# $CO_2$ Transportation for CCS

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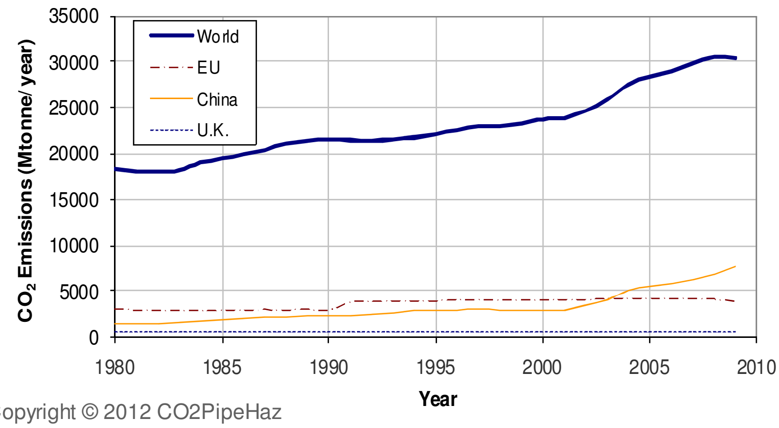
## $CO_2$ Transportation for CCS

Presentation structure:

- $CO_2$ transportation for CCS
- $CO_2$ transport by pipelines:
- past and present experience,
- safety and risks,
- hazard assessment.

## Introduction CO$_2$ transportation – motivation

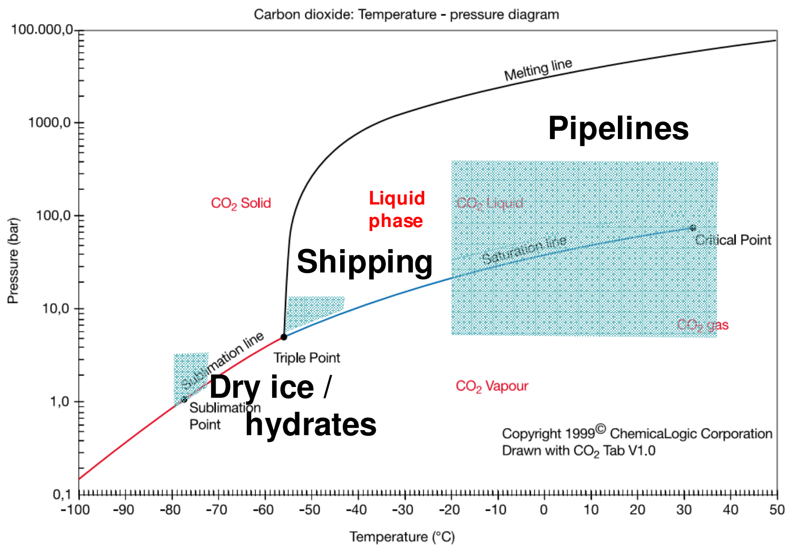
- World global CO$_2$ emissions are currently ~30 Gt/yr
- Potential capture (IPCC, 2005): 21-45% by year 2050
- Transportation from capture to sequestration sites







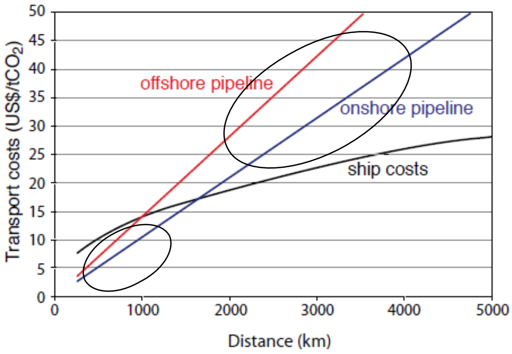

## Introduction CO$_2$ transportation options






CO$_2$PipeHaz

## Introduction $CO_2$ transportation costs




Costs of transportation of $CO_2$ for onshore pipelines, offshore pipelines and ship transport (IPCC, 2005)

At the moment, only pipeline transportation is a mature and cost-effective technology suitable for large-scale use in CCS





## Introduction $CO_2$ pipeline transportation

To reduce the capital costs of $CO_2$ pipelines, the existing/ decommissioned NG pipelines could also be potentially used for $CO_2$ transportation.

Re-use of the NG pipelines depends on:

- the pipeline design operation pressure (typically below 80-90 bar),
- the age and estimated lifetime of the pipeline,
- the degree of corrosion of the pipeline wall material.

In the UK the National Gas Transmission System (NTS) currently operates about 6,800 km of onshore gas pipelines at pressures of 70 to 85 bar (HSE web site, 2008), with some of them designed for operation at above 100 bar (Pershad and Slater 2007).

## $CO_2$ pipeline transportation – past experience

$CO_2$ pipelines in North America (USA and Canada):

- since 1972 (Canyon Reef pipeline),
- more than 5,800 km of onshore high-pressure pipelines,
- transport about 50 Mt/yr of $CO_2$ for EOR (vs 30 Gt/yr worldwide $CO_2$ emissions),
- purified $CO_2$ (>95% $CO_2$): naturally occurring (Cortez, Sheep Mt, Bravo, Central Basin pipelines) and from gasification plants (Canyon Reef, Weyburn, Val Verde, Bairoil pipleines),
- in sparsely populated areas.





## $CO_2$ pipeline transportation – past experience

Other $CO_2$ pipelines:

| CCS project | Country | Oper. date | Pipe diameter | Pipe length, km | Pressure, bar |
|---|---|---|---|---|---|
| Snohvit | Norway | 2008 | 8" | 153 | 200 (MOP) |
| In Salah | Algeria | 2004 | N/A | 14 | N/A |
| Bati Raman | Turkey | 1983 | 10" | 80.5 | 172 (MOP) |
| Reconcavo | Brazil | 1987 | N/A | 183 | N/A |
| Lacq | France | 2010 | 8" - 12" | 27 | 27 |
| Barendrecht | Netherlands | cancelled | 360 - 700 mm | 20 | 40 |

Public concerns about safety.

## $CO_2$ pipeline transportation – hazards

At concentrations higher than 10%, $CO_2$ gas can cause severe injury or death due to asphyxiation.

In case of accidental leakage/ release of $CO_2$ from a pipeline (typically containing several Mt of inventory), the released $CO_2$ dense gas cloud:

- could accumulate to potentially dangerous concentrations in low-lying areas,
- could cover an area of several square kilometres

Courtesy of Laurence Cusco, HSL





## $CO_2$ pipeline transportation – hazards

Given that most power generation plants are built close to energy consumers, the number of people potentially exposed to *risks from $CO_2$ pipelines will be greater than* the corresponding number exposed to potential *risks from $CO_2$ capture and storage* facilities (IPCC, 2005).

Two key areas that need to be demonstrated to gain public acceptance of $CO_2$ pipelines are that *such mode of transport is safe*, *and its environmental impact is limited.*

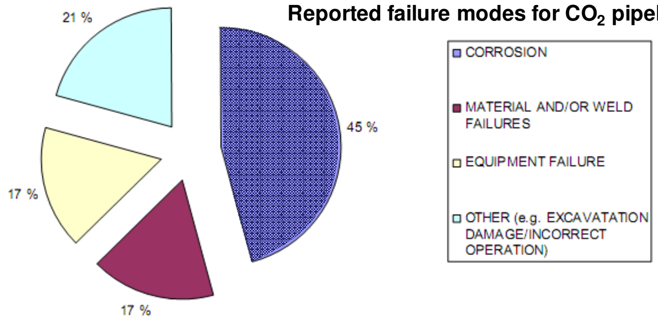
## $CO_2$ pipeline transportation – past experience

### Statistics on failure of the $CO_2$ pipelines

Serious accidents (2002 – 2008) (Parfomak *et al.*, 2009):

- USA $CO_2$ pipelines - 31 leaks, no injuries.
- Natural gas (NG) and hazardous liquids pipelines - 2,059 accidents causing 106 fatalities and 382 injuries.

**Reported failure modes for $CO_2$ pipelines (IPCC, 2005)**






## $CO_2$ pipeline transportation – past experience

### Statistics on failure of the $CO_2$ pipelines

However, the North American $CO_2$ pipelines:

- are mainly routed through unpopulated areas,
- have total length less than 1% of the length of the NG and other hazardous liquids transportation pipelines.

Therefore, the above data is not sufficient to draw a firm statistical conclusion about the safety of $CO_2$ transportation pipelines.

## $CO_2$ pipeline design standards

At the moment, there are no standards/ codes and regulations for pipelines transporting the dense-phase $CO_2$.

Therefore, $CO_2$ pipelines are designed using existing national standards for gas and liquid transportation pipes, while additional *$CO_2$ specific design considerations* are made by the pipeline construction/ operation company to guarantee reliable and safe operation of a pipeline.





## $CO_2$ pipelines risks

The *additional requirements for $CO_2$* transportation pipelines are aimed to minimise the risks of:

- formation of two-phase liquid-vapour flow;
- rapid changes in the flow;
- significant cooling of the flow, resulting with:
  - formation of solid phase $CO_2$ (dry ice);
  - embrittlement of material of the pipe wall, valves, compressors and seals.
- fracture propagation along the pipeline;
- corrosion of carbon steel pipelines carrying $CO_2$ mixed with free water and acid gases ($SO_x$, $O_2$);
- accidental discharge of $CO_2$ from a pipeline constructed in urban areas.

## $CO_2$ pipelines risks

Currently the impacts of various factors on the above risks are not well understood and are subject to scientific research.

The following factors/phenomena are of particular interest:

- properties of $CO_2$ with impurities,
- hydrogen embrittlement of pipe wall,
- hydrate formation,
- fracture propagation,
- corrosion of pipe wall,
- outflow and dispersion modelling.

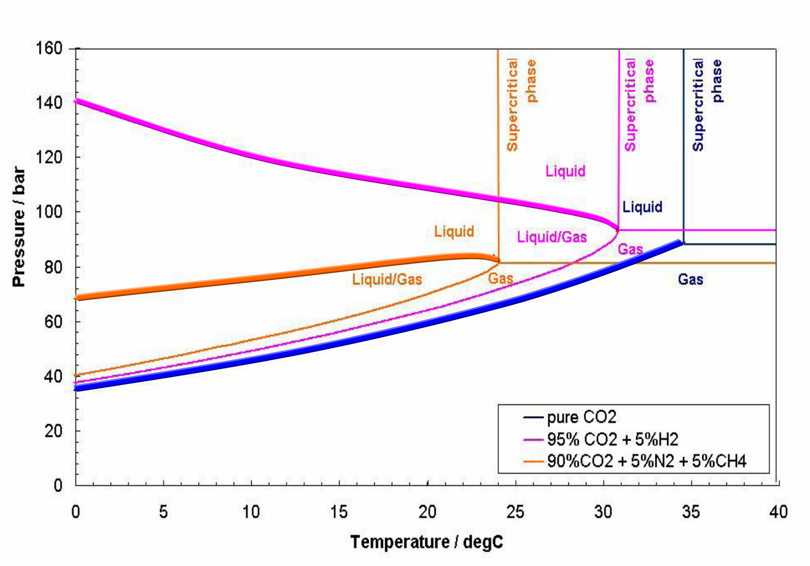



## Impact of impurities

Impurities in $CO_2$ stream affect the physical properties of the fluid, and

- modify the compressor requirements,
- affect pipeline integrity (hydrogen embrittlement, corrosion and hydrate formation),
- adversely impact $CO_2$ pipeline hazard profile.

## Impact of impurities: Fluid state







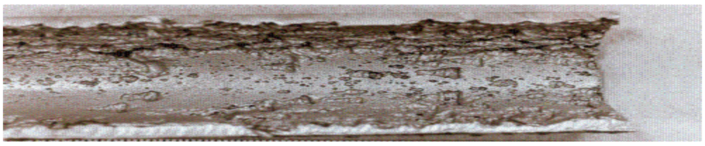

## Impact of impurities

| | Post-Combustion | Pre-Combustion | Oxyfuel |
|---|---|---|---|
| $CO_2$ | >99 vol% | >95.6 vol% | >90 vol% |
| $CH_4$ | <100 ppmv | <350 ppmv | |
| $N_2$ | <0.17 vol% | <0.6 vol% | <7 vol% |
| $H_2S$ | Trace | 3.4 vol% | Trace |
| $C_2$+ | <100 ppmv | <0.01 vol% | - |
| CO | <10 ppmv | <0.4 vol% | Trace |
| $O_2$ | <0.01 vol% | Trace | <3 vol% |
| $NO_x$ | <50 ppmv | - | <0.25 vol% |
| $SO_x$ | <10 ppmv | - | <2.5 vol% |
| Ar | Trace | <0.05 vol% | <5 vol% |

Water removal in dehydration

*(Oosterkamp and Ramsen, 2008)*

## Impact of impurities: Corrosion



- Presence of small amount of water in $CO_2$ stream will be inevitable.
- Corrosion can occur when free water is in a direct contact with the pipeline material acting as an electrolyte or react with $CO_2$ forming carbonic acid.
- The solubility of water in $CO_2$ in the presence of impurities was not characterised.

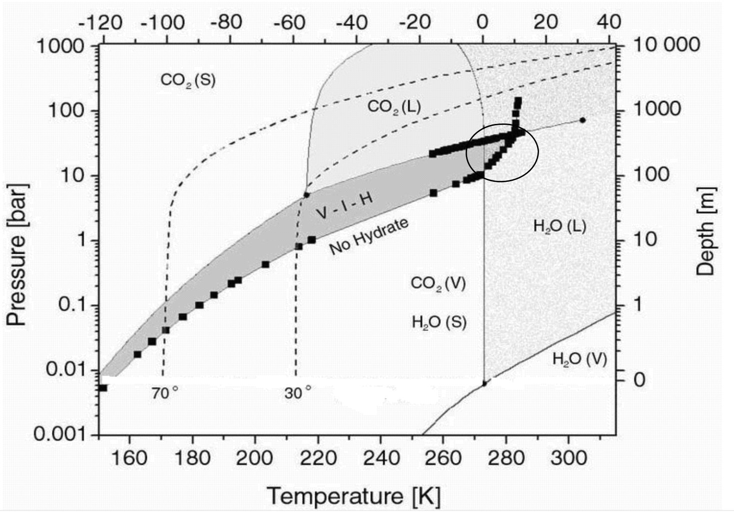




## Impact of impurities: Hydrate formation

- Gas hydrates form as a result of the combination of water and gas molecules at suitable temperature and pressure.
- Hydrates can cause the blockage of the pipeline, giving rise to serious operational and safety issues.

## Impact of impurities: Hydrate formation

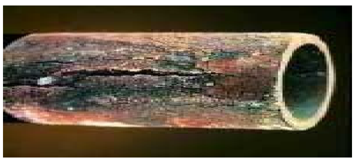



$CO_2$/water phase diagram





## Impact of impurities: Hydrogen Embrittlement

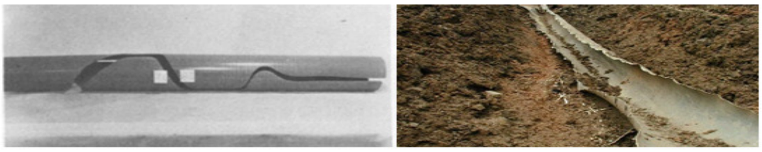


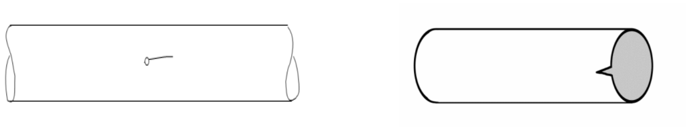
- Molecular hydrogen may diffuse into the pipeline material.
- This reduces pipeline ductility and tensile strength thus promoting brittle fractures.

## Fracture Propagation – Failure Type

**Brittle Fracture**
- Little or no plastic deformations

**Ductile Fracture**
- Significant plastic deformations





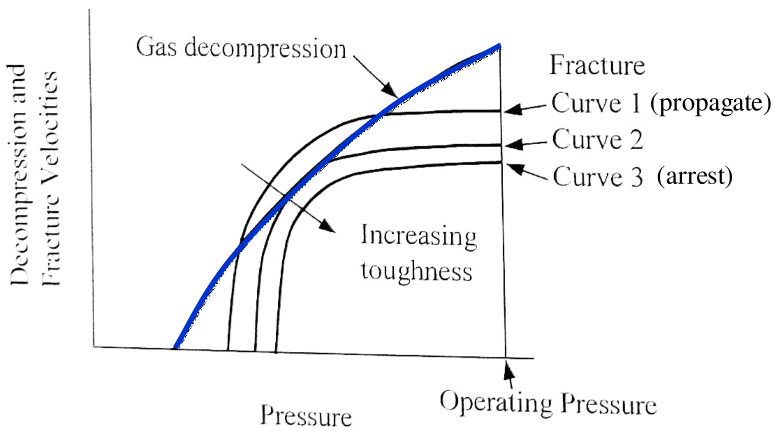
Implementation of mitigation measures (pipe material, fracture arrestors, operation pressure and temperature) require knowledge of the details of mechanisms of fracture propagation





## Ductile Fracture (DF) Analysis

DF propagation is accompanied by pressure drop in the pipeline
DF arrest: speed of decompression > speed of DF propagation




A typical diagram for Battelle Two Curve Methodology

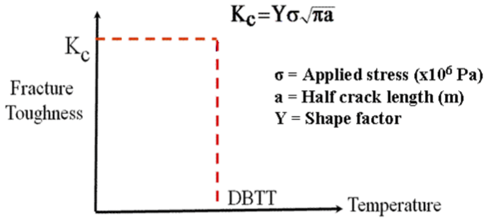
## Brittle Fracture

At the ductile/brittle transition temperature (DBTT), the fracture toughness is characterised by $K_c$.

At T < DBTT, the fracture toughness drops significantly (ca. 100% for carbon steel) and a fast running *brittle fracture* followed by a catastrophic failure of a structure, can happen.

The critical pipeline fracture toughness

$$K_c = Y\sigma\sqrt{\pi a}$$

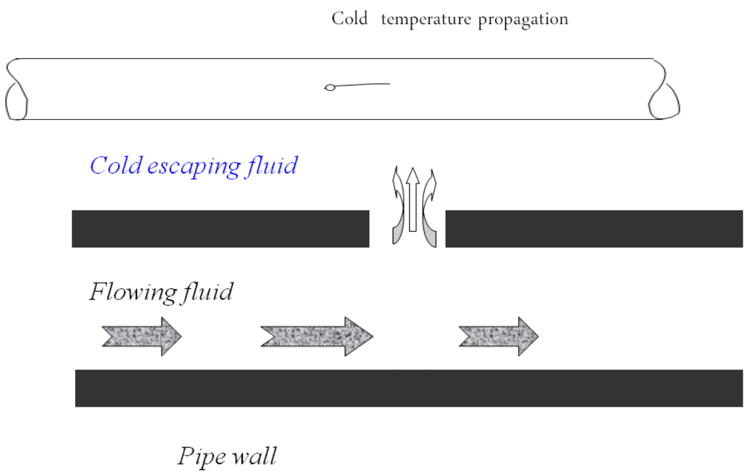



A schematic representation of ductile-brittle transition





## Brittle Fracture




Both the localised *pressure* and *thermal* stresses contribute to the mechanism of brittle fracture initiation and propagation.

## CO2 Pipeline Fracture Propagation

$CO_2$ pipelines are more susceptible to brittle fractures because:

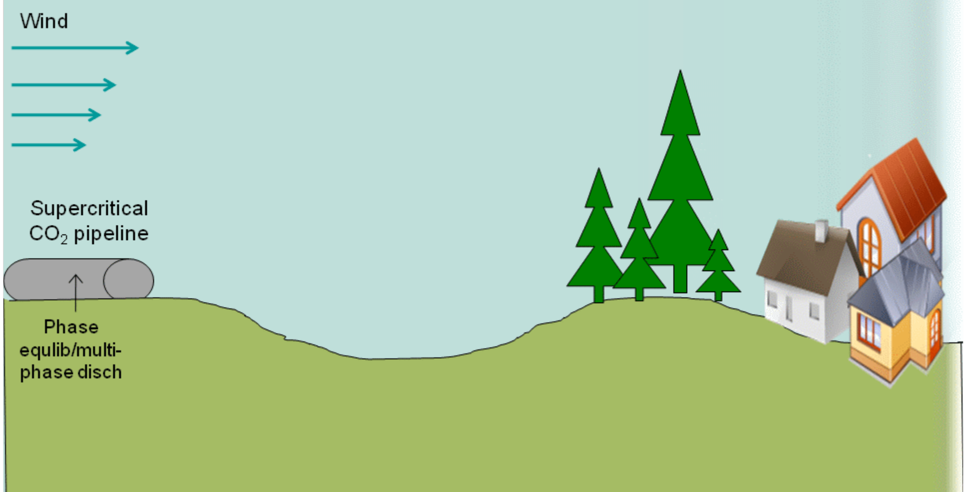
- $CO_2$ exhibits a prolonged phase transition during depressurisation.
- $CO_2$ undergoes significant Joule-Thomson expansion cooling during rapid depressurisation.

*Bilio, M., Brown, S. Fairweather, M. and Mahgerefteh, H. (2009) $CO_2$ PIPELINES MATERIAL AND SAFETY CONSIDERATIONS. Hazards XXI, IChemE Symposium Series, N 155, pp.423-429.*





## **$CO_2$PipeHaz:** Quantitative Failure Consequence Hazard Assessment for Next Generation $CO_2$ Pipelines: The Missing Link



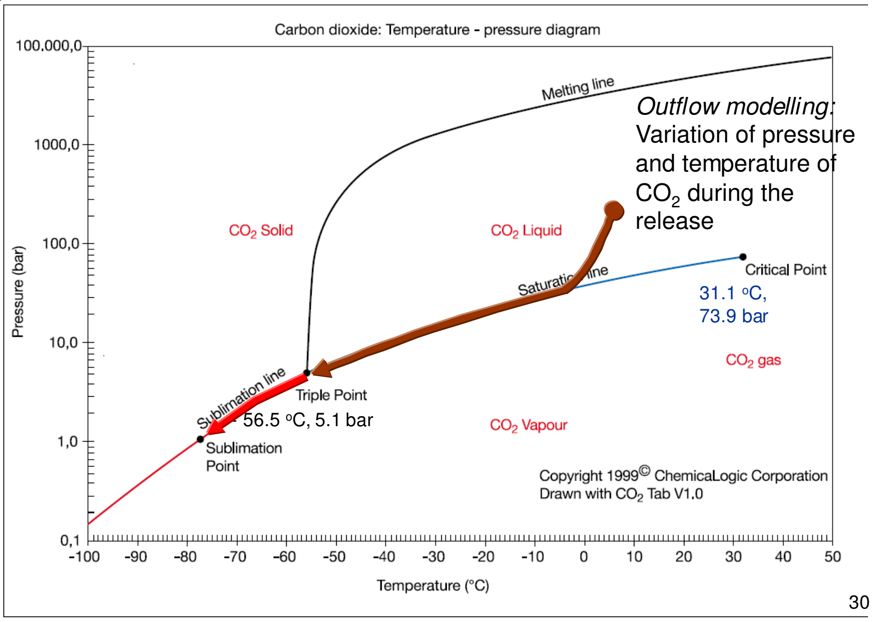
## $CO_2$ releases – risks of solids formation

- In the past  methodologies for assessment of the pipeline hazard profile were developed assuming the fluid to be in the liquid or vapour state.
- However, due to large values of the Joule-Thomson coefficient of $CO_2$, its rapid expansion from compressed state is accompanied by significant cooling effect, resulting in the formation of solids ("dry ice").



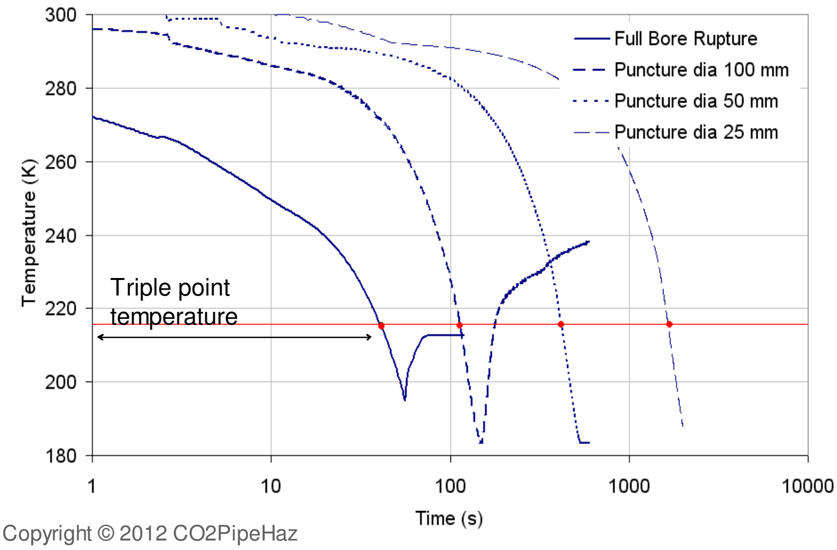


## $CO_2$ releases – risks of solids formation



## $CO_2$ releases – risks of solids formation

Temperature variation of $CO_2$ fluid during the release







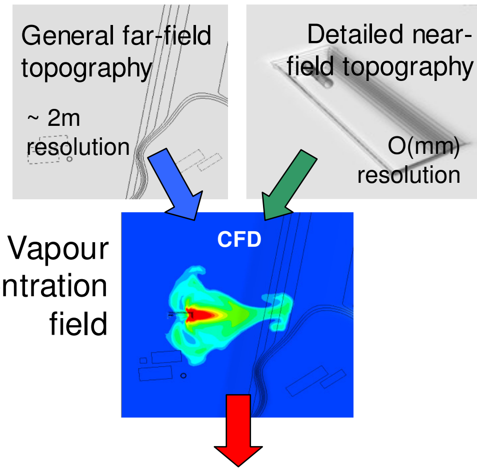

## $CO_2$ releases – risks of solids formation

- Experiments confirm that solid $CO_2$ can form upon release from high-pressure vessels.
- The processes of sublimation and rainout of solids in the flow may affect:
  - the atmospheric dispersion of $CO_2$ and
  - the hazard profile of the pipeline

# $CO_2$ Pipeline hazard profile

Accurate modelling of the consequences of an accidental release: CFD analysis of the atmospheric dispersion: the real terrain data, atmospheric conditions, multiphase nature, physical properties of the fluid

Geographical Information System (GIS) data



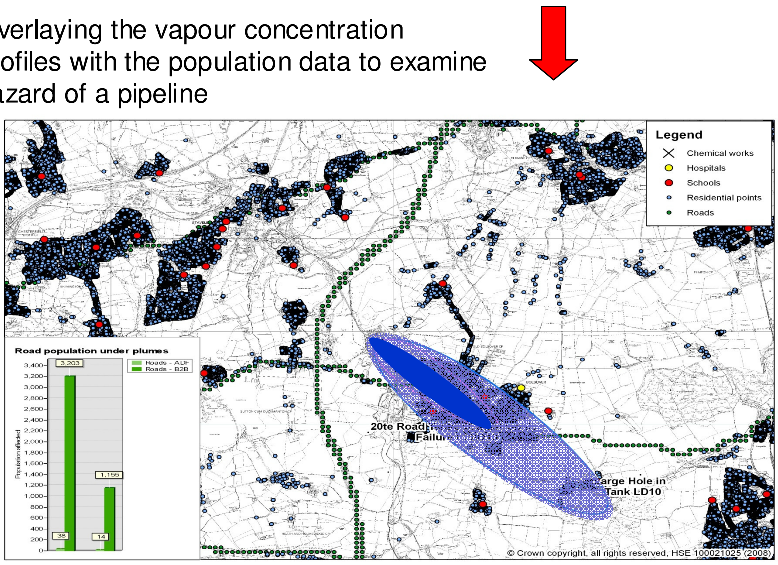

Vapour concentration field





# $CO_2$ Pipeline hazard profile

Overlaying the vapour concentration profiles with the population data to examine hazard of a pipeline



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Thank you ☺

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