Pipeline Transport of CO2 – remaining challenges to be solved

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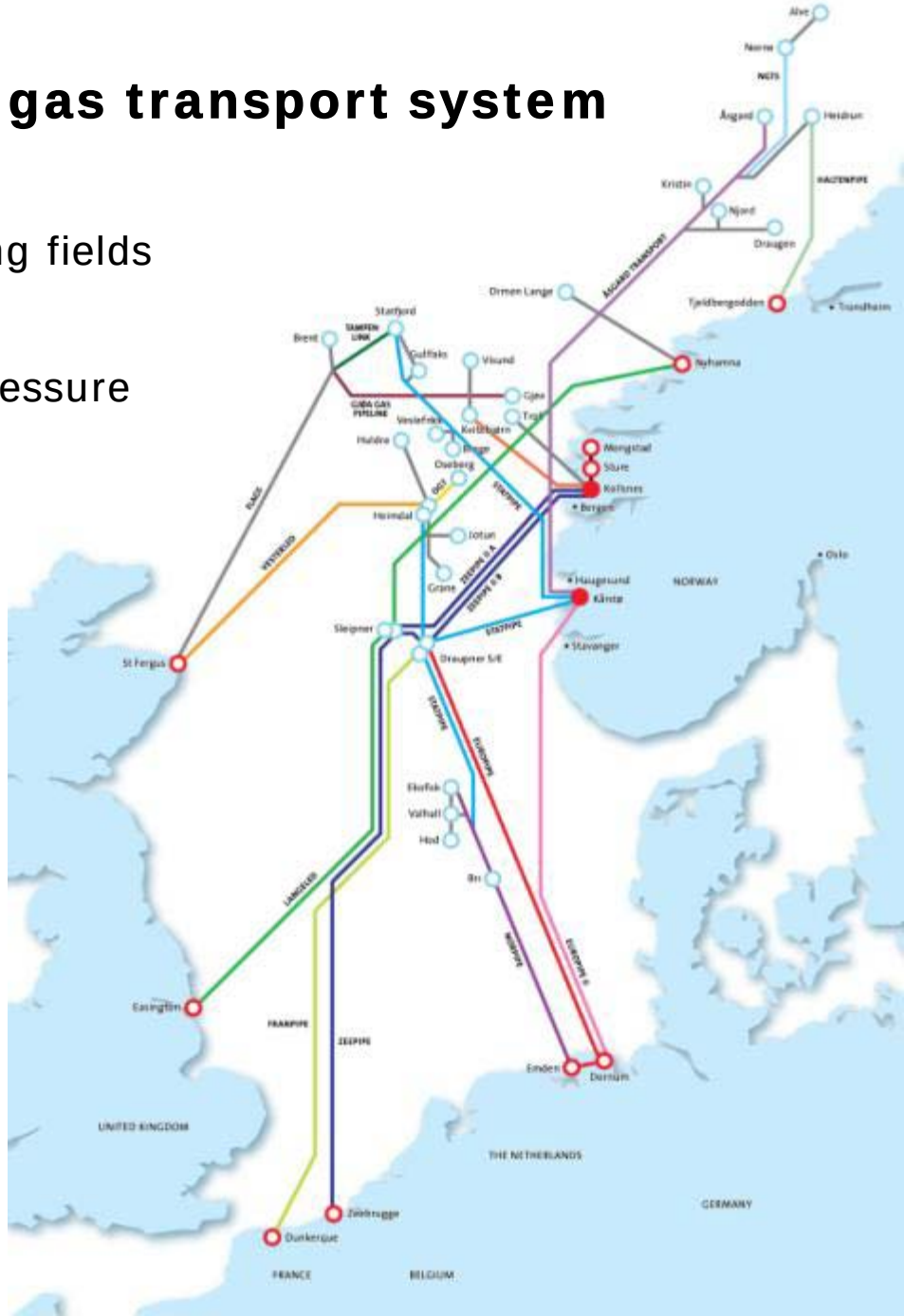
The integrated Norwegian gas transport system

- Connected to all major gas-producing fields on the NCS
- 7 975 km of large-diameter, high-pressure pipelines
- Riser platforms
- Large processing facilities in Norway
- Receiving terminals in four European countries
- Connected to major downstream gas transmission systems in Europe and the UK
- Transports appx 100 bcm of natural gas each year



GASSCO

Gassco and CO_2

- 2006: Gassco, Gassnova and Petoro evaluating potential for use of CO_2 to Enhanced Oil Recovery
- 2007: Project start-up; full scale transport of CO_2 from Kårstø and Mongstad
- 2007: Project for ship based transport of CO_2 to Snøhvit from Technology Centre at Mongstad
- 2009: Gassco evaluating CO_2 capture from the gas processing plant at Kårstø
- 2009: Pre-engineering of CO_2 pipeline from Kårstø (Naturkraft gas fired power plant)
- 2009 →: Preparations for pre-engineering of CO_2 pipeline from Mongstad
- 2009 →: Evaluation of integration between Kårstø gas terminal and Naturkraft gas fired power plant
- 2009 →: Gassco participation in the CO_2Europipe project and ZEP (European Technology Platform for Zero Emission Fossil Fuel Power Plants)
- 2009 →: Start-up of technology qualification program for CO_2 pipeline transport
- … in addition; Gassco is defined through regulations as the gas network "architect" on the Norwegian Continental Shelf, including solutions related to CO_2 challenges in the natural gas

Norwegian CCS initiatives – Full scale CCS projects

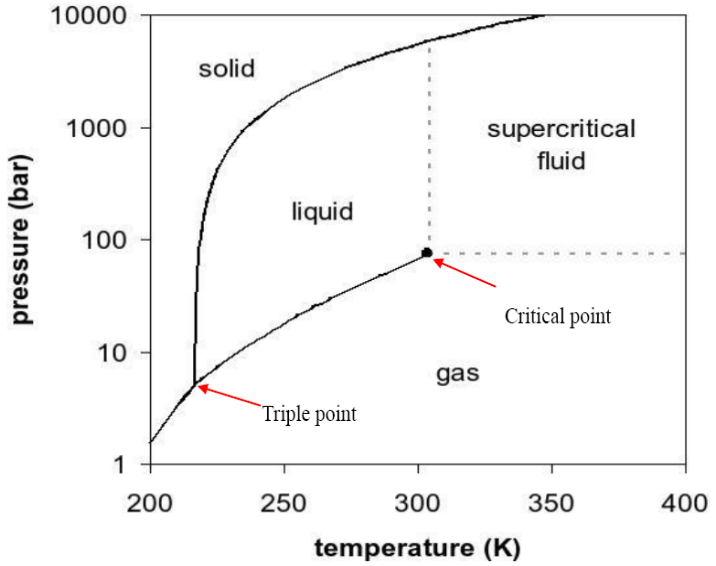
- Mongstad – capture of up to 2.2 Mtonnes CO_2/year
  - From CPH plant and oil refinery process
  - Technology selection based on TCM experiences
- Kårstø – capture of 1.1 Mtonnes CO_2/year
  - From Naturkraft gas fired power plant (430 MW)
- Pipeline transport to the Norwegian Continental Shelf
  for subsea geological storage
  - Several locations evaluated

Transport and storage solution for the Kårstø CCS project


Example; gas fired power plant and CO_2 capture plant
Source: www.gassnova.no

CO2 technology qualification challenges - background

- Pipeline studies found that CO2 pipelines can probably be operated, choosing a very conservative approach
- Potential for great optimization and areas of uncertainty
  → Identified technology gaps that Gassco want to close
- Launched a technology qualification program, with the aim to close the gaps before such a pipeline commences operation
- Funded by Ministry of Petroleum and Energy on an annual basis
- The maturation of the technologies shall follow industry approved methodologies.



Technology gaps:

- Noise – level must comply with regulations
- Dispersion – level must comply with regulations
- Transient behaviour – immature CO2 flow assurance
- Corrosion – CO2 contains H2O and impurities
- Propagating fractures – fracture arrest during decompression
- Soft materials – dissolve in CO2
- Pigging – mostly issues with soft materials

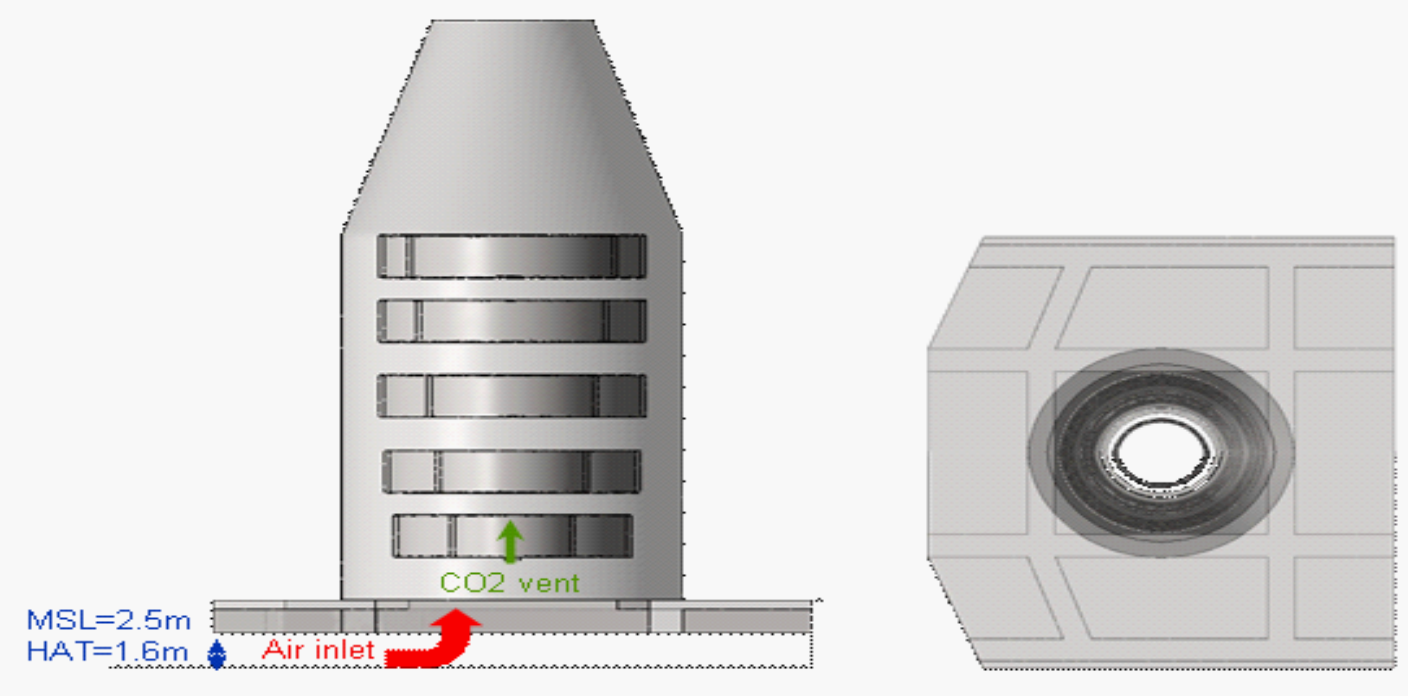
→ Technology qualification in progress

→ To a large extent based on participation in industry initiatives

Noise

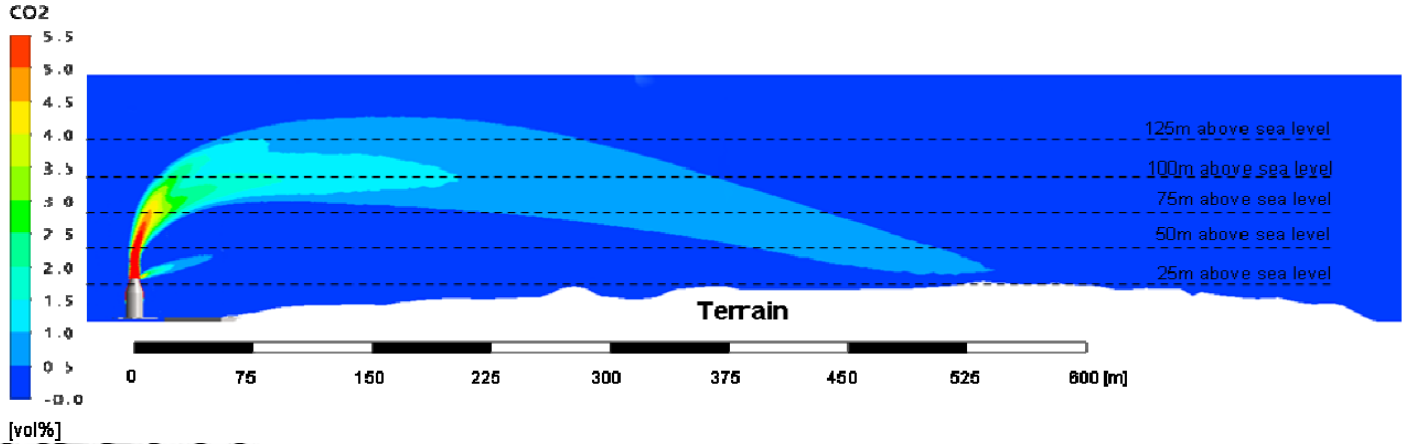
- Blow down of pipeline not part of normal operation
  - Controlled blow-down required during emergency situation,
- Noise levels during blow down can cause hearing damage (appx 170 dBA peak @ 1m)
  - Cold vent → high speeds
  - Shock waves
- Emissions license from KLIF, depending on area classification
  - Eg. Nearest neighbourhood restricted to 45 dB.
  - Absolute and global restriction of 130 dBC peak (causes immediate permanent hearing damage)
  - Not clear what limits that apply
- Noise attenuation is required to avoid evacuation.
- A tower like concrete structure has been suggested and initial simulations are promising.
- The tower will disperse CO2 in such a way that the level of 0,5 vol % is not exceeded.
- DNV is subcontracted to investigate the scalability of the technology.
- A formal TQP for the technology is initiated with DNV.

Noise



Dispersion

- Dispersion from blow down or pipeline rupture is calculated with CFD for Mongstad and Kårstø (DnV)
  - Modelled as a combination of solid and gas phase after vent.
  - Three phase behaviour is not well treated and understood.
- Simulations indicate cloud will not touch ground at concentrations above 0,5 vol %.
- Worst case scenario shows acceptable levels
- Dispersion rate limited by accepted noise levels and temperature of CO2.
- 264 kg/s is simulated for Mongstad case
  - Ok for dispersion, noise exceeds the limit



Dispersion

- Release testing needed to validate models
- Experiements planned by COSHER and CO2PIPETRANS
- Plan to test different modelling tools with the data
- Petrell wants to improve CFD models, simulating all 3 phases

Transient behaviour

- Steady-state conditions handled well with existing simulation software.
- Challenge of CO2 compared with natural gas:
  - Operating close to vapour/liquid eq. line and critical point
  - Discontinuity represents a challenge, phase transitions
- Strong transients are challenging:
  - Blow-down causes low temperatures and two-phase
  - Risk of dry ice formation during pressure relief (in pipeline and out of vent)
- Heat transfer, icing of pipelines during depressurisation.
- Dispersion simulation tools require pipeline conditions upstream release as input – understanding pipeline behaviour close to a release point is key.
- Presence of impurities reduce decompression speed.
- Pipeline simulation tools like OLGA are not properly validated for CO2 need new tools?
- EOS (Equation of state) for CO2 with impurities do not exist.
- Experimental data are required.

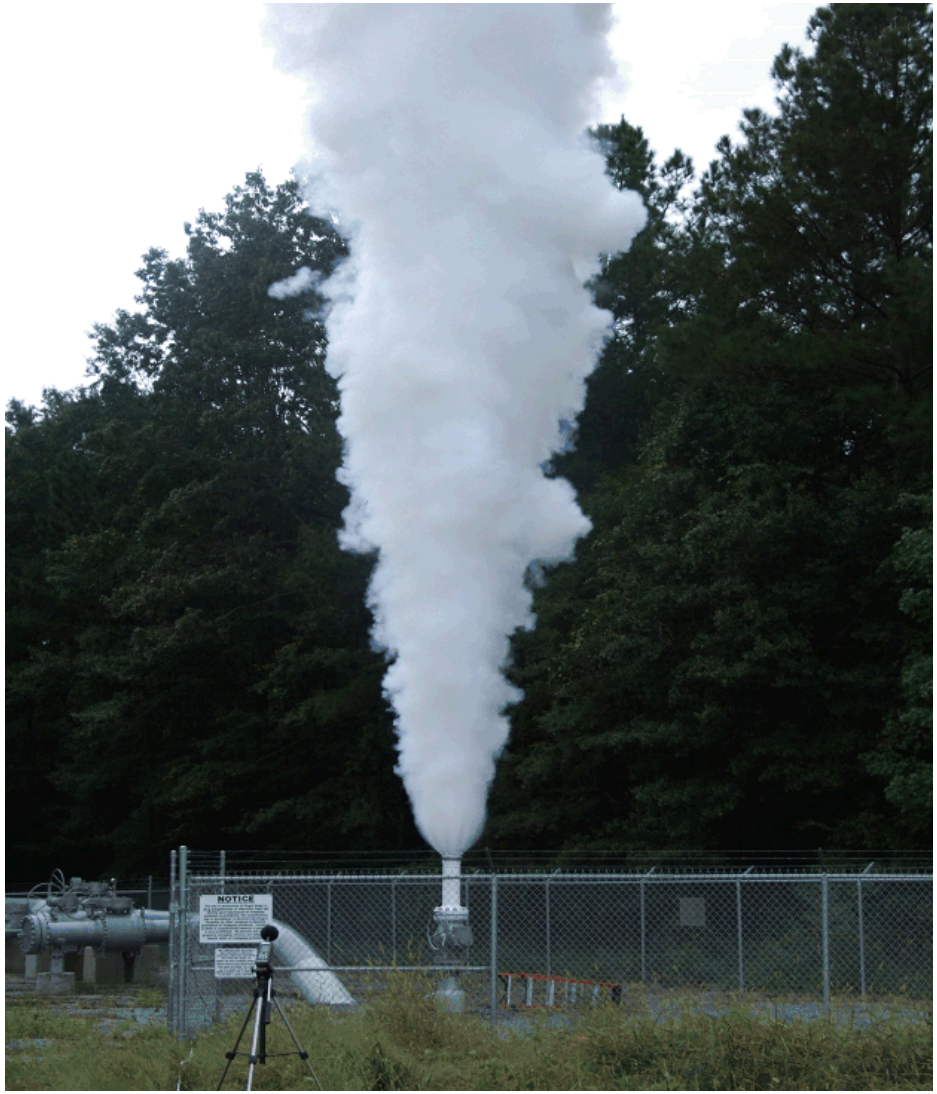
Transient behaviour

- Pressure relief
  - COSHER (KEMA)
  - CO2Pipetrans (DnV)
- Petrell
  - Develop 3D CFD-model, focus on dry ice formation
- CO2Dynamics
  - Equations of state, with different degrees of impurities
  - Pressure wave propagation
- DTU
  - Research on equation of state for CO2 with large degree of impurities

Pressure relief in Denbury

Experiments from Denbury US, exclusive measurements by Gassco

- Pressure relief from a 50 km CO2 pipeline (10,000 tonne/10 hours)
- Measured
  - pressure and temperature at different locations along the pipeline
  - Measured noise and dispersion of the CO2 cloud
- Olga is verified against these measurements
- More details in presentation by S. Clausen.



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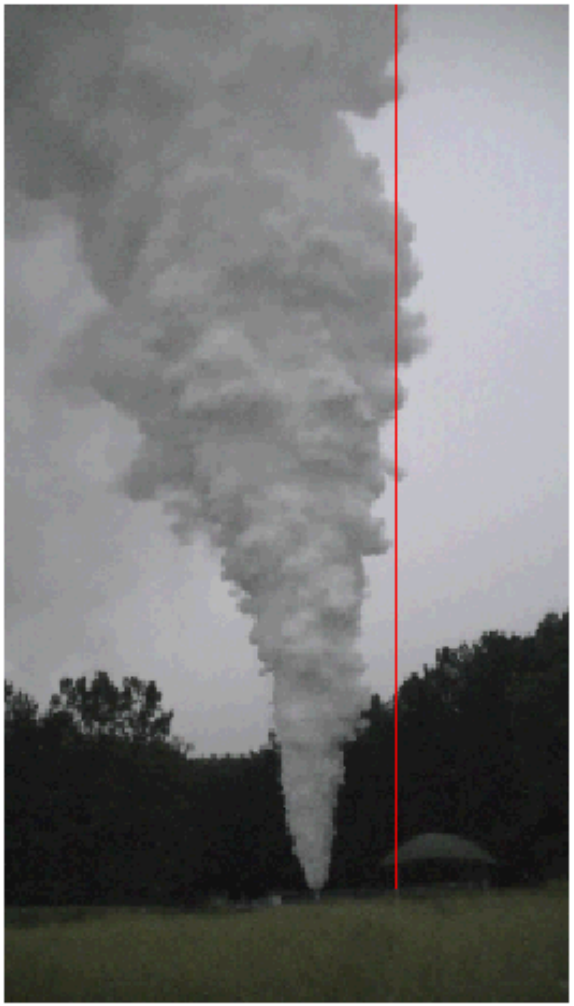
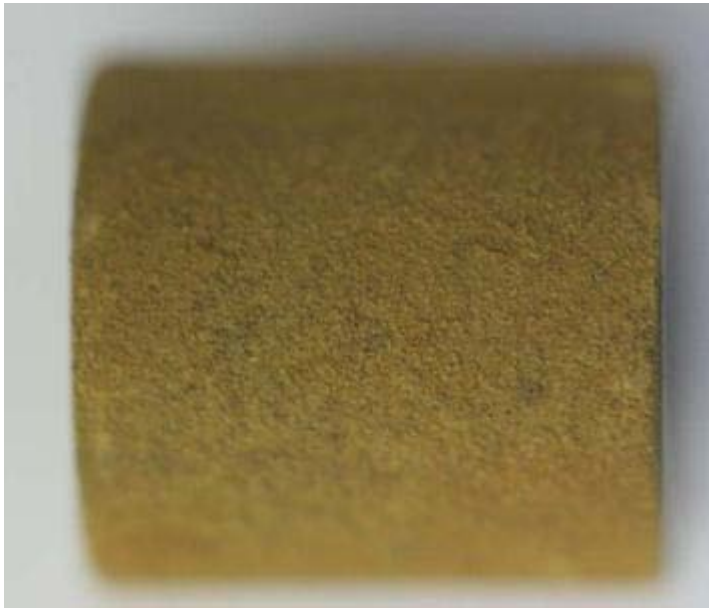


15 minutes after start of relief,
Red line 105 metres high

Corrosion

- CO2 highly corrosive, can threaten the whole pipeline's integrity
- Current Gassco concept is to monitor the water content closely, quickly shut down pipeline in case of excess water. (intermediate section with stainless steel)
- Purity of CO2 is a cost driver at capture plant
- Zero corrosion of carbon steel if there is no water, existing pipelines build using this conservative approach.
- Initial spec was conservative at max 10 ppm O2 and 50 ppm H2O. (solubility of water appx. 1,000 ppm) (based on Snøhvit experience)
- Based on early testing carried out by IFE O2 is increased to 200 ppm and H2O of 100 ppm is allowed for short periods of time (still 50 ppm steady-state) → 2008/2009



Pipeline steel with NOx corrosion product . Source: Doc 55430 Corrosion in dense phase CO2 with small amounts of impurities- phase IV

Corrosion

- Recent experiments: Presence of NOx, SOx, H2S, O2 and MEG/TEG complicates the picture more than anticipated
- Need to understand how different combinations of these components influence corrosion
  - Corrosion rate
  - Localized attacks?
  - Evenly distributed?
- What happens during pressure relief, when two phases occur? Can one of the phases be very corrosive?
- Further tests contracted to Institute for Energy Technology
- Initiate JIP activities with IFE and investigate corrosion control measures. (IFE KDC)
  - Gassco? Statoil? Shell? Total?

Propagating fractures

- Fracture arrest in CO2 may be different from an ideal gas (though not perfectly known in natural gas either)
- Evaluation has shown that fracture arrestors may not be necessary (Kårstø and Mongstad cases). Calculated by DnV, using traditional two curve Battelle test.
- Uncertainty whether propagating fractures is a challenge
- Investigating decompression speed for CO2, PRCI (Pipeline Research Council International).
- Decompression speed strongly related to level of impurities.
- BIGCCS, coupled model of transient fluid behaviour and material fracture
- Large scale tests required to validate the Battelle TCM for CO2.
- Retrofitting fracture arrestors to existing pipelines would make it possible to re-qualify existing pipelines for CO2 service.

Soft materials

- Contact between CO2 and soft materials used in valves, pig trap doors, pigs, flanges, instruments and internal flow coating.
- Soft materials are swelling because of presence of CO2 (penetration of CO2) and/or Chemical reaction
- Degradation by rapid gas decompression (RGD) explosive decompression and swelling.
- It should be possible to produce grades resistant to CO2, but there is a lack of tested and qualified products on the market.

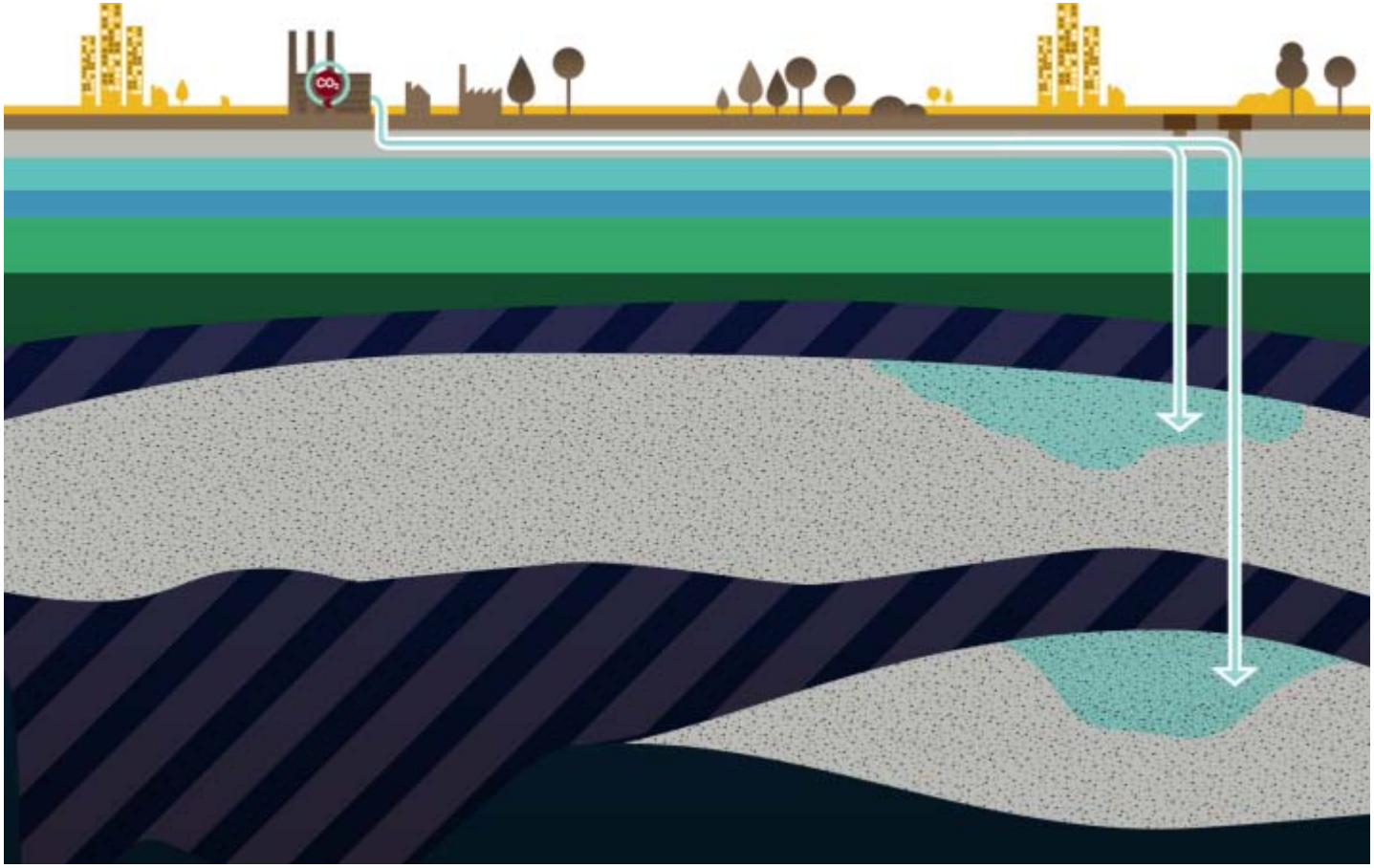
Test results for RGD with CO_2. From left: FKM Terpolymer 90, Aflas 90, FKM (Viton ETP 90), HNBR 80, FFKM 90 and HNBR 95 ED (Carbon fibre and PTFE filled). Source: Doc 028012 Soft materials in valves for CO2 transport in Offshore pipelines.

Soft materials

- Gassco is producing a test matrix with the aim for JIP participation(PECAR) or subcontracting activities.
- Experience transfer from operators of existing CO2 lines is required.
- Some soft seals can be replaced by metal seals
- Partly covered by PRCI studies
- Believed not to be critical

Pigging

- Which inline inspection technology to be used?
- Soft discs on the pigs
- Expect US operators to have relevant knowledge
- There is a need for experience transfer from other operators (Snøhvit)
- Contact established with relevant service providers with experience in the field
- Presentations on pig runs in CO2 pipelines will be held in June 2011 by Rosen Inspection and Gassco will be present at this venue. (The Second International Forum on Transportation of CO_2 by Pipeline, http://www.clarion.org/CO2/CO2_jun11/program.php)



Source: http://www.zeroemissionsplatform.eu/library/publication/101-ccs-powerpoint-presentation.html

Thank you for your attention.