CO_2 Transportation for CCS

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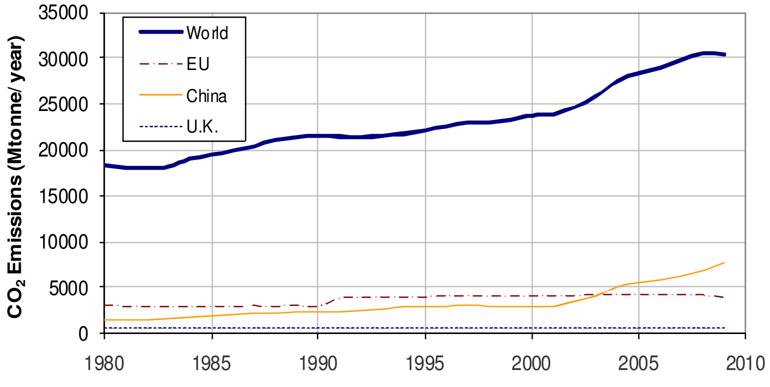
CO_2 Transportation for CCS

Presentation structure:

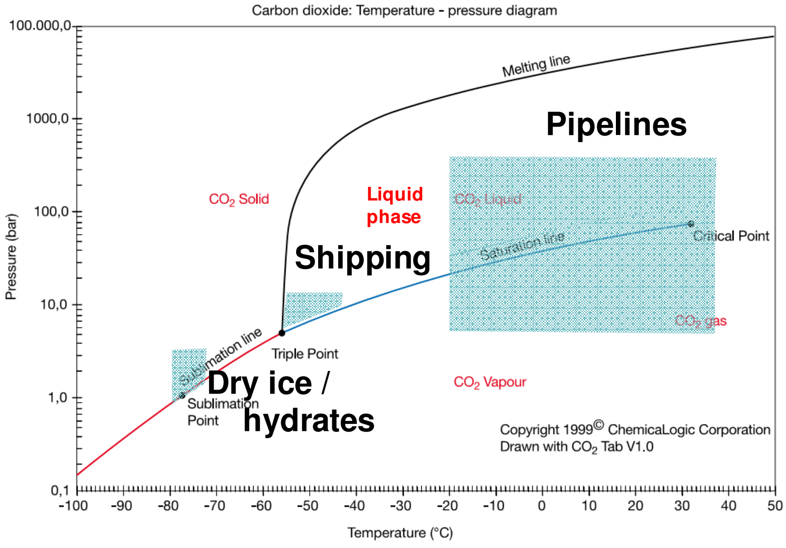
- CO_2 transportation for CCS
- CO_2 transport by pipelines:
- past and present experience,
- safety and risks,
- hazard assessment.

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

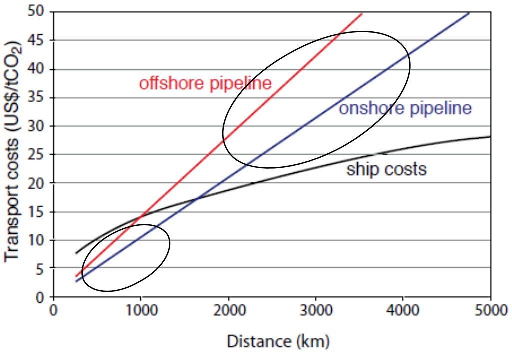


Introduction CO$_2$ transportation options



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.*

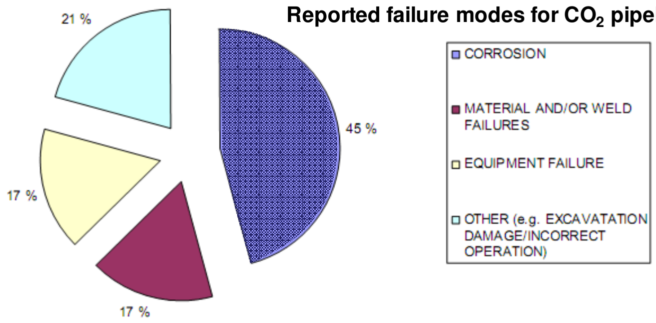
CO_2 pipeline transportation – past experience

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:

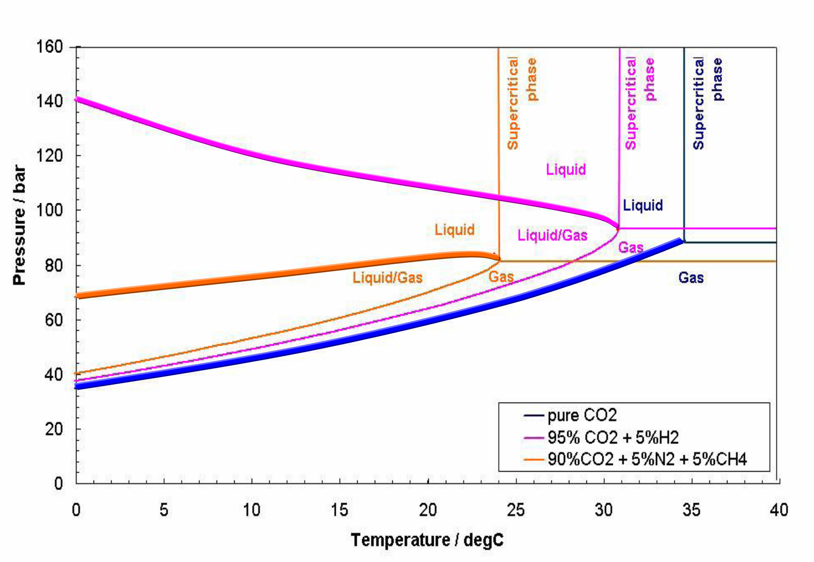
- properties of CO_2 with impurities,
- hydrogen embrittlement of pipe wall,
- hydrate formation,
- fracture propagation,
- corrosion of pipe wall,
- outflow and dispersion modelling.

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



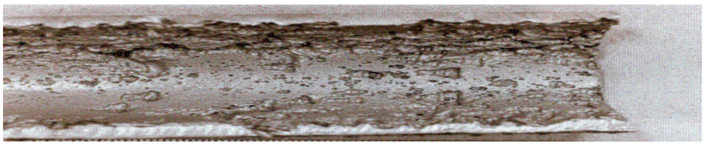
Impact of impurities

	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

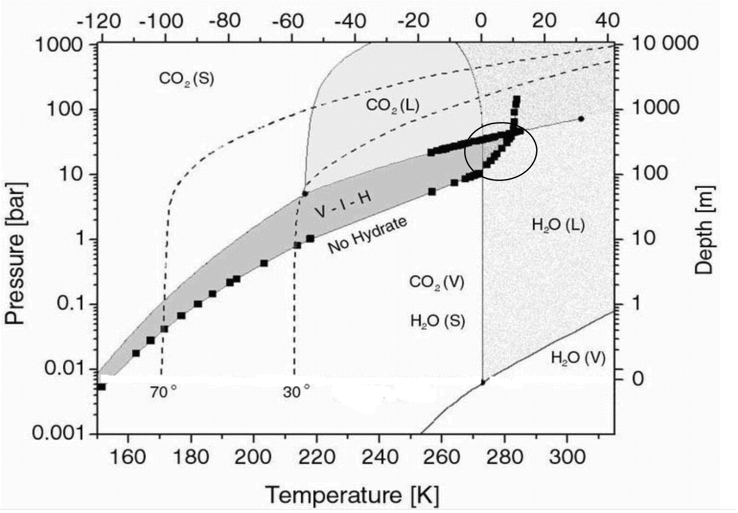


- Presence of small amount of water in CO_2 stream will be inevitable.
- Corrosion can occur when free water is in a direct contact with the pipeline material acting as an electrolyte or react with CO_2 forming carbonic acid.
- The solubility of water in CO_2 in the presence of impurities was not characterised.

Impact of impurities: Hydrate formation

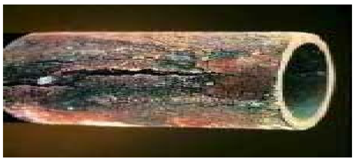
- Gas hydrates form as a result of the combination of water and gas molecules at suitable temperature and pressure.
- Hydrates can cause the blockage of the pipeline, giving rise to serious operational and safety issues.

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.

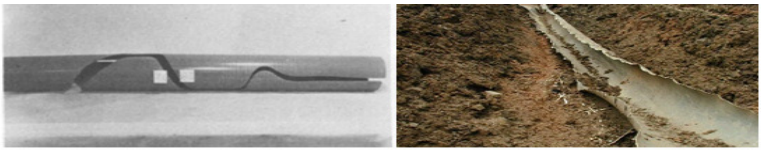
Fracture Propagation – Failure Type

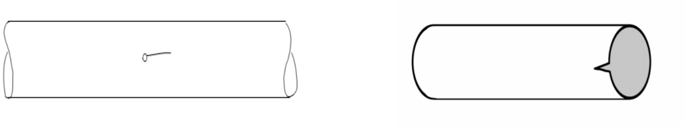
Brittle Fracture

- 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

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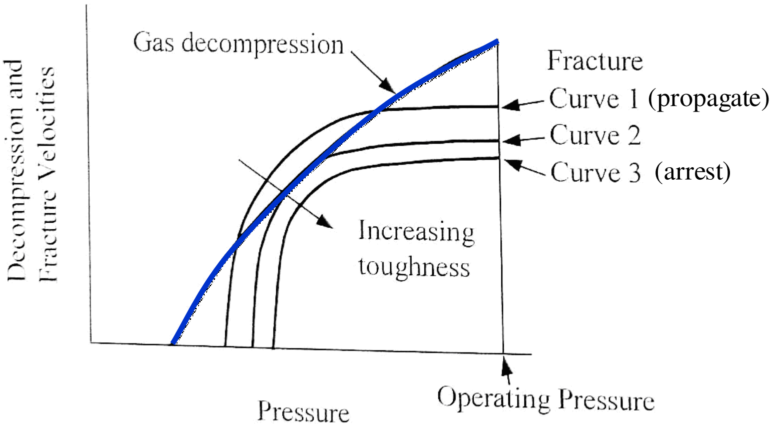
Ductile Fracture (DF) Analysis

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

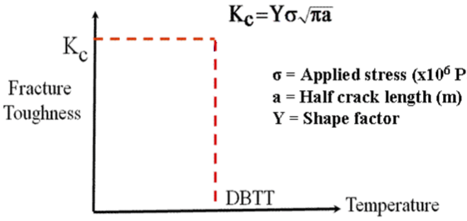
At the ductile/brittle transition temperature (DBTT), the fracture toughness is characterised by K_c.

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

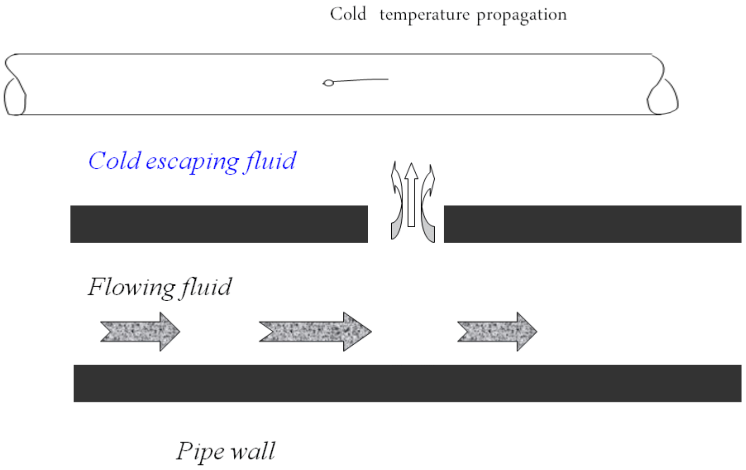
$K_c = Y\sigma\sqrt{\pi a}$

σ = Applied stress (x10^6 Pa)
a = Half crack length (m)
Y = Shape factor



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.

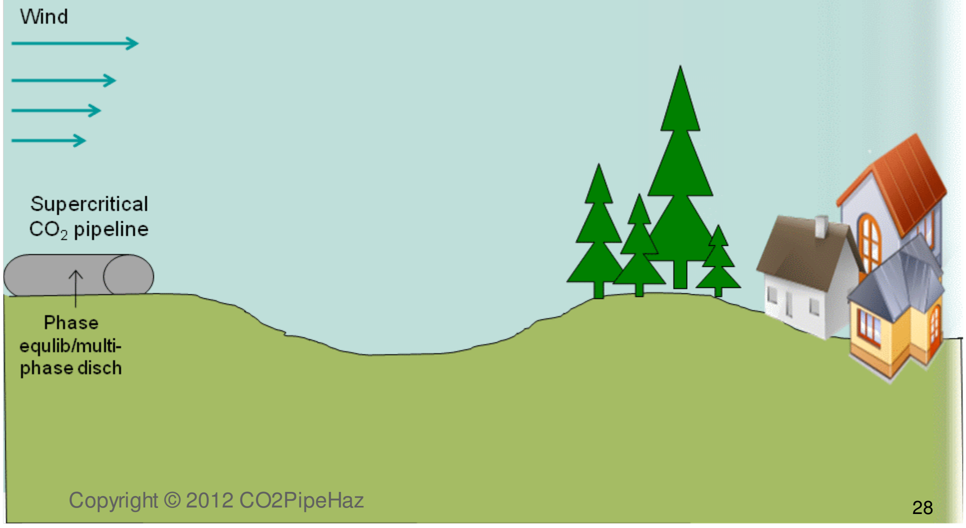
CO2 Pipeline Fracture Propagation

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.

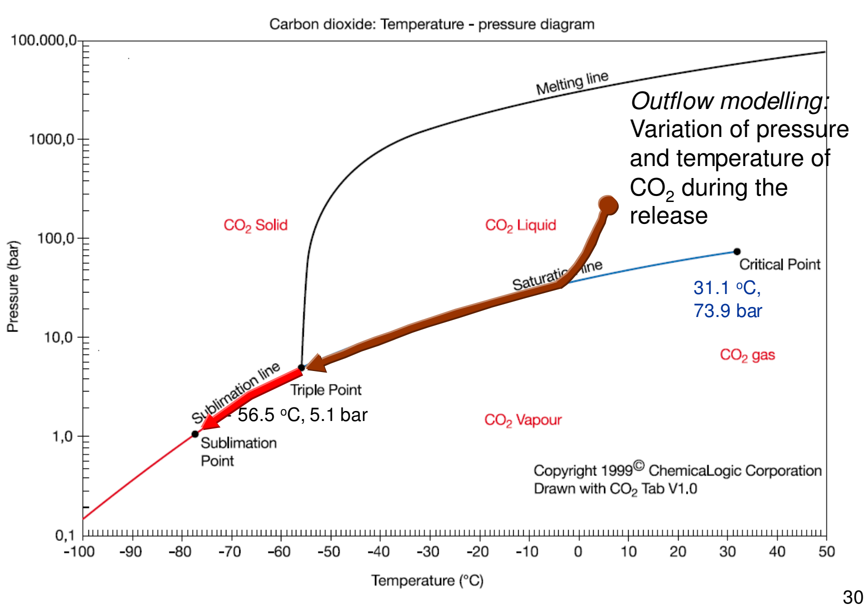
CO_2PipeHaz: Quantitative Failure Consequence Hazard Assessment for Next Generation CO_2 Pipelines: The Missing Link



CO_2 releases – risks of solids formation

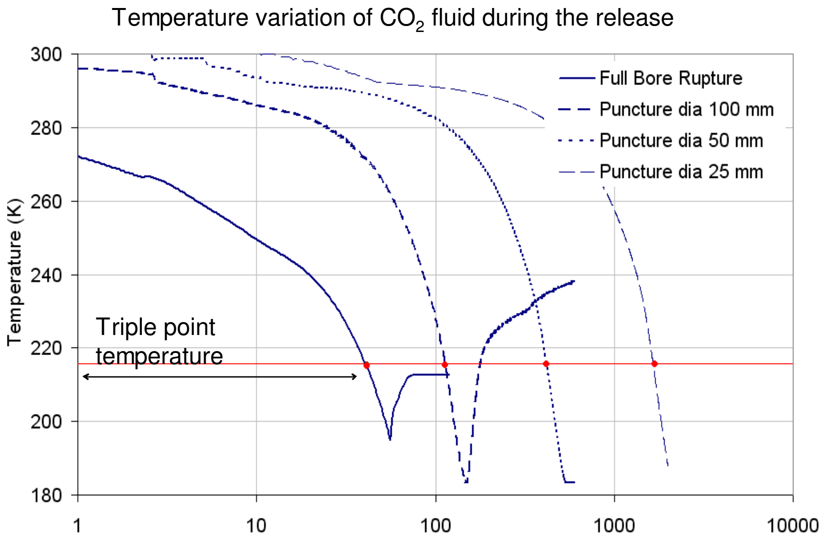
- In the past methodologies for assessment of the pipeline hazard profile were developed assuming the fluid to be in the liquid or vapour state.
- However, due to large values of the Joule-Thomson coefficient of CO_2, its rapid expansion from compressed state is accompanied by significant cooling effect,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

CO_2 releases – risks of solids formation



Outflow modelling:
Variation of pressure and temperature of CO_2 during the release

CO_2 releases – risks of solids formation


Temperature variation of CO_2 fluid during the release

CO_2 releases – risks of solids formation

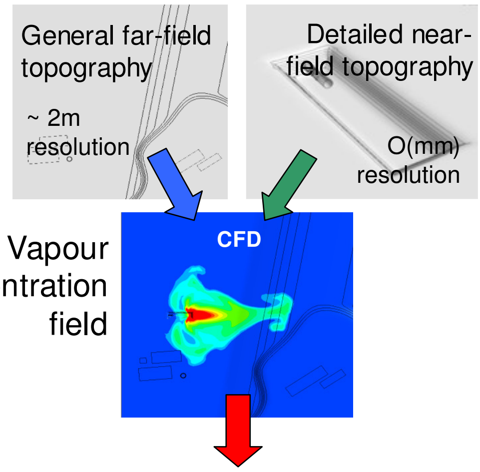
- Experiments confirm that solid CO_2 can form upon release from high-pressure vessels.

- 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



General far-field topography

~ 2m resolution

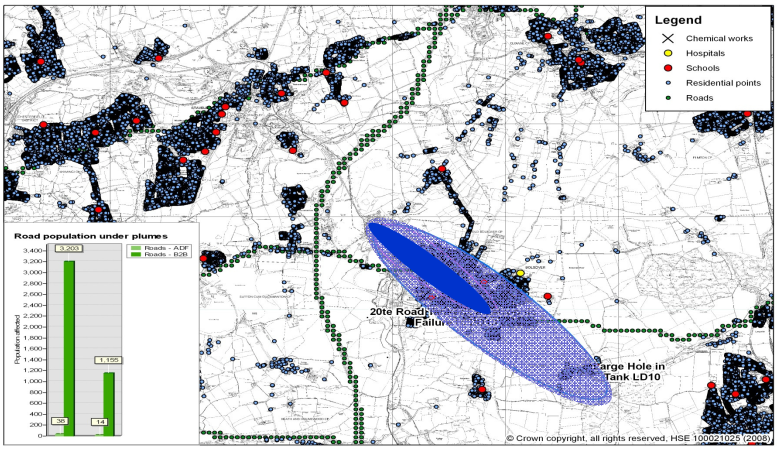
Detailed near-field topography

O(mm) resolution

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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