Applications – Thermodynamics

- If suction temperature is over 100°F (38°C), sp.gr. is low and sp. heat (Cp) is low. That means it will take much more head (and many more stages or rpm) to achieve dP.

- With low specific heat, temperature rise due to pump inefficiency will be greater (not a major issue but lowers average sp.gr. slightly).

- For pump applications, results from many applications tell us to cool to 80 to 90°F (27 to 32°C) if at all practical to maximize density, reduce # of stages, reduce heat of compression, and Cp

\[
\begin{array}{|c|c|c|}
\hline
90 \text{ deg. F, 1250 psia suction} & \text{avg. Cp} & \text{Avg. Density} & \text{Avg. sp.gr.} \\
\hline
0.714 & 47.303 & 0.759 \\
\hline
100 \text{ deg. F, 1250 psia suction} & \text{avg. Cp} & \text{Avg. Density} & \text{Avg. sp.gr.} \\
\hline
0.799 & 37.941 & 0.609 \\
\hline
110 \text{ deg. F, 1250 psia suction} & \text{avg. Cp} & \text{Avg. Density} & \text{Avg. sp.gr.} \\
\hline
0.739 & 27.945 & 0.449 \\
\hline
115 \text{ deg. F, 1250 psia suction} & \text{avg. Cp} & \text{Avg. Density} & \text{Avg. sp.gr.} \\
\hline
0.637 & 26.046 & 0.418 \\
\hline
\end{array}
\]

NOTE: Cp for 1250 psia at 100°F too close to Tc/Pc; Averaged CP from 90°F and 110°F at 1250 psia

0.759 vs 0.418 = 45% fewer stages
Very High dP CO2 Pump Selection

- Isentropic fluid data at inlet and outlet provides mean density for pump selection
- Pump performance curve is used for input for stage by stage polytropic analysis
- Speed or impeller diameter is then corrected
- Check for inlet temperature increase due to balance line return in suction – especially on lower flow / very high head pumps where efficiency is lower & temperature rise due to inefficiency is greater

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Pressure</th>
<th>SG</th>
</tr>
</thead>
<tbody>
<tr>
<td>95°C, &gt; 500 Bar</td>
<td>203°F, &gt; 7300 psi, SG=0.88</td>
<td></td>
</tr>
<tr>
<td>95°C, &gt; 500 Bar</td>
<td>248°F, &gt; 7300 psi, SG=0.82</td>
<td></td>
</tr>
<tr>
<td>35°C, &lt; 100 Bar</td>
<td>95°F, &lt;1400 psi, SG=0.66</td>
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</tbody>
</table>

Density Change = 24%
Supercritical CO₂ Applications
– Multistage Pump Rotor Construction

- Supercritical CO₂ has the viscosity of a very light hydrocarbon, and low surface tension – it is not a good lubricant
- Design rotor to prevent galling if contact is made during operation
- If within MAWP & Max Suction Pressure limits, API 610 Type BB3 is most common multistage pump type in N. America with center bushing and throttle bushing for rotor axial balance and rotor dynamic stability.
- For higher pressures, use API 610 Type BB5 radial split barrel pumps
  - Inline rotor stack is least expensive, but check rotor dynamics with worn clearances before blindly applying inline stacked rotor. Use Back-to-Back rotor stack if there are any questions on stability with worn clearances.
- Carbon or PEEK are common non-metallic wear parts.

Stationary Non-Metallic Throat Bush, Throttle Bush & Impeller Eye Ring

(1)
Low Lubricity Applications - Light hydrocarbon

- There are hundreds of multistage pumps running on 0.4 to 0.55 sp. gr. (450 to 550 kg/m³) Ethane-Propane Mix and Propane pipeline applications for over 30 years. Wear parts are often non-galling metal against hardened 12% chrome.
- In past 15 years we have successfully applied horizontal split multistage pumps on supercritical ethylene pipelines with 100 bar (1450 psi) suction pressure.
- Sp. Gr. is typically 0.26 to 0.3 (260 to 300 kg/m³) at ambient temperatures.

API 610 Type BB3
Axially Split Multistage

Some of our engineers refer to these as "fog" pumps due to very low specific gravity.
The back-to-back rotor stack in API 610 type BB3 pumps reduces axial thrust load.

That allows a fan cooled ring oil lubricated sleeve radial / ball thrust bearings for simplicity. Pipeliners prefer not having a lube system if the power level and pump design will allow it.

On high energy pumps or inline rotor stack BB5, there maybe no choice but to use hydrodynamic radial and thrust bearings which require a bearing lubrication system.

Sleeve/Pivot Shoe bearings, instrumentation & lube system add $100,000 to $200,000
That leaves the mechanical seals. In 1983, double mechanical seals were used on supercritical CO2 to provide oil to the seal faces (CO2 has very low lubricity at high pressure). A large seal oil system with 30 kW (40 hp) oil pumps was needed to make the high dP and flowrate.

Oddly, the 30 kW (40 hp) oil pumps were needed on CO2 pumps that may have only a 200 kW (250 hp) main driver.

Larger 2.2 MW (3000 hp) CO2 pumps used 95 kW (125 hp) oil pumps.

This gives a general perspective on the size of the seal oil system vs pump size. The 200 liter (50 Gal) oil tank is not shown. The larger pumps had 2280 liter (600 Gal) oil tanks.
API Type BB3 - 4 stage  1984 (seal oil system on next slide)

80 deg F,  
Ps - 2000 psia,  Pd - 2555 psia  
220 to 417 GPM, 1548 Ft,  
1800-3600 rpm using VFD  
250 hp motor, 40 hp seal oil pumps

Seal Oil skid is nearly as large as pump skid

[Photo courtesy of Flowserve]
API Type BB3 - 4 stage 1984 (seal oil system)

High Suction Pressure produced high face loads and high seal oil flow rate. High Pressure CO2 mixes with the seal oil on the seal faces like it does with oil underground. It took a while to figure all that out.

photos courtesy of Flowserve
This pump has a double suction 1st stage impeller. Would we need it if the CO2 was at 1200 psi suction pressure?

Ts = + 9 deg. C ( +48 deg F)
Ps = 50 Bara (730 psia)
Pd = 145 Bara (2100 psia)
160 m3/h, (700 GPM) 1128m (3700 Ft)
3560 rpm, 750 kW (1000 HP) motor
8 stg Wasson Field CO2 - 1983

48 deg F (9 deg C),
Ps - 730 psia, Pd - 2100 psia
700 GPM, 3700 Ft, 3560 rpm
1000 hp motor

50 Bara (730 psia) suction pressure allowed use of small seal oil system

Lube system

Photo courtesy of Flowserve
The 1983 seals with the 2000 psi suction pressure didn't last and there was a steep learning curve on the seal oil system design. CO2 Pumps at Wasson and Seminole had much better luck with lower suction temperature and suction pressure.

Several years later another oil company bought much larger 2.2 MW supercritical CO$_2$ pumps for Rangely, Colorado. Those triple seals were about 460mm (18") long & weighed about 60 kg (130 lbs) each.

In mid 1990's, API 610 Type BB3 6 stage pumps were supplied for supercritical ethylene. They had aluminum impellers and carbon wear parts. Gas seals were installed and the seal leakage rate was reportedly so low that it wouldn't keep the flare lit. There obviously was no seal oil system.

There is no oil system on gas seals so they save many kW (hp)! Be sure to add seal flush flow to 1st stage.
CO₂ Applications – Mechanical Seals

- Since that time more API 610 type BB3 pump with 10 to 12 stages have been applied on supercritical ethylene. They also use gas seals and have been running for many years now.
- In 1993, Mobil converted an old API type BB3 pipeline pump to CO₂ service. The service center converted it to carbon wear parts, beefed up the flanges and installed gas seals. It is still in Sundown, Texas on supercritical CO₂.
- In late 1990's we converted the dual seals in the Salt Creek 12 stage CO₂ injection pumps, to gas seals and deleted the seal oil systems. They are still in service. The oil system was eliminated and seal maintenance reduced measurably.
- Similar gas seal systems have become the norm.
The old seal technology: Cortez CO2 Pipeline pumps

**EXISTING CO2 SEAL TECHNOLOGY 1**

- RADIAL SPLIT WITH DOUBLE BACK TO BACK DESIGN
- HIGH PRESSURE LUBE SYSTEM
- BARRIER FLUID PRESSURIZED 100# ABOVE SUCTION BETWEEN THE TWO MECHANICAL SEALS
- BARRIER FLUID, AUXILIARY PUMP, RESERVOIR, COOLER, FILTER, SUMP

Picture courtesy of Champion Seals
Gas Seal CO₂ installations

Plan 11 Seal Flush to primary seal using supercritical CO₂ with over 100 Bar suction pressure.

Seal friction on primary flashes CO₂ to vapor and it is vented between primary and secondary seal.

Be sure to add 20 GPM x 2 = 40 GPM (9 m³/h) seal flow to rated flow on first stage. Be sure total power includes that wasted power. Adjust pump efficiency accordingly.
Not all Gas Seals are the same….

- For super critical CO2, seals that work at temperatures less than critical temperature, may not be so successful at higher temperatures.
- Be sure to discuss the application with seal manufacturers.
- Be sure to give them the gas constituents. A little nitrogen and methane can make a big difference in pump and seal performance.
- Be sure to give them the suction temperature range, the suction pressure range, rpm range, and shaft size. All can have an effect on seal selection.
- Be sure to ask them for the required seal flush flow and pressure to each seal. Since most CO2 pumps have 2 seals, add that flow to the rated flow for number of stages needed to achieve the seal flush pressure. Correct pump power accordingly.

New Construction pipeline dirt can destroy seal faces.
Invest in high pressure dual seal flush filters.
One can be cleaned while the other is running.
Supercritical CO₂ Applications

Summary

- Understand the Thermodynamics – Suction pressures in 86-150 Bar (1250 to 2100 psia) at 26-35C (80-90F) are common. Bubble size near critical pressure is microscopic, so Ps excursion down to about 76 Bar (1100 psi) can be tolerated. NPSH is not a consideration since cavitation is impossible above critical pressure.

- In N. America, use BB3 (Axial split Multistage) type if it will handle MAWP & MASP. Otherwise, use radially split Type BB5. On high energy pumps, they may be direct drive, or high speed, BB5 with bearing lube system.

- Due to low lubricity pay attention to Rotor Construction – Avoid lots of stages on inline rotor stack. Specify non-galling metals, Carbon, or PEEK, vs hardened 12% chrome wear parts. 12% Chrome vs 12% Chrome will not work.

- Check rotor dynamics with 2 x clearances and check for acoustic resonances at all speed, temperature and pressure combinations.

- Use liquid or gas seals with a track record. Do not use gas seals with N2 injection on cold /subcritical pressure services as gas will affect NPSH.
Where are we today (2010 – 2011) ?

These large 5 stage API 610 Type BB3 pumps were started in Sept 2010 on supercritical CO2 with suction pressure varying between 100 Bar (1450 psi) and 150 Bar (2100 psi). Pump MAWP is > 210 Bar (3000 psi). Suction temperature is from about 10 to 38 C (50 to 100 F) with associated change in density.

Driver is 1670 kW (2250 HP) and is VFD.

Gas Seals

Curve drawing software included NPSHr curve which is not applicable.

curve courtesy of Sulzer Pumps
Recent CO2 pumps - 2010

W. Texas 2010: 8x10x13 API 610 Type BB3 - 5 stage. 2250 hp, 3600 RPM VFD motor, Quasi Gas seals with plan 11 and secondary vent. SFP filters added after startup – pipeline construction dirt wiped the seals.
Ultra-high pressure CO2 Pumps

CO2 with up to 23 molar % of hydrocarbons
Ps = 300 Bar (4350 psi)
Pd = 540 Bar (7830 psi)
dP = 240 Bar (3480 psi)
Ts = 15 to 40°C
  (60 to 104°F)
2.2 MW (2950 HP)
7600 RPM
VFD utilized for varying density

For pilot project, 4 pumps had to be run in series for low flow of 10 kg/s (79,200 lb/hr) with dP as shown above. For pilot, total train only consumes about 800 kW (1100 hp) at 3600 RPM. At rated flow each pump will consume 2.2 MW at 7600 rpm. Above from Bergamini / Vescovo / Milone paper which was presented here in 2011.

Photo courtesy of GE Oil & Gas

Offshore CO2 reinjection in Brazil, 2010
Safe Harbor Disclosure

Some of the information contained in this document contains "forward-looking statements".

In many cases, you can identify forward-looking statements by terminology such as "may," "will," "should," "expects," "plans," "anticipates," "believes," "estimates," "predicts," "potential," or "continue," or the negative of such terms and other comparable terminology. These forward-looking statements are only predictions and as such inherently included risks and uncertainties. Actual events or results may differ materially as a result of risks facing Dresser-Rand Company (D-R) or actual results differing from the assumptions underlying such statements. These forward-looking statements are made only as of the date of this presentation, and D-R undertakes no obligation to update or revise the forward-looking statements, whether as a result of new information, future events or otherwise. All forward-looking statements are expressly qualified in their entirety by the "Risk Factors" and other cautionary statements included in D-R’s annual, quarterly and special reports, proxy statements and other public filings with the Securities and Exchange Commission and other factors not known to D-R. Your decision to remain and receive the information about to be presented to you shall constitute your unconditional acceptance to the foregoing.
SAFETY Moment…..

Watch Your Step!!!
**Agenda**

- CO2 Compression Applications
- CO2 Compressor Design Considerations
- CO2 Compression Experience
CO₂ Experience

• Dresser-Rand has more than 500 units on carbon dioxide service
  – More than 150 Centrifugal Compressors
  – More than 350 Reciprocating Compressors
• More than 300 of these are on CO₂ injection service
  – Highest pressure over 8000 psia (>550 bar)
CO$_2$ Miscible Flooding - EOR

- CO2 Injection for EOR has a four-fold benefit
  - Lowers viscosity of the oil in place.
  - Provides a measure of pressure drive.
  - Can penetrate more types of rocks better than other enhancing agents.
  - Leaves a cleaner well behind.
- CO2 Injection proven to be one of the most efficient EOR methods since its introduction in the early 1970’s.
CO$_2$ Capture and Storage (CCS)
SLEIPNER CO2 INJECTION COMPRESSOR

First CO2 re-injection project for the purpose of mitigating greenhouse emissions

9 Million TONS CO2 injected

Harald Underbakke  Statoil
Sleipner CO2 Injection

- Objective: Reduce the CO2 cont. from 9% to 2.5% (sale spec.)
- Capture the CO2 by an amine plant
- CO2 storage in an aquifer
- Start up: Aug 1996
- Injection: ~ 1 million tons CO2/yr
- Regularity: 98-99%
**CO₂ Compression and Injection Systems**

- **Suction pressure**: 1 bara
- **Injection pressure**: ~ 65 bara

- **1st stage**: 4 bar / 170 °C
- **2nd stage**: 15 bar / 180 °C
- **3rd stage**: 32 bar / 120 °C
- **4th stage**: 66 bar / 130 °C

Pressure control by cooling (CO₂ density)
COMPRESSOR GENERAL ARRANGEMENT
PLATFORM AND INJECTION MODULE
1st AND 2nd STAGE COMPRESSOR
CO2 Booster Compressor for CO2 Production
CO₂ EOR Recycle Injection - 2000 psi
Gas Properties Evaluation

- Normal evaluation includes the following
  - Comparison of experimental data (PVT) with standard Equation of State (EOS) models
  - Comparison of site specific experimental data with EOS models
  - An EOS model is selected based on vendor and client consensus
- Phase maps are created for each operating condition
  - Review presence of liquids or hydrates
  - Review blow down scenarios for Emergency Shutdown
  - Review gas seal seal inlet conditions
The compressibility factor is used to determine the polytropic head required to compress a gas from a inlet condition to the desired discharge pressure.

\[ \text{Head}_p = ZRT_1 \frac{n}{n-1} \left[ \left( \frac{P_2}{P_1} \right)^{(n-1)/n} - 1 \right] \]

The amount of polytropic head required affects both the power and speed requirements of the compression train.
CO2 Phase Diagram
$\text{CO}_2$ Phase Diagram

Need data
Comparison of Gas Mixture PVT Data to “LKP” and “BWRS” Equations-of-State Prediction of Compressibility Factor “Z”
Shaft End Seals - Dry Gas Seals

- Minimum leakage - approx. 1 scfm
- Requires seal gas supply
  - Normally comes from compressor discharge
  - Alternate supply source is usually required for start-up
- D-R manufactures their own high-quality gas seals
In order to predict compressor performance it is critical to use the proper gas properties.

Extensive Gas Properties testing at South West Research.

Equation of State subject to continuous improvement.

Source: Donnelly and Katz, 1954
550 Bar CO₂ Compressor
Type I curves very close to Type II results
Mechanically stable across entire range
Three (3) different Gas Compositions tested
Max Pressure - 581.4 Bara
World Record Density (Centrif) - 556.2 kg/m^3
Rotordynamic Stability Test Results

<table>
<thead>
<tr>
<th>Discharge Pressure</th>
<th>1st Mode</th>
<th>Rotating Speed</th>
<th>2nd Mode</th>
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<tbody>
<tr>
<td>65 barA</td>
<td></td>
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</tr>
<tr>
<td>156 barA</td>
<td></td>
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<td></td>
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<tr>
<td>319 barA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>526 barA</td>
<td></td>
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</tr>
</tbody>
</table>

- Notice reduction in amplitude
- No evidence of 1st mode
- Even 2nd mode is Minimized
550 Bar CO2 Compressor Trains
Toxic effects of H2S

- 1 PPM Smell
- 10 PPM 8 hr. TWA
- 100 PPM Loss of smell
- 300 PPM Loss of consciousness with time (~ 30 min.)
- 1000 PPM Immediate respiratory arrest, loss of consciousness, followed by death
Challenges with CO$_2$ Compression

- The presence of water together with CO$_2$ creates carbonic acid which is corrosive to carbon steels. The use of stainless steel for any components in contact with wet CO$_2$ eliminates the problem.
- Special O-ring materials required to resist explosive decompression due to entrapped CO$_2$.
- Existing Equations of State and gas properties may not be accurate at very high pressure especially for gas mixtures.
- Very high gas density SCO2 (55 lb/cu.ft. @ 12 ksi) may raise mechanical design technology gaps.
- Very high power density SCO2 may raise material strength issues as compressor and turbine physical size decreases.
Final Exam

- Can we use gas seals with N2 injection on cold CO2 below critical pressure?
- Do we use a pump, or a compressor, on 60°F CO2 at 30 psig?
- What do we use to move CO2 at -70°F at 14.7 psia?
- What is the surface tension of CO2 compared to propane?
- How does one always avoid seal problems on startup?
- No, use a seal isolation system. Gas will kill the NPSHa.
- A compressor as we are on the right side of the dome.
- A truck – its dry ice.
- 10% of the surface tension of propane. Hydrotest with surfactant and air test at low pressure.
- One gets transferred before startup.
Thank you for your attention.

Questions??