Porthos

CO2 transport and offshore storage from Rotterdam, the Netherlands

Michiel Spits
June 14, 2022
Development of CC(U)S in the Netherlands
Re-use of depleted gas fields

Onshore & offshore pipelines

New compressor station

Re-use of platform
Client contracts have been signed, subsidies have been granted

Air Liquide, Air Products, ExxonMobil, Shell

FEED engineering has been completed

Storage license concept received from Ministry

Succesful decommissioning of complex well

Ready for FID

Dutch govt grants $2.4 billion in subsidies to huge carbon storage project
Look ahead

Current
- Permit procedures
- Technical preparations
- FID deliverables
- European tenders construction compressor station and offshore pipeline

Second half of 2022
- Final Investment Decision (FID)

2023
- Start construction

2024/2025
- System operational

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Goal and System Approach for start-up and operation

**Goal:**
Have a safe and operable system able to transport, inject and maintain CO$_2$ from emitter into storage reservoir.

**Supply:**
- Storage capacity, at least 2.5 Mton CO$_2$/annum
- Transport capacity 360 t/h
- 4 Emitters, supply curve data
- SDE++ criteria (subsidy 15 years)
- CO$_2$ composition

**Storage:**
- P18-2/4/6 Reservoir characteristics
- Constraints: Injectivity, Well Integrity, Geo-mechanical, Near well behaviour, Max. cooling potential reservoir (Thermal effects on formation)
- Function of each reservoir
- Storage Capacity: 37 Mton

**FAS (flow assurance study):**
- Operating Envelope (normal, transients, start-up, depressurisation and shutin)
- Constraints: Thermodynamics (downhole temp > 15°C and wellhead > 0°C @ steady state), JT effects, Cold start-up, Slugging
- CO$_2$ phase behaviour, ref CO$_2$ specification.

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Gas fields have a proven geological containment.

Reservoir pressure is low (20 bar, was >350 bar).

CO2 transport is high pressure, dense mode.

Challenge is pressure drop.

Temperature drops with pressure drop.

Low temperatures in wells and reservoir.

Reservoir pressure will remain lower than (CO2) virgin pressure.

CO2 specification affects phase behaviour.
## Effect of composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Mole basis:</th>
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<tbody>
<tr>
<td>CO₂</td>
<td>≥ 95%</td>
</tr>
<tr>
<td>H₂O</td>
<td>≤ 70 ppm</td>
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<tr>
<td>Sum [H₂+N₂+Ar+CH₄+CO+O₂]</td>
<td>≤ 4%</td>
</tr>
<tr>
<td>H₂</td>
<td>≤ 0.75%</td>
</tr>
<tr>
<td>N₂</td>
<td>≤ 2.4%</td>
</tr>
<tr>
<td>Ar</td>
<td>≤ 0.4%</td>
</tr>
<tr>
<td>CH₄</td>
<td>≤ 1%</td>
</tr>
<tr>
<td>CO</td>
<td>≤ 750 ppm</td>
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<tr>
<td>O₂</td>
<td>≤ 40 ppm</td>
</tr>
<tr>
<td>Total sulfur-containing components (COS, DMS, H₂S, SO₂)</td>
<td>≤ 20 ppm</td>
</tr>
<tr>
<td>H₂S</td>
<td>≤ 5 ppm</td>
</tr>
<tr>
<td>Ethanol</td>
<td>≤ 20 ppm</td>
</tr>
<tr>
<td>Methanol</td>
<td>≤ 620 ppm</td>
</tr>
<tr>
<td>Hydrogen cyanide (HCN)</td>
<td>≤ 2 ppm</td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>≤ 3 ppm</td>
</tr>
<tr>
<td>Total NOₓ</td>
<td>≤ 5 ppm</td>
</tr>
<tr>
<td>Total aliphatic hydrocarbons (C2 to C10)</td>
<td>≤ 1200 ppm (0.12%)</td>
</tr>
<tr>
<td>Total aromatic hydrocarbons (C6 to C10 incl. BTEX)</td>
<td>≤ 0.1 ppm</td>
</tr>
<tr>
<td>Total volatile organic compounds (excl. methanol, ethanol, aldehydes)</td>
<td>≤ 10 ppm</td>
</tr>
<tr>
<td>Total aldehyde components</td>
<td>≤ 10 ppm</td>
</tr>
<tr>
<td>Total amine components</td>
<td>≤ 1 ppm</td>
</tr>
<tr>
<td>Total glycol components</td>
<td>Covered by dewpoint line</td>
</tr>
<tr>
<td>Total carboxylic acid and amide components</td>
<td>≤ 1 ppm</td>
</tr>
<tr>
<td>Total phosphorus-containing components</td>
<td>≤ 1 ppm</td>
</tr>
<tr>
<td>Dew point for all liquids (for full composition)</td>
<td>&lt; -10 °C (at 20 bara)</td>
</tr>
</tbody>
</table>

### Porthos

2-phase region

### Table

<table>
<thead>
<tr>
<th>Comp</th>
<th>Pure CO₂</th>
<th>Expected</th>
<th>Max impurities</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>100</td>
<td>99.04</td>
<td>95.45</td>
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<tr>
<td>H₂</td>
<td>0.19</td>
<td>0.75</td>
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<tr>
<td>CH₄</td>
<td>0.14</td>
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<tr>
<td>CO</td>
<td>0.05</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>0.58</td>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>

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Rationale of Warm Injection Philosophy:
What if => Cold injection – bottomhole conditions

Cold injection at low reservoir pressure
Porthos reservoir ~15000 mD.m

- WHT < 0 degC
- Mostly two-phase flow
Rationale of Warm Injection Philosophy: Solving BHT issue – gas phase injection
Rationale of Warm Injection Philosophy: Compared to cold injection above 50 bar

- Above 50 bar BHT problems disappear
- Narrow operating envelope remains issue!

- Top: Porthos operating envelope

- Bottom: operating envelope with cold injection

- Project requirement for Porthos to have continuous flow range between 80 – 360 t/h cannot be met
Operational limits & control philosophy

- **Quality Control CO₂ Composition**
  - Onshore LP pipeline 30 km
  - Bypass mode: F: 0-15 kg/s P: 24-35 bar T: 5-20 °C

- **Supercritical mode**
  - F: 15-100 kg/s P: 80-130 bar T: 40-80 °C

- **Gas mode**
  - F: 0-65 kg/s P: 30-60 bar T: 80 °C
  - Controlling during gas mode, fully open during SC mode, closed during bypass mode

- **Controlling during SC mode**, fully open during gas mode

- **Open during bypass mode**

- **DTS Continuous measurement and monitoring of P&T**

- **Offshore pipeline**: 16" ± 22 km

- **Wellhead**

- **P18 reservoir P: 17 - 340 bar**

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Supply Curve from Emitters to Porthos
Operating the base case:

Injection plan / Operating Envelopes Wells

<table>
<thead>
<tr>
<th>Step</th>
<th>Time (day)</th>
<th>Rate (bbl/day)</th>
<th>Description</th>
<th>Flow rate (MPa)</th>
<th>No. of wells</th>
<th>Wells</th>
<th>Area adjacent (ha)</th>
<th>Area pumped (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>17</td>
<td>First start-up increase to 200 bbl</td>
<td>80</td>
<td>1.3</td>
<td>3</td>
<td>1.66</td>
<td>1.66</td>
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<tr>
<td>2</td>
<td>2</td>
<td>5</td>
<td>Commissioning compressor</td>
<td>60</td>
<td>5</td>
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<td>1.66</td>
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<td>6</td>
<td>Increase flow</td>
<td>40 - 200</td>
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<td>3</td>
<td>1.66</td>
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<td>4</td>
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<td>5</td>
<td>Operative fluid 260 bbl</td>
<td>250</td>
<td>5</td>
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<td>1.66</td>
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<td>9</td>
<td>Operative fluid 260 bbl</td>
<td>200</td>
<td>3</td>
<td>3</td>
<td>1.66</td>
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<td>6</td>
<td>6</td>
<td>15</td>
<td>Maximum 240 bbl</td>
<td>220</td>
<td>3</td>
<td>3</td>
<td>1.66</td>
<td>1.66</td>
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</table>

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Thank you for your attention!

For more information, please visit: www.porthosCO2.nl
Back-Up
Reuse of Facilities

- Life time extension assessment
- Convert to zero emissions platform
- Maintenance philosophy: from break-down to preventive
- Concurrent operations: gas production & CO2 injection
- Change operations & logistics to daylight only and boat access
- Gas price development impacts cease of production dates
Re-use of gas wells

Well integrity
• Cement bond logs reliable?
• Status of casing, liners and conductors
• Annulus pressures

Well Design
• New completions
• Thermal loads and tubing of Cr25
• DTS / DAS monitoring
• Developed SSSV’s for arctic conditions

Well Containment
• Thermal loading: debonding of casing-cement-rock face
• Hydrostatic head/pressure as containment barrier
Closure of gas production wells

Well Abandonment:

• Re-entry of suspended wells

• Complex wells, not designed for re-use or re-entry

• Full bore formation plugs become the standard?

Successful well campaign pre-FID to de-risk the project
Key Technical Aspects

A. Containment
1. from the reservoir laterally
2. from the reservoir vertically
3. from injection wells, during injection
4. from wells after plugging and abandoning

B. Seismicity
5. Fault slippage -> “earthquake”
Storage in depleted fields is new

- Gas fields have a proven geological containment
- Reservoir pressure is low (20 bar, was >350 bar)
- CO₂ transport is high pressure, dense mode
- Challenge is pressure drop
- Temperature drops with pressure drop
- Low temperatures in wells and reservoir
- Reservoir pressure will remain lower than (CO₂) virgin pressure
- CO₂ specification affects phase behaviour
Steady state operation envelopes

- Flow simulations – done by TNO/EBN – lead to a range of allowable well configurations

<table>
<thead>
<tr>
<th>Config</th>
<th>20t/h</th>
<th>40t/h</th>
<th>60t/h</th>
<th>80t/h</th>
<th>100t/h</th>
<th>120t/h</th>
<th>140t/h</th>
<th>160t/h</th>
<th>180t/h</th>
<th>200t/h</th>
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<th>320t/h</th>
<th>340t/h</th>
<th>360t/h</th>
<th>380t/h</th>
<th>400t/h</th>
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</tr>
</tbody>
</table>

- These are translated into injection plan covering full injection period
Hydrate formation in near-wellbore

- Water salinity is estimated at 80,000 – 120,000 ppm NaCl
- This reduces HET (Hydrate Equilibrium Temperature) by 4 degC
  - HET at 50 bar reduces from 10.4 to 6.0 degC
- The minimum temperature in the near-wellbore model was obtained from all runs used for BHP tables

<table>
<thead>
<tr>
<th>Well</th>
<th>k.h [mD.d]</th>
<th>Min T [degC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A1</td>
<td>3150</td>
<td>8.5</td>
</tr>
<tr>
<td>2A3</td>
<td>17426</td>
<td>15</td>
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<td>2A5</td>
<td>22875</td>
<td>14</td>
</tr>
<tr>
<td>4A2</td>
<td>9175</td>
<td>9</td>
</tr>
</tbody>
</table>

- 15 degC injection (BHT) does not result in a hydrate risk for any wells

k.h: product of reservoir permeability and thickness
Flow conditions in well – normal injection (pure CO$_2$)

- In normal operation, platform arrival temperatures are kept high by pipeline insulation
- CO$_2$ arrives at choke in supercritical state
- As it expands to FTHP, conditions drop to the phase line
  - Wellhead temperature is entirely determined by FTHP
  - Phase fraction is determined by the arrival temperature
- As it travels down the well it is heated by the formation
- At high arrival temperature, wellhead liquid fraction is low
  - Liquid CO$_2$ evaporates, until only gas is left BH (see plot)
  - BHT is now not determined by the phase line
- At lower arrival temperature, wellhead liquid fraction is higher
  - Some liquid CO$_2$ remains at bottom hole conditions
  - BHT is determined by the local pressure
- At low reservoir pressure, WHP and BHP are low
  - This can result in unacceptably low temperatures due to the above behaviour
  - The pipeline should not be operated in supercritical mode at low reservoir pressure
Flow conditions in well – cold start-up (pure CO₂)

- OLGA simulations were used to determine at which reservoir pressure dense phase operation is possible
  - Cold start-up: pipeline has cooled to seawater temperature
  - Wellbore temperatures lower than during steady injection
- Simulation shown was done at reservoir pressure of 40 bar
- CO₂ arrives at choke in much colder conditions
- As it expands to FTHP, conditions drop to the phase line
  - Wellhead temperature is entirely determined by FTHP
  - The simulated temperatures do not pose a risk to the annulus fluids
- Liquid fraction is much higher due to lower temperature in pipeline
  - Formation heat influx cannot fully evaporate CO₂
- Bottomhole conditions also lie on the phase boundary
  - BHT dictated by BHP.
  - BHP of 48 bar results in a BHT of 12 °C, below the 15 °C limit for hydrates
- Simulations were repeated at 50 bar reservoir pressure
  - Higher BHP results in acceptable BHT
  - Base operating philosophy is to switch to dense phase injection at 50 bar
Operating & Control Philosophy

- **Operating & Control Philosophy**
  - **Emitters**
  - **Compressor Station**
  - **Platform**
  - **Local Control Room**
    - **Remote Control Room Porthos**
    - **Full Control**

- **Nominations**
- **Info Signals**
- **Control Signals**

- **Control Room**
  - **LP Pipeline**
  - **Compressor Station**
  - **HP Pipeline**
  - **Control Room Platform**

Information for planning of capacities, exchanged 24 hours ahead. In Technical operation phase dictated mainly by Gas field limitations. In Commercial operation phase dictated mainly by emitters.

Instrument signals exchanged for info (not controls), including information when systems have tripped.

Instrument signals exchanged including setpoints and selection of operating modes and opening/closing of valves.

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General Control Strategy

- **Quality Control CO₂ Composition**
- **Supercritical mode**: F: 15-100 kg/s, P: 80-130 bar, T: 40-80°C
  - Controlling during gas mode, fully open during SC mode, closed during bypass mode
- **Gas mode**: F: 0-65 kg/s, P: 30-60 bar, T: 80°C
  - Open during bypass mode
- **Bypass mode**: F: 0-15 kg/s, P: 24-35 bar, T: 5-20°C
- **Offshore LP pipeline**: 30km
- **Compressor bypass line**
- **Onshore/Offshore Pipeline**: 16" ± 22km
- **Wellhead**
- **Continuous measurement and monitoring of P&T**
- **P18 Reservoir**: P: 17 - 340 bar

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What-if scenario’s

1. Emitter delivers off spec CO2
2. Emitter measurement instrument fails (no real time data available)
3. Spec at compressor station does not comply with emitter measurements
4. Pipeline rupture (near Rozenburg)
What-if scenario 1: Emitter delivers off spec CO2

Preventive measures:

- Measurement system emitters according to requirements as defined in Annexes
- Measurement system at Porthos compressor station
- In case of an Outage due to off spec delivery, Customer shall be required to pay to Porthos the full Fees for those Outage hours
- Customer’s liability is limited to EUR 50,000,000 (fifty million euros) (TSC Article 13.3 unlimited liability) per event or series of related events if and to the extent caused by Non-compliant CO2 that has not been accepted by Porthos in accordance with GCFI Article 3 and that has been fed into the Porthos System by Customer (TSA Article 9.4)

Actions:

- If Customer detects Non-compliant CO2 that is labelled as “safeguarding” in Annex B it shall ensure that the CO2 Flow is immediately and automatically discontinued (TSC/GCFI Article 3.2)
- If Customer detects Non-compliant CO2, it shall (i) promptly notify Porthos thereof and include in its notification all relevant information relating to the Non-complaint CO2 (TSC/GCFI Article 3.3)
- Porthos is entitled to discontinue Customer flow
- Porthos shall inform Customer of decision if proceeding supply of CO2 is allowed and under which conditions (TSC/GCFI Article 3.4)
- Customer is only allowed to re-start CO2 supply after Operator has been convinced the off-spec. CO2 is solved
- In case Customer violates agreement more frequently, Porthos is entitled to suspend the performance of the TSA until Customer has demonstrated to Porthos’ satisfaction that it has taken adequate measures to ensure that the chance of such situations reoccurring has been significantly reduced (TSC Article 6.4)
**What-if scenario 2:**
Emitter measurement instrument fails
(no real time data available)

**Preventive measures (TSC/GCFI Article 4 Metering and Measuring terms):**
- Customer shall continuously meter the CO2
- Customer shall comply with provisions w.r.t construction, maintenance, and operation of metering station
- Customer shall comply with the standards and provisions in Annex A, B, C and E, including requirements regarding the use of the Porthos Information Service (or its successor) and the transmission of all (telemetry/metering) data.
- Measurement outage limited to max. five days

**Actions:**

**Flow:**
- Emitter to solve issue asap. Flow monitored and calculated with use of Porthos metering at compressor station

**Quality:**
- Safeguarded components: If measurement is labelled as “safeguarding” (Annex B) it shall ensure that the CO2 Flow is immediately and automatically discontinued (TSC/GCFI, Article 3.2)
- Non-safeguarded components: Flow to continue, compressor station measurement is leading.
What-if scenario 3:
Spec at compressor station does not comply with emitter measurements

**Preventive measures:**
- Strict requirements w.r.t. measurement equipment
- Inspection rights
- Regular calibration/validation requirements

**Actions:**
- Step 1: Observe the different compositions of the customers and the trend of these compositions
- Step 2: Based on the comparison with the CS composition, determine the most likely deviating customer composition (for example, a distinctive peak of one of the components)
- Step 3: In case of risk- consider discontinuing the flow of this customer. Ask for verifications, corrective actions.
What-if scenario 4: Pipeline rupture (near Rozenburg)

Preventive measures:
- The Porthos backbone lies in the pipeline corridor (leidingenstrook) which requires strict supervision of excavation work.
- At the area Rozenburg the pipeline has been built stronger (20%) than in the rest of the route.
- Valve locations have been planned to be able to block the pipe section along Rozenburg in the event of a pipeline incident.
- Pressure sensors are installed and a monitor that closes the block valves when a large pressure drop is detected in the system unexpectedly, e.g. due to a pipe rupture.
- Once the pipeline is in service, there will be continuous monitoring of the operational and structural conditions within the pipeline.
- "Safety and Risks for Porthos CO2 pipeline"- study by DNVGL- risks are negligible.

Actions:
- Pipeline section (Rozenburg) will be blocked in by means of remote operated shut-in valves.
- Inform legal authorities and emitters.
Steady state and blocked-in cooled down

**LP pipeline and compressor station:**
- $\geq 4^\circ$C and $\geq 24\text{bar}$

**HP pipeline:**
- $\geq 0^\circ$C and $\geq 30\text{bar}$

**Platform and wellheads:**
- $\geq -5.8^\circ$C and 10bar
Methanol sensitivity

- The following graphs indicate the composition of the liquid that would knock out and the P & T range where this would occur.

- The graphs show these for the different amounts of methanol (0ppm, 350ppm and 650ppm) at same amount of water (50ppm) and CO2 as the remainder.

Notice that:
- methanol moves the dewpoint lines to the right and up (liquid to start dropping out at higher temperatures and pressures), which means that the water will knock out sooner, when approaching from the gas side.

- Liquid CO2 is also present in the liquid phase (dissolved in the methanol). So it is not purely H2O and methanol.

- The concentration of H2O in the liquid will be less due to the presence of methanol and CO2. At 10bar, this reduces from ~80% (with 0 methanol) to ~ 15% (with 350ppm methanol) to ~6% (with 650ppm methanol).
Methanol sensitivity with 50ppm H₂O (HYSYS SRK Twu)

0ppm MeOH

350ppm MeOH

650ppm MeOH

Liquid vol fraction

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Methanol sensitivity

with 50 ppm H₂O (HYSYS SRK Twu)

0 ppm MeOH

350 ppm MeOH

650 ppm MeOH

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Calc for amount of H2O present from transients

- The rectangles indicate at which pressures some of the transient lines would cross the dewpoint line.
- An example is shown in the next slide for 50ppm and 350ppm MeOH composition. (This has not yet been done for higher amounts.)
• The water fraction x liquid fraction can be used to calculate how much water would be present at certain temperatures and pressures.
• This is shown in the above graph for 50ppm H2O and 350ppm MeOH. Volume fractions are shown because this number can be multiplied by the volume of the pipe to calculate how much water would be present. (Mass flow rate cannot be used when the flow rate is zero, such as during a shut-in case.)
• The transient sims can be used to determine how long the water would be present, but note that in practise it will take longer to boil-off liquids.