CO_2 Underground Storage

w/ Focus on Water Chemistry

K. S. Pedersen, Kapexy Aps – May 1, 2025

Outline

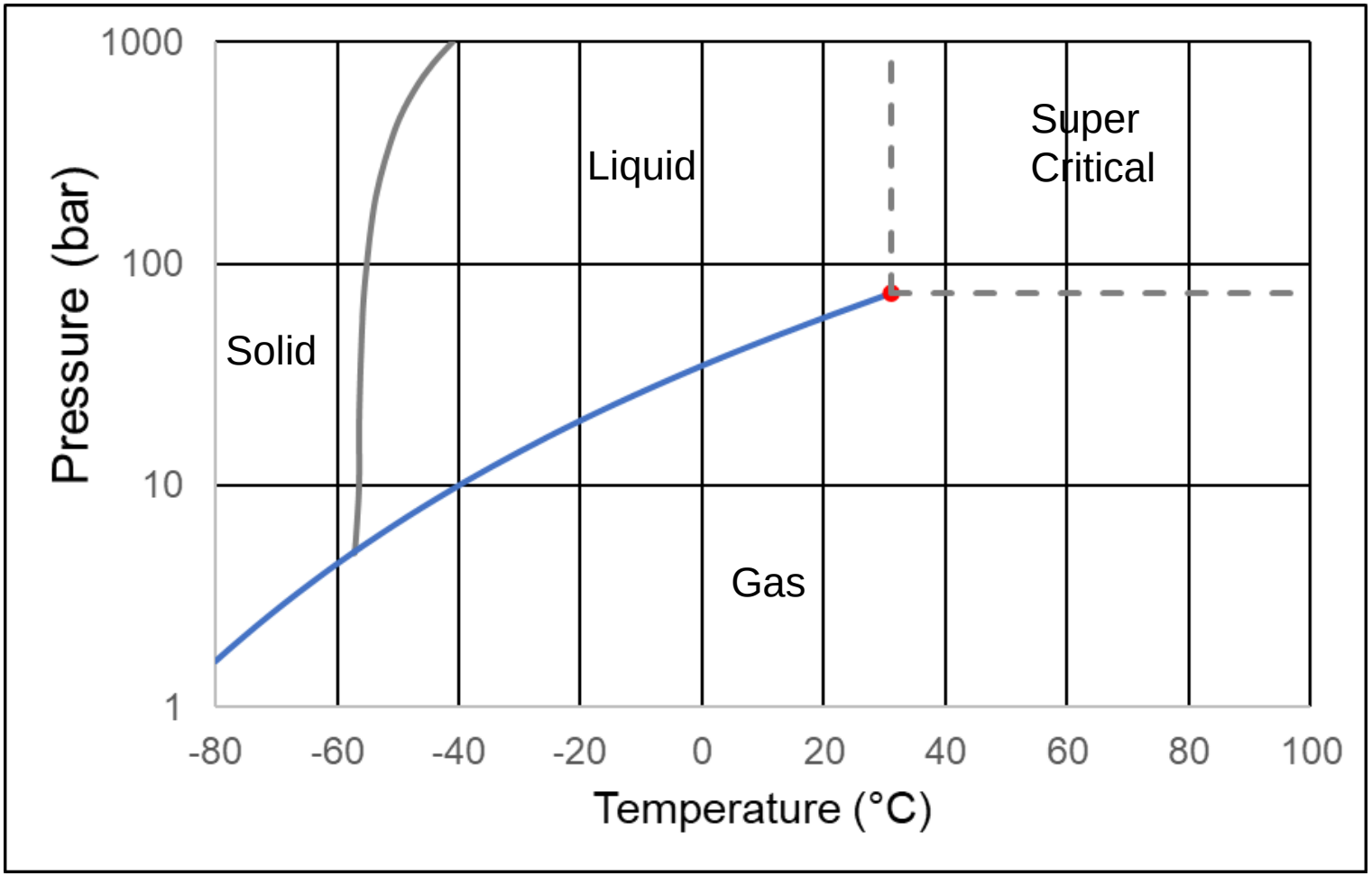
- K. S. Pedersen (brief CV)
- Pure CO_2 & Volumetric considerations related to Havnsø
- CO_2 Enhanced Oil Recovery
- Reactions of CO_2 + water with iron and minerals
- Selected quotes from reports and presentations
- For further consideration

Karen Schou Pedersen (brief CV)

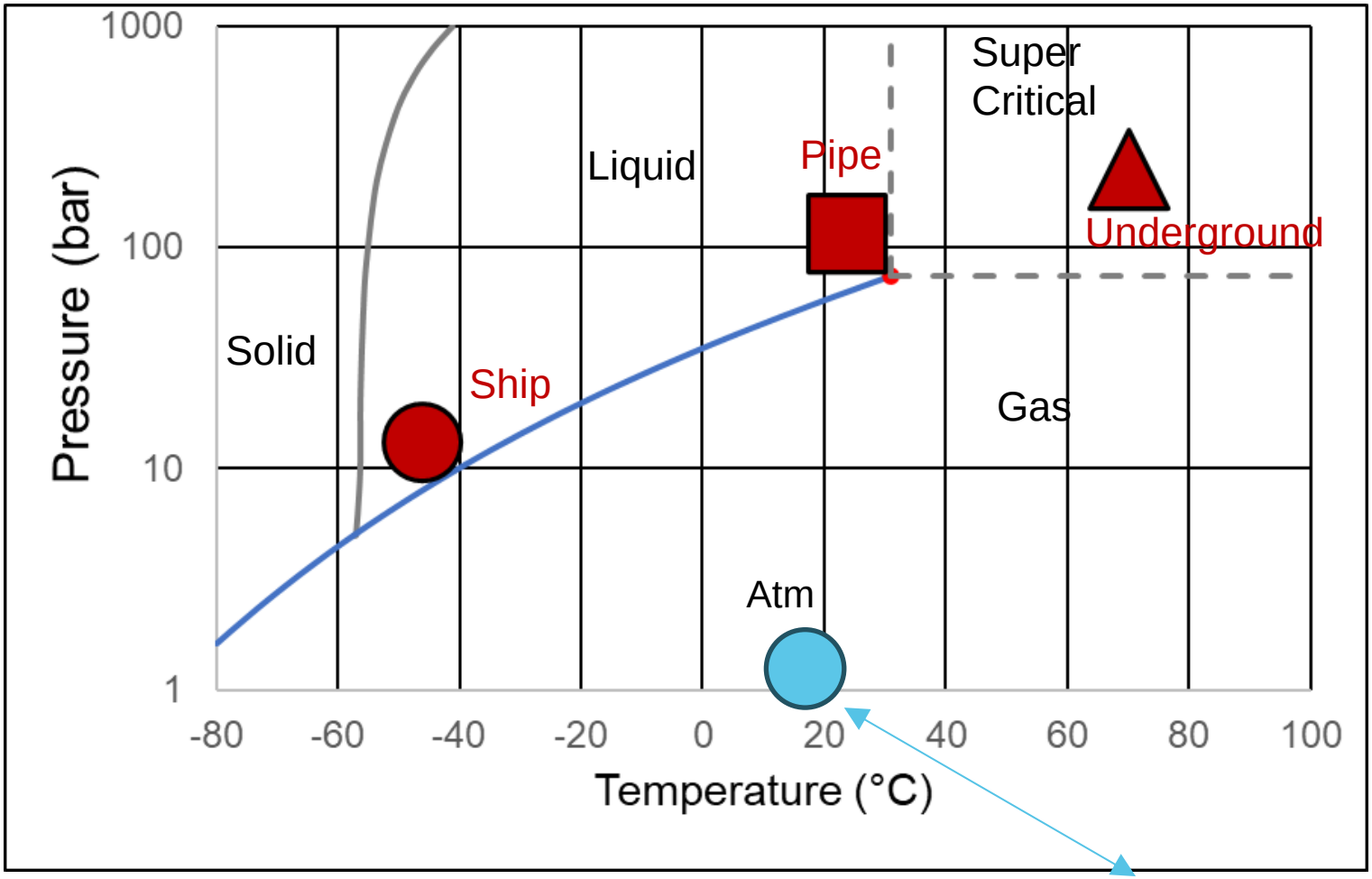
- 1980 Ph.D. in Physical Chemistry, DTU
- 1980-1981 Institut Laue-Langevin, Grenoble
- 1981-1984 Statoil/DTU, Modeling of oil & gas properties
- 1984-2022 Founder and manager of Calsep A/S (www.calsep.com).
  Offices in Lyngby, Houston, Dubai and Kuala-Lumpur
- 2022 – Kapexy Aps
  Consulting within oil & gas properties
- Other 5 books on oil & gas properties
  60+ scientific papers
  Technical Expert Macondo Oil Spill (2010)
- CO_2 Technical interest – Not a profession

Pure CO_2 & Volumetric Considerations Related to Havnsø

CO_2 from Phase Diagram

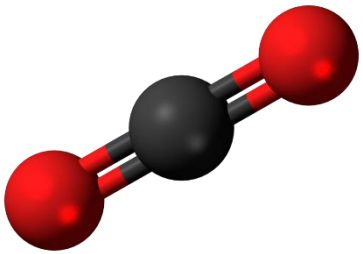


Typical CO_2 Transport and Storage Conditions

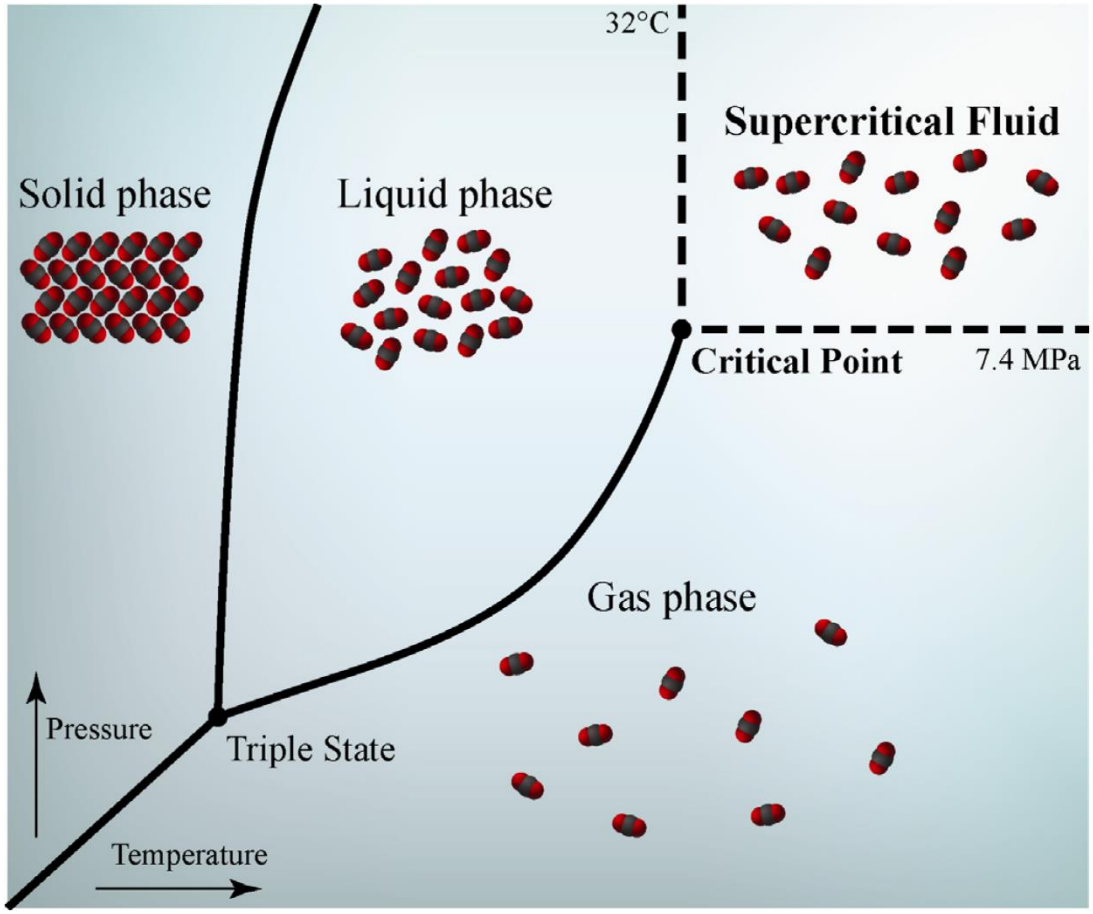


CO_2-gas kan ikke antændes og er ikke eksplosiv, men er kvælende da den kan fortrænge den omgivende ilt ved høje koncentrationer. Derfor er sikkerhedsaspekter vigtige for trans-

CO_2 Molecule & CO_2 Density Qualitative Diagram



Shape of CO_2 molecule favors dense phases



CO_2 – A Spacious Waste Product

Combustion

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

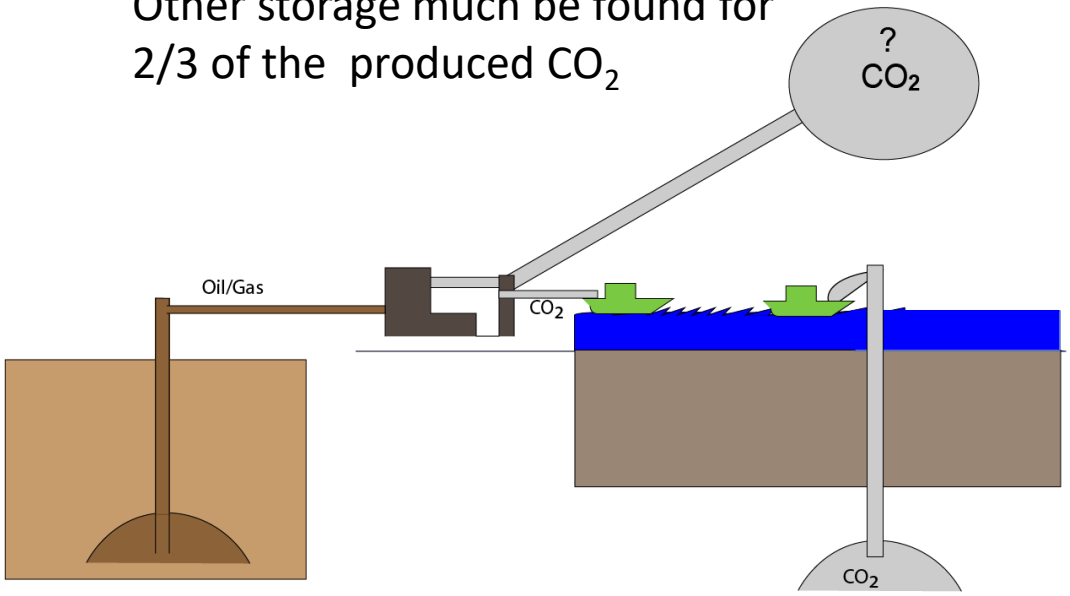
Mw =16 Mw=44

1 weight unit Oil

↓

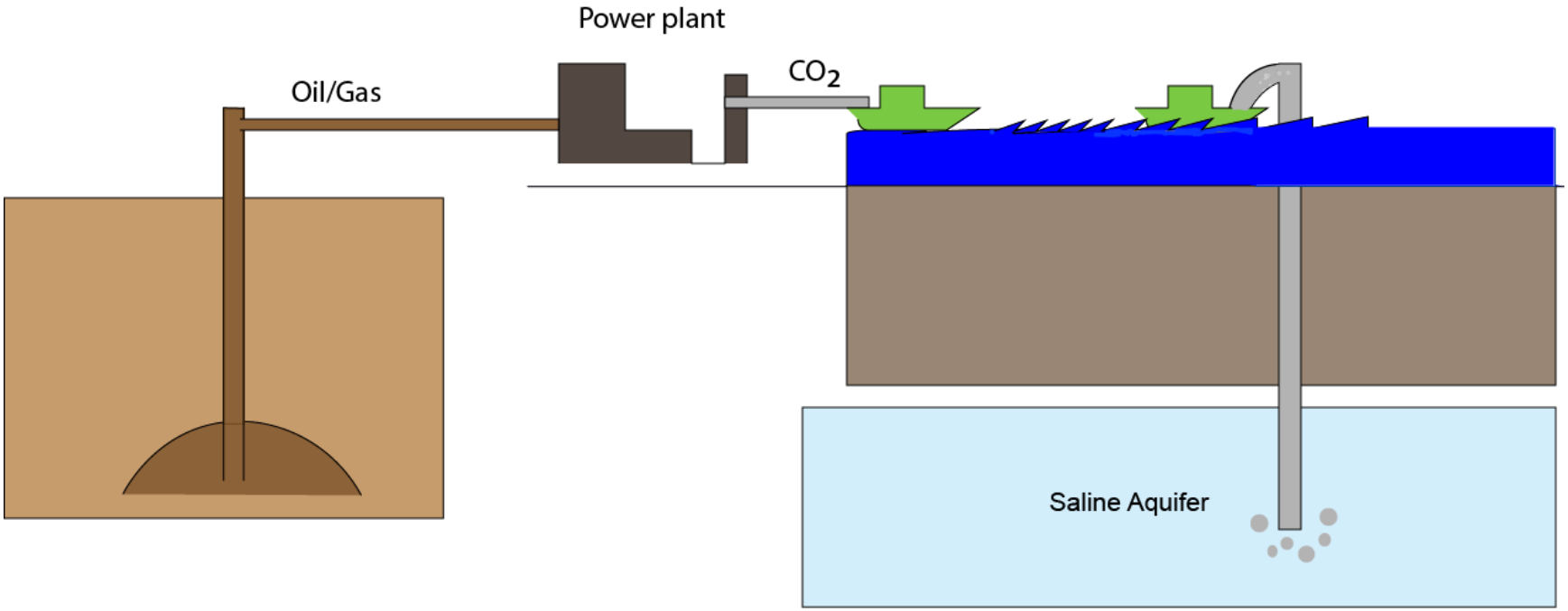
~3 weight units CO_2

Other storage much be found for 2/3 of the produced CO_2



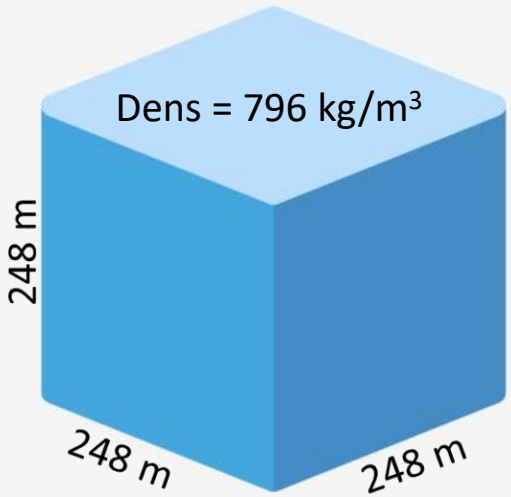
1/3 of produced CO_2 can be stored in depleted oil fields

Exploiting Additional Storage Capacity



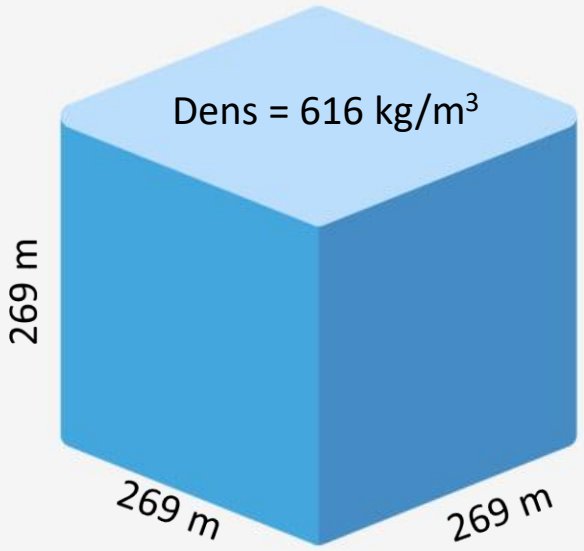
Volume of 12 mill tons $CO_2^{*1)}$ (planned annually Havnsø)

Temp = 51°C & Pressure = 210 bar



Volume = 15.2 mill m^3

Temp = 80°C & Pressure = 210 bar

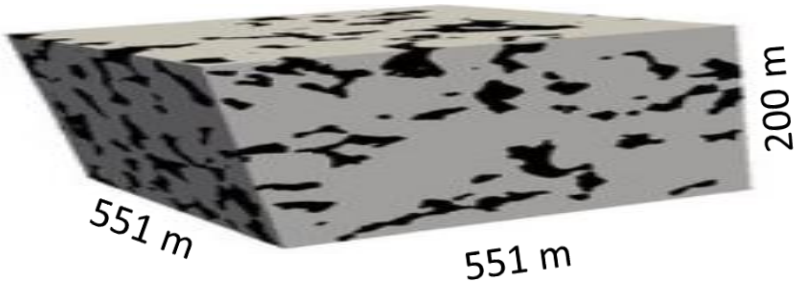


Volume = 19.5 mill m^3

*1) The volumes of CO_2 in pure form and not be taken as the volumetric distribution of CO_2 in an underground storage, which will be significantly larger.

Volume of 12 mill tons CO_2 with 25% Porosity*1)

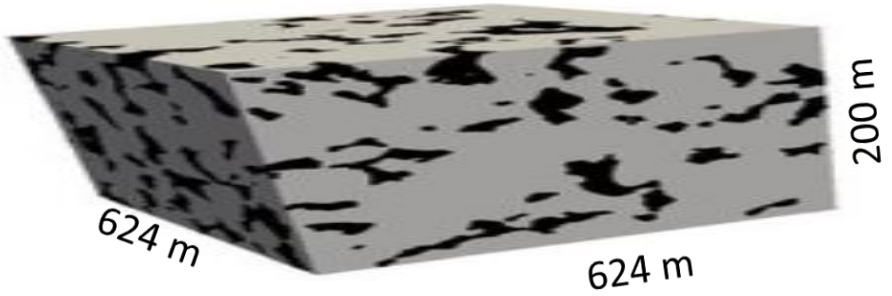
Temp = 51°C & Pressure = 210 bar



~ 42 soccer fields

Volume = 60.7 mill m^3

Temp = 80°C & Pressure = 210 bar



~ 53 soccer fields

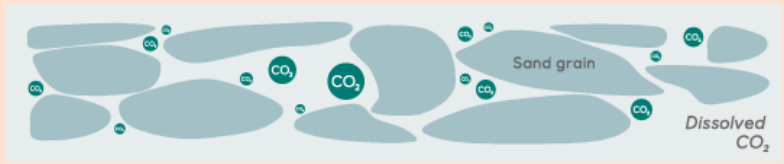
Volume = 77.9 mill m^3

*1) Assuming that all voids are filled with pure CO_2. In reality, CO_2 will not displace all the water in the pores, and some CO_2 will dissolve in the water. Therefore, CO_2 will spread over a much larger area.

Equinor CCS Brochure

1. The injected CO_2 occupies pores between the sand grains of the storage formation. Capillary forces are the cause for typically ca. 20 to 35% of the injected CO_2 being permanently trapped as microscopic bubbles in the pores.

2. CO_2 dissolves in the subsurface water. Over time, all the injected CO_2 will dissolve in the salt water in the reservoir, which will become denser and tends to sink down, further reducing the risk of spills.

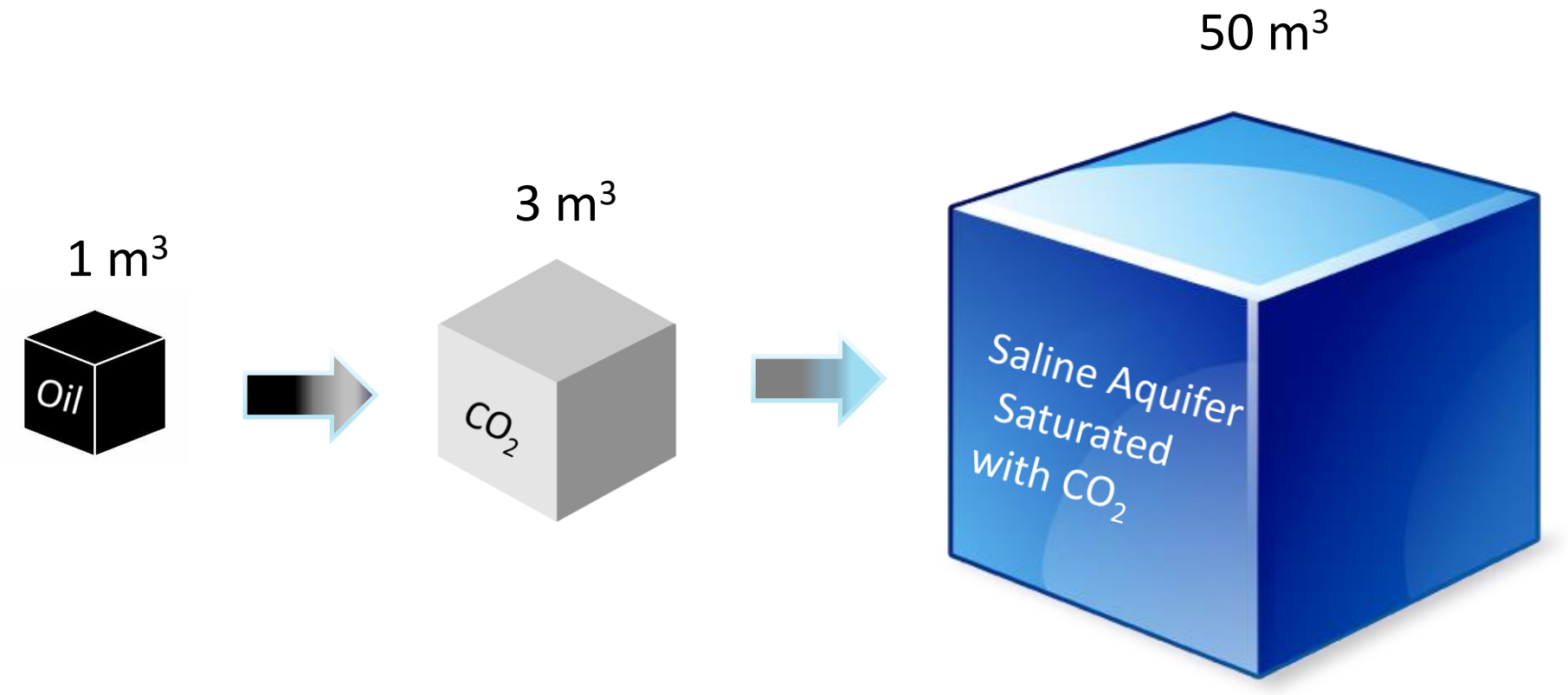


3. Some dissolved CO_2 will form minerals, thus becoming completely immobile.

In combination, these trapping mechanisms result in progressively less CO_2 being present in a separate, mobile phase and reduce the risk of leakages.

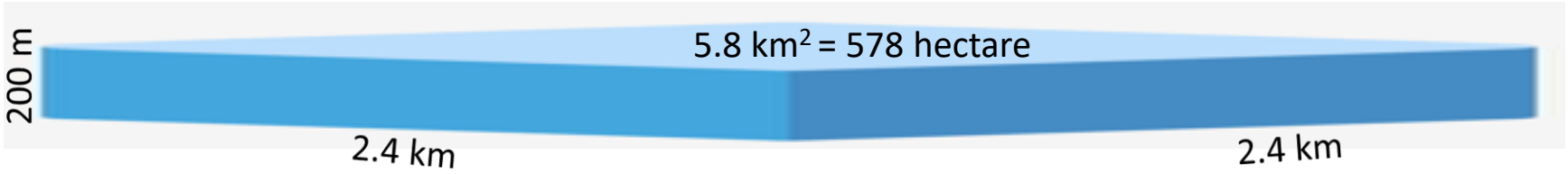
"CO_2 dissolves in the subsurface water. Over time, all the injected CO_2 will dissolve in the salt water in the reservoir"

If all CO_2 were to Dissolve in Water



Transferred to Havnsø – Storage of 12 mill ton CO_2 *1)

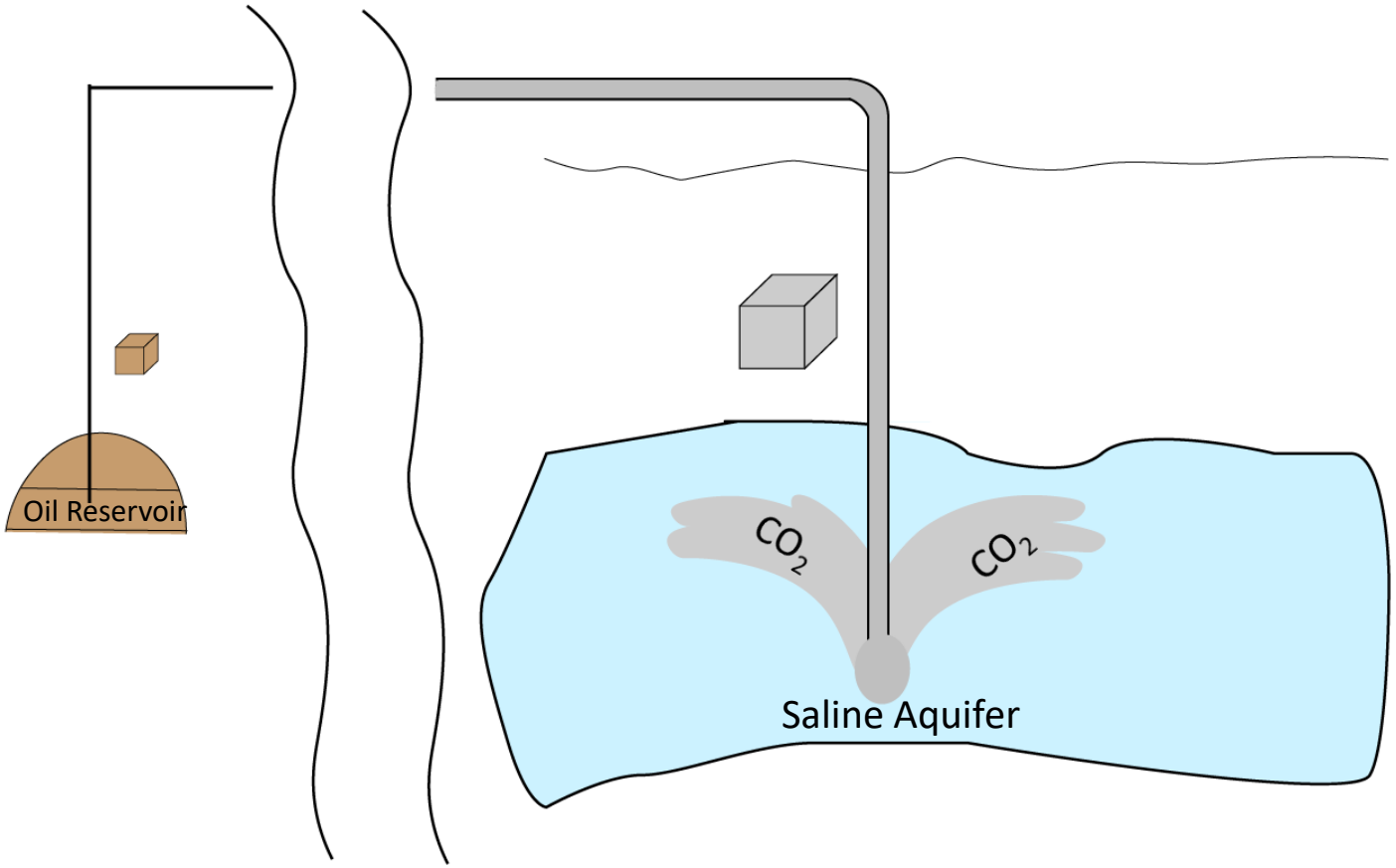
All CO_2 dissolved in water in formation of 25% porosity



~ 789 soccer fields

*1) To show how much water is required to dissolve the annual amount of CO_2 to be injected. That much water is unlikely to be available, and it would also take long to dissolve the CO_2 in the water. Most of the injected CO_2 will be in free form and is likely be spread over a much larger area.

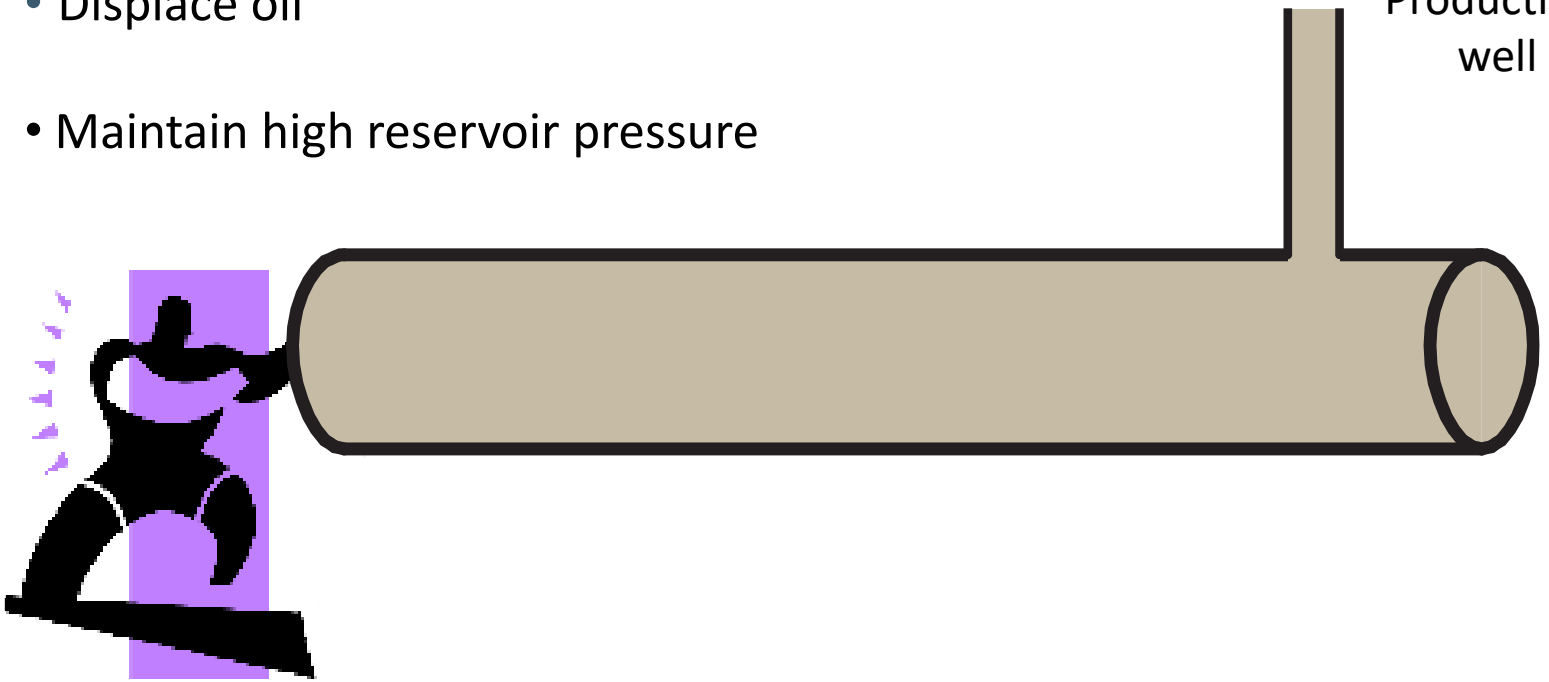
If all CO_2 not dissolved ..



CO_2 Enhanced Oil Recovery (EOR)

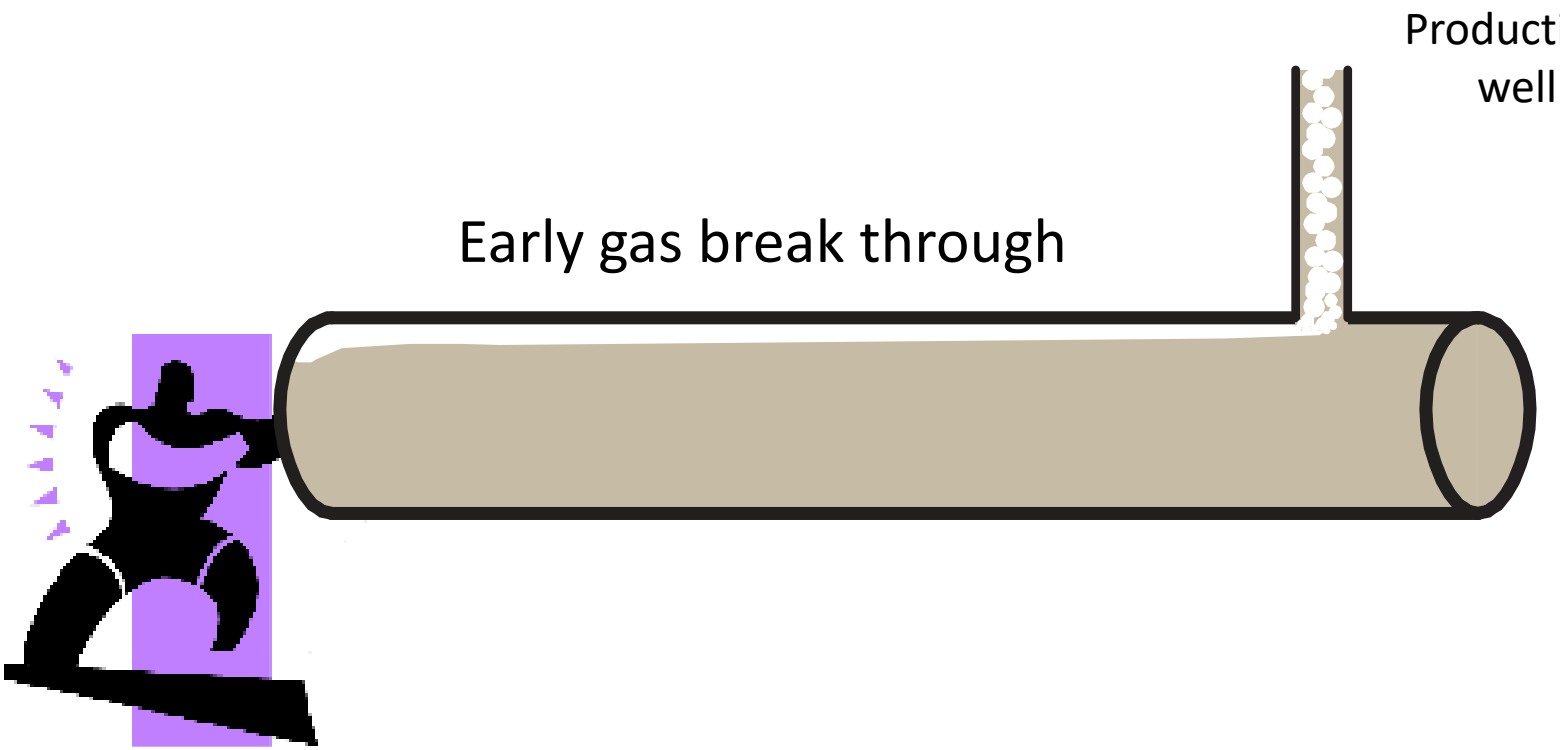
Gas Injection EOR

- Displace oil
- Maintain high reservoir pressure

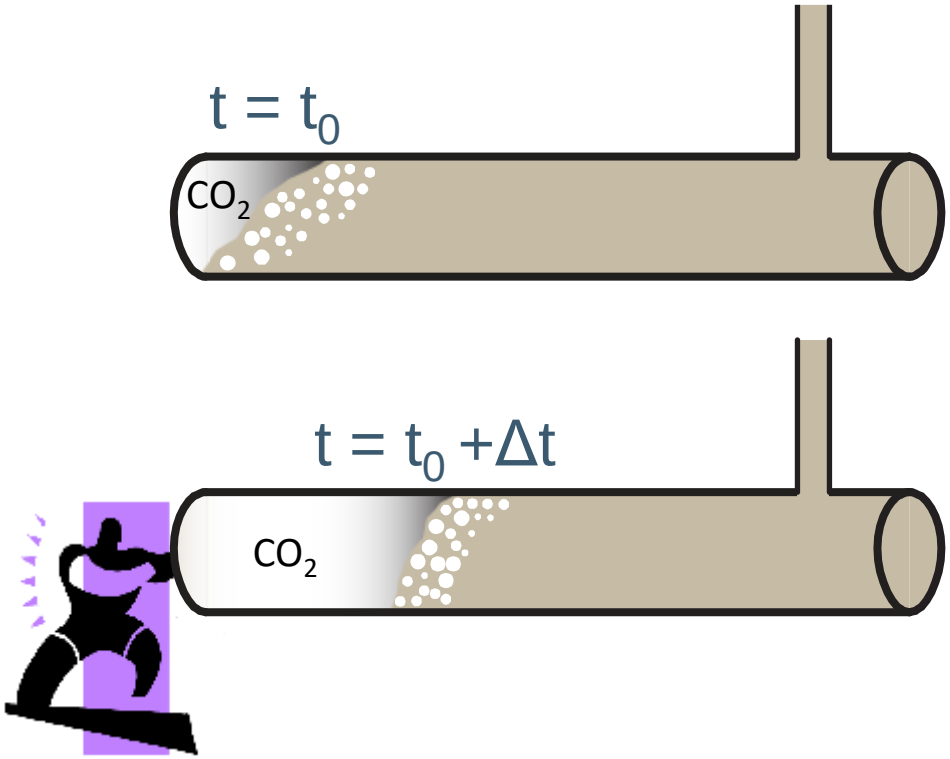


Gas Injection
Hydrocarbon
CO_2

Immiscible Drive

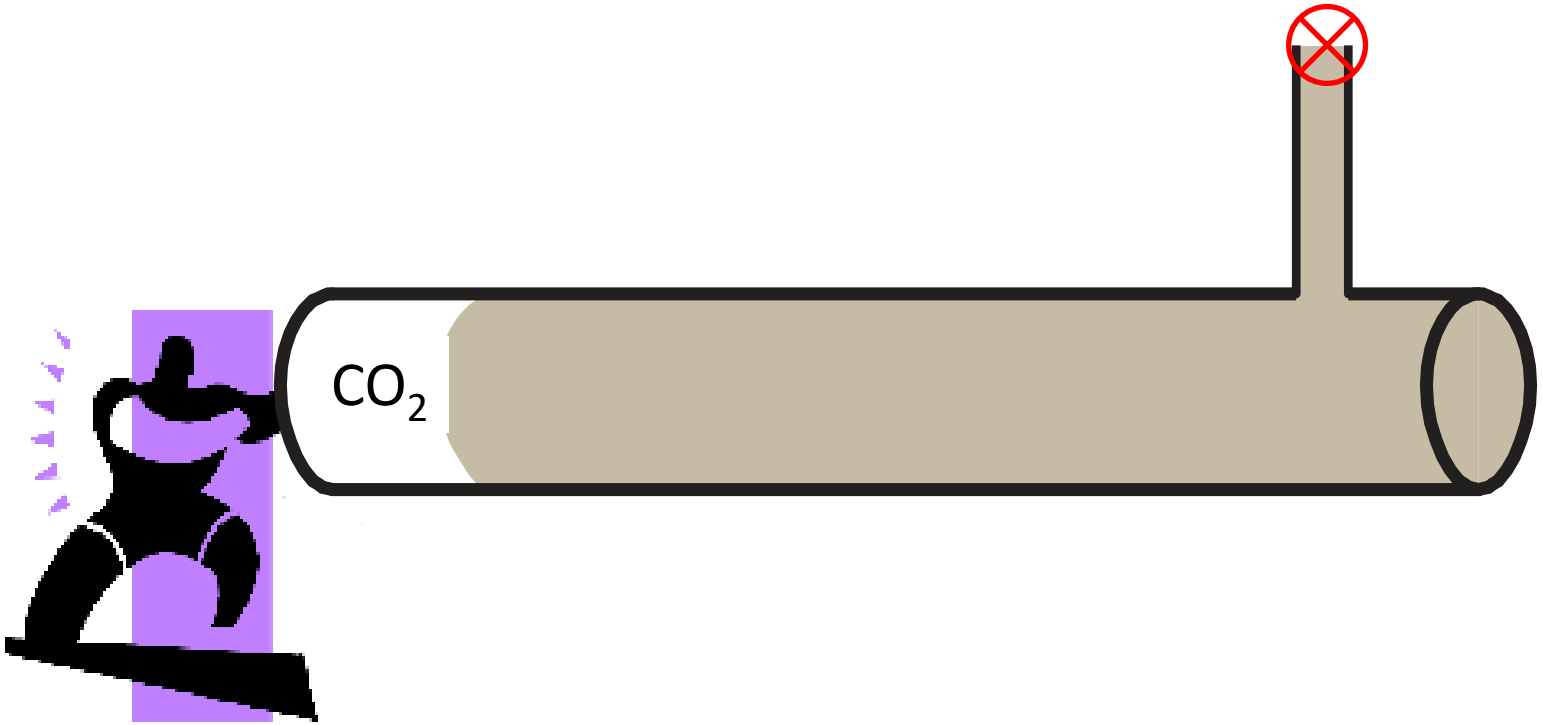


Miscible Drive – The Wanted Scenario



- Recovery can be > 90%
- Safe because
  - Pressure controlled to not exceed original reservoir pressure
  - CO_2 does not react with hydrocarbons
  - CO_2 does not get in touch with water
  - Reliable simulation tools exist based on 40+ years of field experience

CO_2 Gas EOR not Allowed in Denmark



A ban against EOR oil production limits the amount of CO_2 that can be stored in depleted oil fields in Denmark

Reactions of CO_2 + Water, with Iron and Minerals

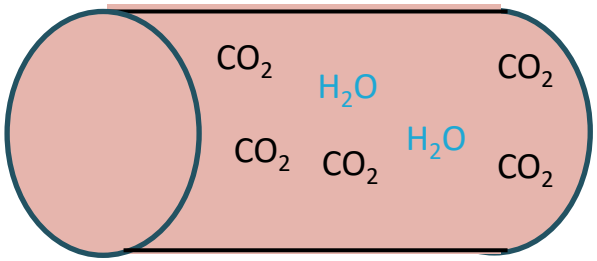
Dry CO_2 & Wet (Hydrated) CO_2

- Dry CO_2
  - Like another hydrocarbon component (e.g. propane C_3H_8)
- $C_3H_8 + H_2O$
  - No chemical reaction
- $CO_2 + H_2O$
  - Forms Carbonic Acid $(CO_2 + H_2O \rightarrow H_2CO_3)$

Awareness of Corrosiveness of CO_2 + H_2O for Pipelines

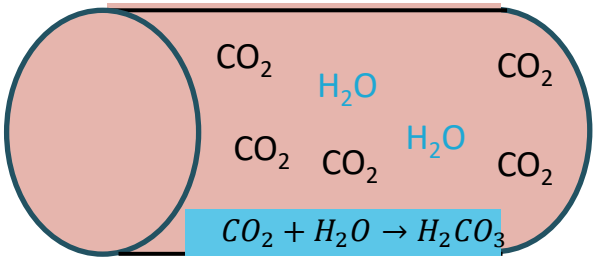
KAPEXY

Non-corrosive



All H_2O dissolved in CO_2

Corrosive



Free water phase with carbonic acid

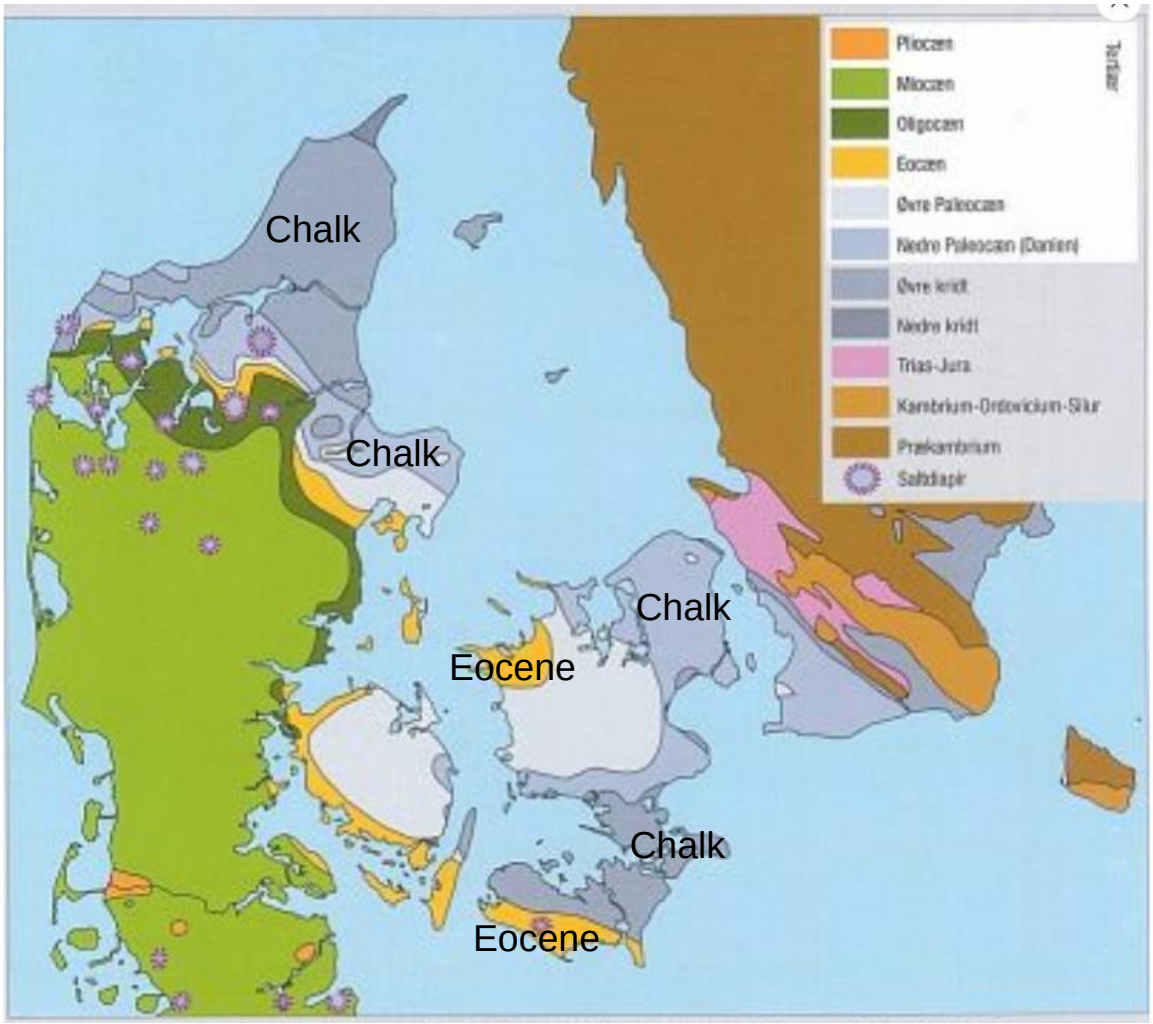
Quote from GEUS report[*1)]:

CO_2 skal være dehydreret ved transport, da små mængder vand kan lede til tekniske problemer, hvor vandet kan krystallisere til CO_2-hydrat. Dette kan give problemer i tanke ved ventiler, varmevekslere mm. Små mængder vand kan også gøre CO_2'en ætsende for kulstofstål, hvilket kan give problemer i rørtransport.

[*1)] Fangst, lagring og anvendelse af CO2 (CCUS). Tekniske barrierer for CCUS I Danmark

Acidification of Oceans

Denmark Underground (Chalk is $CaCO_3$)



The GEUS Reports name the Havnsø formation as Sandstone

Sandstone is composed of Quartz or Feldspar

Feldspar

Feldspar is the general term for a group of aluminosilicate minerals containing sodium, calcium, or potassium and having a framework structure.

Feldspars are the most common minerals in the Earth's crust

In humid tropics many granite boulders can be kicked into a pile of grains - because the feldspar grains which originally form an interlocking crystal network weather to a loosely adhering clay called kaolinite.

$K\ Al\ Si_3\ O_8$ ---> $Al_2Si_2O_5(OH)_4$

(feldspar) (water) (kaolinite)

Notice that this equation does not balance exactly, the extra potassium (K) and silicon (Si) not appearing on the right hand side are carried away in solution (just like coffee is removed from the crushed coffee beans).

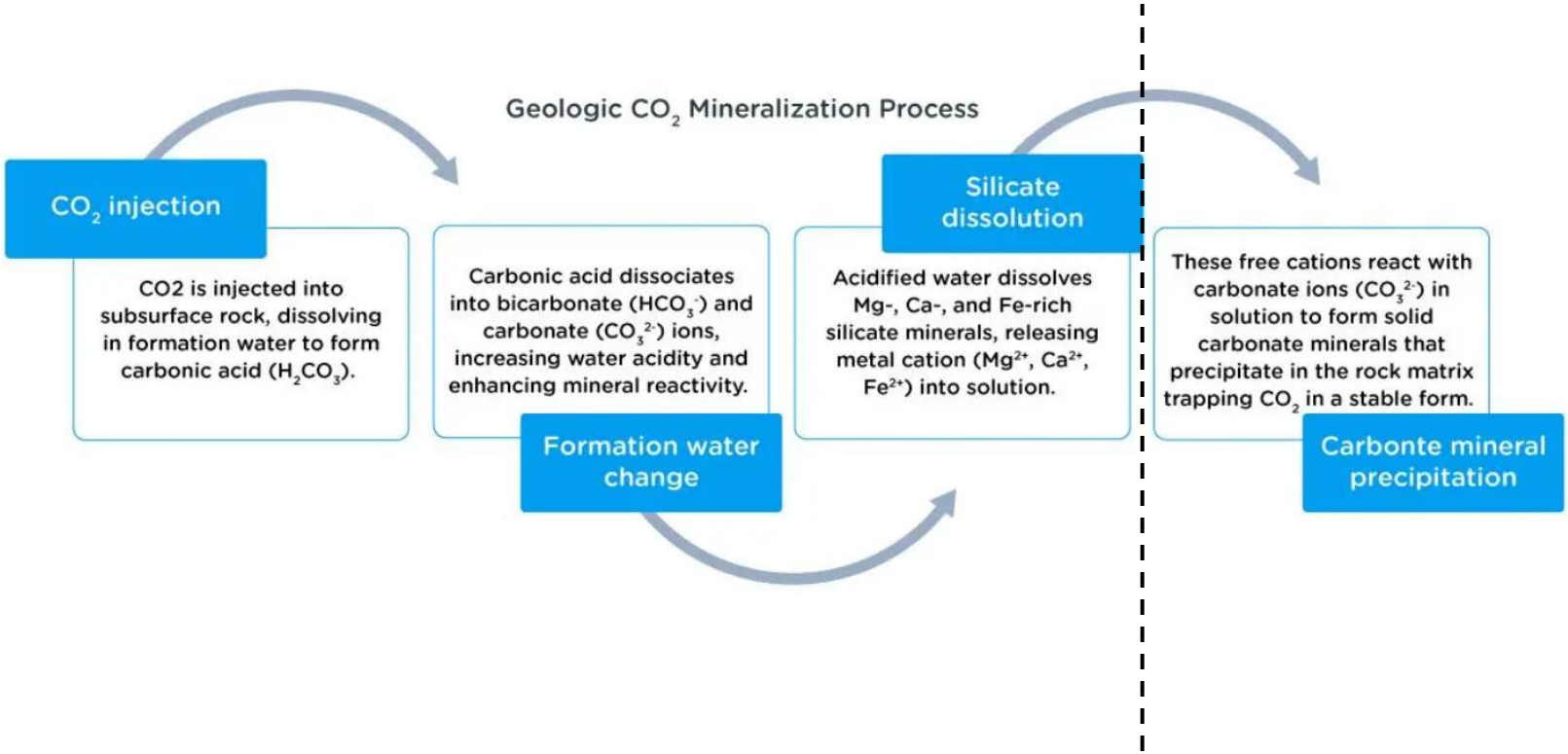
We say that the potassium and silicon is *leached* away and that the feldspar is *hydrated* (water consumed). This process is accelerated by carbonic acid!

Feldspars to clay

+ H_2CO_3 (acid)

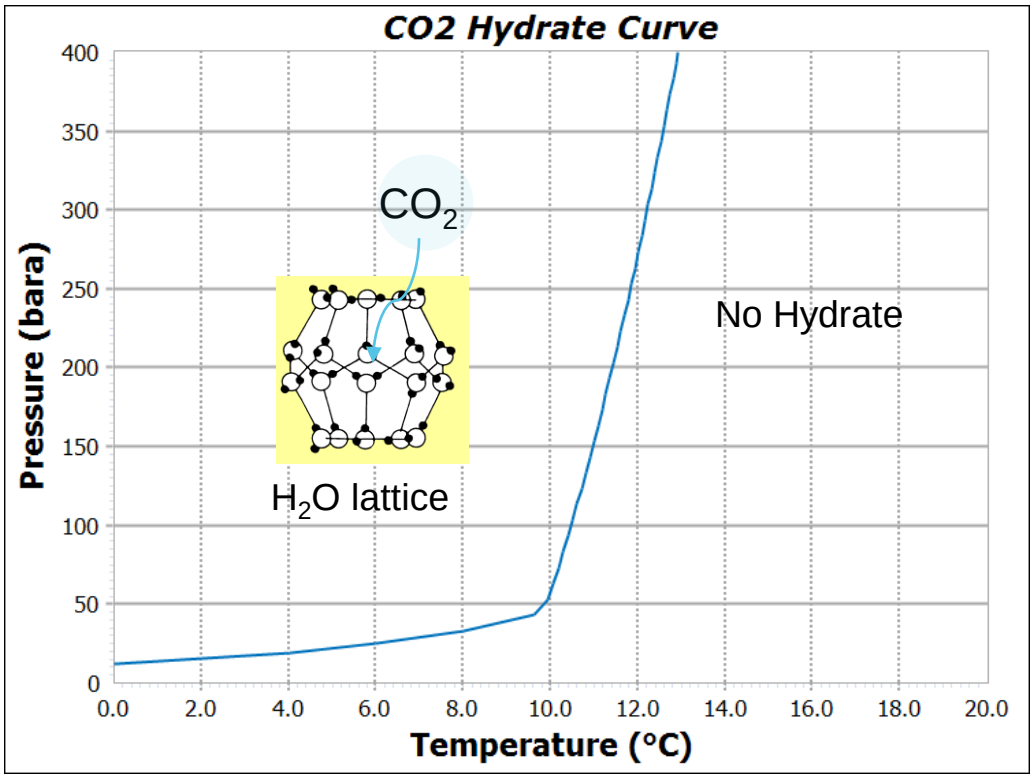
Loosely adhering clay called kaolinite

Claimed CO_2 Mineralization Process (Rambøll)



What if process stops here?

CO_2 Hydrate



- Could be a problem in pipelines and process equipment (valves)
- Potential problem in injection well near surface
- Not a problem in deep aquifer storage

Selected Quotes from Reports and Presentations

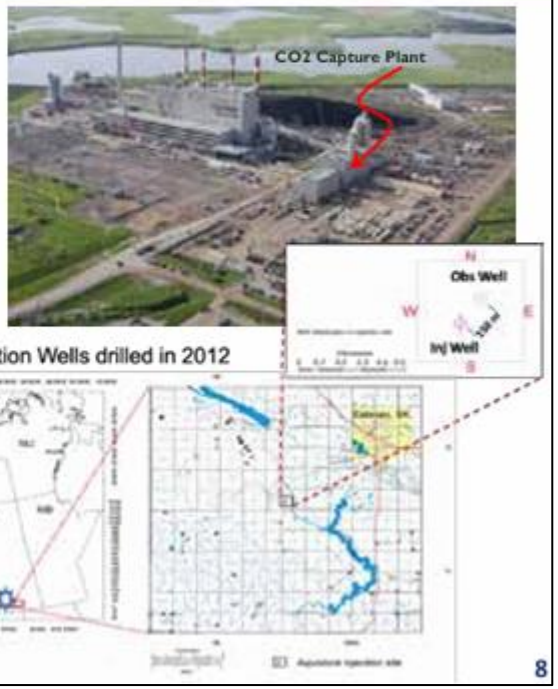
Society of Petroleum Engineers Meeting

IEAGHG Weyburn-Midale Project in Saskatchewan in Canada

Injection Rate of 400 ton/day (Pilot Scale)

Aquistore CO_2 Storage Site

- Storage component of SaskPower's Boundary Dam Carbon Capture Project managed by the Petroleum Technology Research Centre (PTRC)
- Injection and Observation wells drilled in 2012 and Injection commenced April 16, 2015
- Averaged injection rate ~ 400 T/day but tested to confirm acceptance of up to 2400 T/day and more than 580,000 tonnes of CO_2 (as of Jan. 2024)
  [~ 10% of total CO2 captured at Power Plant]



Havnsø: 12 mill ton/year corresponding to 32877 ton/day

Sleipner & Snøhvit by Institute for Energy Economics and Financial Analysis

KAPEXY

Despite the studies, experience and passage of time, the security and stability of the two fields have proven difficult to predict. In 1999, three years into Sleipner's storage operations, CO_2 had already risen from its lower-level injection point to the top extent of the storage formation and into a previously unidentified shallow layer. Injected CO_2 began to accumulate in this top layer in unexpectedly large quantities. Had this unknown layer not been fortunate enough to be geologically bounded, stored CO_2 might have escaped.

At Snøhvit, problems surfaced merely 18 months into injection operations despite detailed pre-operational field assessment and engineering. The targeted storage site demonstrated acute signs of rejecting the CO_2. A geological structure thought to have 18 years' worth of CO_2 storage capacity was indicating less than six months of further usage potential. This unexpected turn of events baffled scientists and engineers while at the same time jeopardizing the viability of more than US$7 billion of investment in field development and natural gas liquefaction infrastructure. Emergency remedial actions and permanent long-term alternatives needed to be, and were, identified on short notice and at great cost.

Could be because injected CO_2 did not dissolve in the water and did not displace the water

Reservoir Simulators

Reservoirmodeller og simuleringer udført for Havnsø strukturen indikerer, at der kan injiceres og lagres 250 Mt i strukturen, hvis der anvendes 3 injektionsboringer, hver med en gennemsnitlig pumperate på 1 Mt CO_2/år [29]. Der kan injiceres i ca. 85 år før trykket stiger til det kritiske fraktureringstryk for formationen, som er sat til 75% af det lithostatiske tryk. Lagrings-

Reservoir simulators are developed for oil and gas and not necessarily representative for CO_2 storage in aquifers.

CCS Handled in UAE (SPE 222367-MS – ADIPEC 2024)

Regional Site Screening Analysis	Regional proximity analysis	Social and human population commercial areas	Identify existing and planned human population and social commercial areas, civil infrastructures; assess minimum requirements on segregation distances between potential CO2 storage sites and these areas
		Environment protected sensitive areas	Identify existing and potential future environmentally protected sensitive areas; assess minimum requirements on segregation distances between potential CO2 storage sites and these areas
		Industrial areas	Identify existing industrial areas/complexes; assess minimum requirements on segregation distances between potential CO2 storage sites and these areas
		Existing or planned resources development	Data should be collected for analysis on existing and planned developments within the region which may interact with CO2 sequestration from a subsurface point of view. For example, any producing fields which share the same saline aquifer (even if the producing field is located at a distance).
		Past developments (legacy wells etc.)	Similar to consideration on existing and planned developments, data on what remain from past development need to be collected and analysis performed. For example, legacy wells may exist from past exploration activities or from nearby abandoned hydrocarbon fields. If
		Distance to CO2 emission capturing point(s)	Assess distance between CO2 storage site and CO2 capturing point: longer distance may imply higher transportation costs, see also pipeline ROWs
		CO2 transport pipeline ROWs	Identify existing pipelines and gathering lines/systems in potential storage areas. Assess potential for conflicts in pipeline routing to CO2 sequestration projects, as well as the potential for use or access to existing pipeline ROWs.
		CO2 Sequestration HUB development approach	Consider CO2 sequestration project approach options, for example, pilot project, phased project, CCS HUB approach etc. Identify and list factors/options which may have positive impact on CO2 sequstration project commercial aspect.

Identify existing and planned human population and social commercial areas, civil infrastructures; assess minimum requirements on segregation distances between potential CO2 storage sites and these areas
Identify existing and potential future environmentally protected sensitive areas; assess minimum requirements on segregation distances between potential CO2 storage sites and these areas

CO_2 in Contact with Water in Underground Storage

Ren og tør CO_2 anses normalt som værende ikke-reaktiv over for mineraler, men især for forseglende bjergarter viser tidligere analyser, at tør superkritisk CO_2 kan reagere med den forseglende bjergart og dermed ændre seglets egenskaber. Således kan tør superkritisk CO_2 forårsage krympning af vandbærende lermineraler (i seglet, hvilket kan skabe nye eller formentlig mere sandsynligt udvide eksisterende sprækker i seglet og derved forøge en mulig opadgående transport af CO_2. Derudover kan interaktionen mellem tør superkritisk CO_2 og seglet i begrænset omfang føre til dannelse af karbonater og mobilisering af sporstoffer.

Need for Lab Data

For at modne potentielle CO_2-lagre anbefales:

- Da lagringskapaciteten ikke vurderes at være den begrænsende faktor, bør man hurtigst muligt iværksætte kortlægning af områder som ikke tidligere har været undersøgt, men som opfylder andre vigtige kriterier, fx nærhed til punktkilde clustre, infrastruktur muligheder, naturbeskyttelsesbegrænsninger eller områder, hvor der er god viden om undergrunden
- Indsamling af nye data (seismisk og boring) vedr. valgte strukturer (som fx Havnsø og Hanstholm), så disse kan modnes til certificering (størrelse, relief, spill point, forekomst af forkastninger, etc.)
- Laboratorieundersøgelser af langtidseffekter af CO_2's påvirkning af reservoir og segl
- Integration af nye og eksisterende data og resultater med henblik på risikovurdering, certificering, optimal udnyttelse af lagerkapacitet og planlægning af overvågning
- Identificere relevante og hensigtsmæssige moniteringsmetoder

For Further Consideration

For Further Consideration

- Formation of carbonic acid must be taken into consideration
- Carbonic acid may dissolve underground structure and cause CO_2 to escape and/or structure to crash.
- Limited solubility of CO_2 in water must be taken into consideration
- Limited field experience with CO_2 storage in aquifers
- CO_2 injected at Sleipner has moved unexpectedly both horizontally and vertically.
- How to test long term effect of CO_2 on reservoir and seal in the lab
- Experience from EOR in oil fields is not representative of CO_2 storage in aquifers
- Reservoir (3D) simulators used in oil and gas production does not consider chemical reactions
- Approach to CO_2 storage internationally is staying well clear of residential areas