CO₂ Dehydration:
Why? How Much? How?

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Never take your eye off the target
Section 1

Who Are We?
Oil & gas EPCM company formed in 1987 – currently employ 250 people

Started acid gas injection early – first project was in 1995

Worked on acid gas projects or provided training in 12 countries outside of Canada, including 6 states in the US

Involved in about 25% of the Alberta acid gas injection projects to date

Published 7 books and over 50 articles and technical papers relevant to acid gas and CO₂ behavior, facility design, and injection operational issues

Patented a novel cost effective acid gas dehydration process
Why ?
How Much ?
How ?
Why Dehydrate?
3 Reasons

Corrosion

Hydrate Formation

Imposed Specs
Corrosion + \text{CO}_2 \quad + \quad \text{H}_2\text{O} \quad = \quad \text{ACID} !
IT IS ALL ABOUT THE CONTAMINANTS

- Carbonic, sulfuric, and nitric acids will form where CO$_2$, SO$_2$, and NO$_x$ are present.
- Excess oxygen allows the corrosion to continue.
- Most likely cause of off-spec water content is carry over of water/glycol from the dehydration process.
- Stainless steel piping alternative is ~4-5 times more expensive than mild steel.

<table>
<thead>
<tr>
<th>Gas Concentration, ppm</th>
<th>Corrosion of Mild Steel, mils/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$_2$</td>
<td>H$_2$S</td>
</tr>
<tr>
<td>8.8</td>
<td>0</td>
</tr>
<tr>
<td>4.3</td>
<td>0</td>
</tr>
<tr>
<td>1.6</td>
<td>0</td>
</tr>
<tr>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td>&lt;0.5</td>
<td>35</td>
</tr>
<tr>
<td>&lt;0.5</td>
<td>150</td>
</tr>
<tr>
<td>&lt;0.5</td>
<td>400</td>
</tr>
</tbody>
</table>

*Temperature 80°F, exposure time 72 hr.
Source: Data of Watkins and Kincheloe (1958) and Watkins and Wright (1953)
**Definition**

A physical combination of water and small molecules producing a crystalline compound having “ice like” appearance but possessing different properties and structure than ice.

**Problem**

At some temperature, above the freezing point of water, the water and acid gas will begin to form a solid called a hydrate.

The Hydrate Formation Temperature and varies according to the pressure, gas composition, and water content of the vapour.

Hydrates cause reduced heat transfer, excess pressure drops, blockages, and safety concerns.
Hydrate Formation

Hydrate Formation Temperature in CO₂ vs. Pressure & Temperature for various Water Content

-87°C
-43°C
-23°C
-1°C
11°C

Pressure, kPa(a)

Temperature, °C

-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140

-12,000
-10,000
-8,000
-6,000
-4,000
-2,000
0
20 ppmV
12 lb/MMscf 250 ppmV
30 lb/MMscf 632 ppmV
75 lb/MMscf 1,580 ppmV
Saturated

Crit Pt
Phase Envelope
**Pipeline Spec**

- CO₂ pipeline operators impose minimum quality requirements for corrosion control and hydrate prevention

- Kinder Morgan CO₂ Pipeline Spec (June 5, 2008)

<table>
<thead>
<tr>
<th>Component</th>
<th>Standard</th>
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</thead>
<tbody>
<tr>
<td>Purity</td>
<td>95% mole percent of Carbon Dioxide</td>
</tr>
<tr>
<td>Water</td>
<td>no free water, not more than thirty (30) pounds of water per MMscf in the vapor phase</td>
</tr>
<tr>
<td>Oxygen</td>
<td>not more than ten (10) parts per million, by weight, of oxygen</td>
</tr>
<tr>
<td>Hydrogen Sulfide</td>
<td>not more than twenty (20) parts per million, by weight, of hydrogen sulfide</td>
</tr>
<tr>
<td>Total Sulfur</td>
<td>not more than thirty-five (35) parts per million, by weight, of total sulfur</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>not more than four mole percent (4%) of nitrogen</td>
</tr>
<tr>
<td>Temperature</td>
<td>not exceed a temperature of 120°F</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>not more than five mole percent (5%) of hydrocarbons; dew point not higher than -20°F</td>
</tr>
<tr>
<td>Other</td>
<td>not contain more than 0.3 (three tenths) gallons of glycol per MMcf and at no time shall such glycol be present in a liquid state at the pressure and temperature conditions of the pipeline</td>
</tr>
</tbody>
</table>
4.8.3 Limitations on water content

“... ensure that no free water may occur at any location in the pipeline within the operational and potential upset envelopes and modes, unless corrosion damage is avoided through material selection.”

- normal operation pressure and temperature envelope
  - safety factor of 2 is recommended
- shut-in pressure combined with minimum ambient temperature
- depressurization scenario
  - water dropout cannot be prevented without very stringent limits

Water content spec needs to be established according to the local transportation conditions

- Piping across the plant site might only require 75 lb/MMscf (1,580 ppmV)
- Above ground piping in Arctic permafrost may require 12 lb/MMscf (252 ppmV)
How Much Dehydration?
Acid Gas Phase Envelopes

Acid Gas Phase Envelopes

Supercritical or 'Dense' Phase

Carbon Dioxide (CO₂)

Hydrogen Sulphide (H₂S)

Nitrogen Dioxide (NO₂)

Sulphur Dioxide (SO₂)

Pressure, kPa(a)

Temperature, °C

Liquid

Vapour

How Much?
How Much?

Water Content - AQUAlibrium

Water Content of H₂S / CO₂ / CH₄ @ 43°C vs. Pressure

- 22,000 ppmᵥ
- 5,000 ppmᵥ
- 1,000 ppmᵥ

Pressure, kPa(a)

Water Content, ppmᵥ @ 15.6°C & 1 atm

100,000
10,000
1,000
100

100%
H₂S
100%
CO₂
100%
CH₄
Water Content - AQUAlibrium

**Water Content in CO₂ vs. Pressure**

- **5,000 ppmᵥ**
- **2,000 ppmᵥ**

**Axes:**
- **Y-axis:** Water Content, ppmᵥ @ 15.6°C & 1 atm
- **X-axis:** Pressure, kPa(a)
How to Dehydrate?
Compression
  - Water content in vapour is reduced as pressure is increased

Desiccant
  - Absorption
    - solid – calcium chloride
    - liquid – glycerin, glycols (TEG)
  - Adsorption – gels, alumina, molecular sieve

Refrigeration – thermodynamic phase separation
  - External (closed)
    - A/C, car, refrigerator, arena, gas plant liquids recovery
  - Internal (auto-refrigeration)
    - Choke plant dew point control
    - DexPro™ (patented)

Separation – ‘mechanical’ membrane permeation
Compression

Water Content in CO₂ @ 49°C vs. Pressure

- Stage 1 inlet: 84,200 ppm
- Stage 2 inlet: 37,900 ppm
- Stage 3 inlet: 15,200 ppm
- Stage 4 inlet: 6,500 ppm
- Dehy inlet: 3,480 ppm
- Stage 5 inlet: 630 ppm

Pressure, kPaa

Water Content, ppm
Absorption

Simplified process overview - glycol

- CO₂ flows from the bottom up through a contactor
- ‘dry’ glycol flows from the top down through the contactor
- glycol absorbs water from the CO₂ as it flows through the glycol
- water, and other absorbed contaminants, are boiled out of the ‘wet’ glycol in a reboiler
- ‘dry’ glycol is recycled back to the contactor
Absorption
Simplified process description - Molecular Sieve

- ‘wet’ CO₂ is dehydrated in one tower while the other tower is regenerating.
- Gas is heated up to 315 degC and reversed to regenerate the tower.
Adsorption
Simplified process description

- **Condenser**
  - refrigerant is condensed to liquid

- **Expansion**
  - liquid refrigerant is expanded across a JT valve to desired temperature

- **Evaporator (chiller)**
  - cold refrigerant absorbs heat from CO₂ and evaporates refrigerant

- **Compressor**
  - refrigerant vapour is recompressed to desired cycle pressure and returned to condenser
Simplified process description - DexPro™

- **TCV or JTV (Joule-Thomson Valve)**
  - Cools a small slip stream of Dry acid gas by reducing the pressure (expansion)

- **DexPro™ Module**
  - Cold Dry Acid Gas mixes with Wet acid gas in the DexPro Module

- **Stage 5 Suction Scrubber/Compressor/Cooler**
  - Condensed water from the DexPro Module is removed in suction scrubber
  - Cool Dry acid gas increases fluid compression efficiency
DexPro™

How?
DexPro™
How do they Compare?
Glycol & Molecular Sieve Dehydration – 49°C
Refrigeration & DexPro™ – 49°C

CO₂ Phase Envelope / Compression / Dehydration / Hydrate - 49°C

- Critical Point
- Phase
- Stage 1
- Stage 2
- Stage 3
- Stage 4
- Stage 5
- Pipeline
- Hydrate (30 lb)
- Hydrate (no dehy)

Stage 4
130°C @ 3,910 kPaa
Compressor Performance vs. Inlet Temperature

Compressor Power vs. Inlet Temperature

- 23.5% Power Reduction at 13°C
- 1,000 tonne/day CO₂
- Pᵢₙ = 4 MPa(a)  Pₒᵤₙ = 12 MPa(a)
- Compressor Efficiency = 100%

% Power Reduction (compared to 50 deg C)

Compressor Power, kW

Inlet Temperature, deg C
Example Case

- 1,000 tonne/day → 538,300 Sm³/d of dry CO₂
- water saturated at 48°C @ 40 kPa(g)
- pipeline inlet design pressure → 13,800 kPa(g)
- 4 compression (centrifugal) stages
- inter-stage / after-cooling between compressor stages
  - 40°C process (CO₂)
- 632 ppmᵥ dehydration requirement (30 lb/MMscf)
  - ~-20°C hydrate formation temperature
<table>
<thead>
<tr>
<th>Process</th>
<th>Horsepower</th>
<th>Cooling</th>
<th>Regeneration</th>
<th>Still Vent</th>
<th>TEG losses</th>
<th>MeOH losses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Com</strong></td>
<td><strong>Horsep</strong></td>
<td><strong>Cooli</strong></td>
<td><strong>Regener</strong></td>
<td><strong>Stil</strong></td>
<td><strong>TEG</strong></td>
<td><strong>MeOH</strong></td>
</tr>
<tr>
<td><strong>Pr</strong></td>
<td><strong>pow</strong></td>
<td><strong>ng</strong></td>
<td><strong>a</strong></td>
<td><strong>h</strong></td>
<td><strong>p</strong></td>
<td><strong>s</strong></td>
</tr>
<tr>
<td><strong>Di</strong></td>
<td><strong>hydration</strong></td>
<td><strong>glycol</strong></td>
<td><strong>external</strong></td>
<td><strong>refrigerat</strong></td>
<td><strong>DexPro</strong></td>
<td><strong>TM</strong></td>
</tr>
<tr>
<td><strong>Comp</strong></td>
<td><strong>ension</strong></td>
<td><strong>main</strong></td>
<td><strong>refrigeration</strong></td>
<td><strong>hp</strong></td>
<td><strong>gas</strong></td>
<td><strong>hp</strong></td>
</tr>
<tr>
<td><strong>Cool</strong></td>
<td><strong>Water</strong></td>
<td><strong>main</strong></td>
<td><strong>condenser</strong></td>
<td><strong>gpm</strong></td>
<td><strong>US</strong></td>
<td><strong>gpm</strong></td>
</tr>
<tr>
<td><strong>Heat</strong></td>
<td><strong>regenera</strong></td>
<td><strong>tor</strong></td>
<td><strong>b</strong></td>
<td><strong>tu</strong></td>
<td><strong>hr</strong></td>
<td><strong>80,257</strong></td>
</tr>
<tr>
<td><strong>Regen</strong></td>
<td><strong>erator Vent</strong></td>
<td><strong>CO</strong></td>
<td><strong>2</strong></td>
<td><strong>t/yr</strong></td>
<td><strong>135.2</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td><strong>t/yr</strong></td>
<td><strong>280.6</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td><strong>Glycol</strong></td>
<td><strong>lb/yr</strong></td>
<td><strong>41.0</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Glycol losses</strong></td>
<td><strong>pipeline</strong></td>
<td><strong>lb/yr</strong></td>
<td><strong>17,788.9</strong></td>
<td></td>
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<tr>
<td><strong>Glycol losses</strong></td>
<td><strong>vent</strong></td>
<td><strong>lb/yr</strong></td>
<td><strong>41.0</strong></td>
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<tr>
<td><strong>Methanol losses</strong></td>
<td><strong>pipeline</strong></td>
<td><strong>lb/hr</strong></td>
<td><strong>23.2</strong></td>
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<td></td>
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<tr>
<td><strong>Methanol losses</strong></td>
<td><strong>bbl/d</strong></td>
<td><strong>2.0</strong></td>
<td></td>
<td></td>
<td></td>
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</table>
### Size

<table>
<thead>
<tr>
<th>TEG Dehy</th>
<th>Weight</th>
<th>DexPro™</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>30&quot; Contactor</td>
<td>6,500 kg</td>
<td>DexPro™ Module</td>
<td>350 kg</td>
</tr>
<tr>
<td>Still Column</td>
<td>200 kg</td>
<td>Regulators</td>
<td>10 kg</td>
</tr>
<tr>
<td>Vent</td>
<td>200 kg</td>
<td>Analyzer</td>
<td>75 kg</td>
</tr>
<tr>
<td>Flash Tank</td>
<td>500 kg</td>
<td>Control Panel</td>
<td>65 kg</td>
</tr>
<tr>
<td>Reboiler/Surge</td>
<td>1,000 kg</td>
<td>Pump/motor</td>
<td>50 kg</td>
</tr>
<tr>
<td>Piping</td>
<td>1,450 kg</td>
<td>Frame</td>
<td>75 kg</td>
</tr>
<tr>
<td>Skid</td>
<td>1,700 kg</td>
<td>Instruments</td>
<td>50 kg</td>
</tr>
<tr>
<td>Wiring</td>
<td>200 kg</td>
<td>Wiring</td>
<td>200 kg</td>
</tr>
<tr>
<td>Glycol</td>
<td>3,000 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>miscellaneous</td>
<td>250 kg</td>
<td>miscellaneous</td>
<td>125 kg</td>
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<tr>
<td><strong>Total (kg.)</strong></td>
<td><strong>15,000 kg</strong></td>
<td><strong>Total (kg.)</strong></td>
<td><strong>1,000 kg</strong></td>
</tr>
<tr>
<td>tonne</td>
<td>15.0 tonne</td>
<td>tonne</td>
<td>1.0 tonne</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Size</th>
<th></th>
<th>Size</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>9.2 m.</td>
<td>Height</td>
<td>1.8 m.</td>
</tr>
<tr>
<td>Length</td>
<td>4.3 m.</td>
<td>Length</td>
<td>1.8 m.</td>
</tr>
<tr>
<td>Width</td>
<td>2.4 m.</td>
<td>Width</td>
<td>0.6 m.</td>
</tr>
<tr>
<td>Footprint (m²)</td>
<td>10.3 m²</td>
<td>Footprint (m²)</td>
<td>1.1 m²</td>
</tr>
</tbody>
</table>

**Lowest Weight:** TEG Dehy (15,000 kg)

**Lowest Area:** DexPro™ (1,000 kg)
## Economics

<table>
<thead>
<tr>
<th></th>
<th>Dehydration Capital Cost</th>
<th>Annual Operating Cost</th>
<th>Annual Maintenance Cost</th>
<th>Total Annual Cost</th>
<th>Present Value of Operating Cost</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>installed</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>No Dehydration</td>
<td>$</td>
<td>$ 2,100,000</td>
<td>$ 1,350,000</td>
<td>$ 600,000</td>
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<tr>
<td>Triethylene Glycol</td>
<td>$</td>
<td>$ 2,513,218</td>
<td>$ 2,479,409</td>
<td>$ 2,533,788</td>
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<tr>
<td>External Refrigeration</td>
<td>$</td>
<td>$ 843</td>
<td>$ 50,812</td>
<td>$ 6,000</td>
<td></td>
</tr>
<tr>
<td>DexPro™</td>
<td>$</td>
<td>$ 210,000</td>
<td>$ 135,000</td>
<td>$ 6,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$ 2,502,206</td>
<td>$ 2,724,061</td>
<td>$ 2,665,221</td>
<td>$ 2,539,788</td>
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</tr>
<tr>
<td>Discount rate</td>
<td>7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Term (years)</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Total NPV</td>
<td>$ 26,508,403</td>
<td>$28,858,740</td>
<td>$28,235,388</td>
<td>$26,906,550</td>
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<tr>
<td>Difference</td>
<td>$</td>
<td>$ 4,450,337</td>
<td>$ 3,076,986</td>
<td>$ 998,147</td>
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</tr>
</tbody>
</table>

- Lowest CAPEX
- Lowest OPEX
- Best NPV

*DexPro™ capital cost does not reflect one time license fee*
DexPro™ has a number of key advantages:

- Lowest capital cost (CAPEX)
- Lowest operating cost (OPEX)
- Best economics (NPV)
- No rotating equipment
- Simplicity of process and equipment
- Extreme turndown
- No fugitive emissions or off-gas handling requirement
- Very small environmental footprint
- Very small physical footprint
QUESTIONS?

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