CO_2 transportation

Key safety challenges

Risk management & assessment for business

TCI RISK MANAGEMENT

AGENDA

1. Introduction

2. General CO_2 Introduction

3. Key CO_2 Challenges
   A. Toxicity
   B. CO_2 modelling
      - Concentration
      - Temperature
   C. Emergency Response philosophy

Speaker

Paul van Rossum

Co-founder TCI / Technical Safety Consultant
MsC Applied Physics

An energetic, positive, out-of-the-box thinker who loves to solve challenging problems.

Experience and competencies

- >15 years experience as TSE
- CCS risk management
- Hydrogen risk management
- Provision of a wide range of consequence modelling and quantitative safety studies (inc. CFD)
- HAZID/HAZOP/LOPA/Bowtie Facilitator
- Reliability, Availability and Maintainability Studies
- Experienced programmer (autonomous robot football)

About TCI Risk Management

WE GOT THIS

Safety Engineering and Risk Management Consultancy

- Consequence and Physical Effects Modelling (incl. CFD)
- Risk Reduction & ALARP
- HSSE / Safety Cases and supporting studies
- HSE Management Systems Development and Implementation
- Facilitation of HAZID and HAZOP workshops
- Functional Safety (FSA, LOPA, SIL)
- BowTie - Barrier Risk Management;
- Identification of Safety & Environmental Critical Elements and Safety & Environmental Critical Tasks
- Optimisation of Fire and Gas Detection System Layouts
- Reliability, Availability, Maintainability (RAM)

www.tci-rm.com

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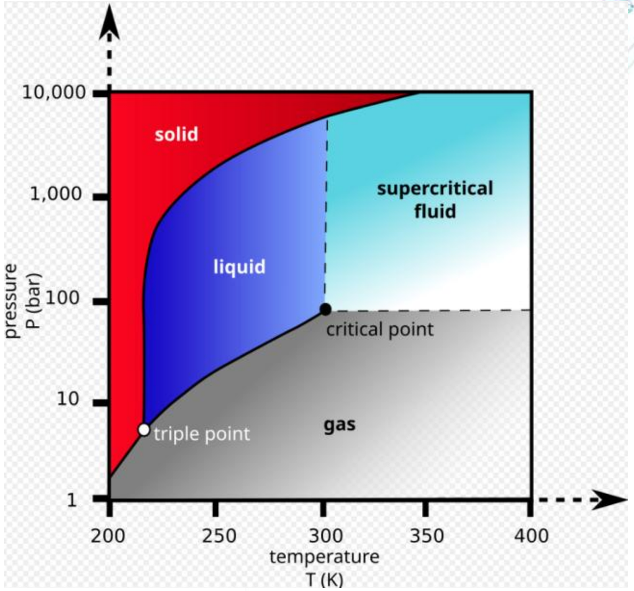
CO_2 properties

O=C=O

- Colourless
- Odourless
- Not Flammable
- Soluble in water
- Heavier than air (MW=44 vs ~29)
- Under atmospheric pressure, gas or solid (not liquid)
- CO_2 transported offshore in Supercritical phase
- Forms a solid “dry ice” at -78°C
- CO_2 is a Greenhouse gas



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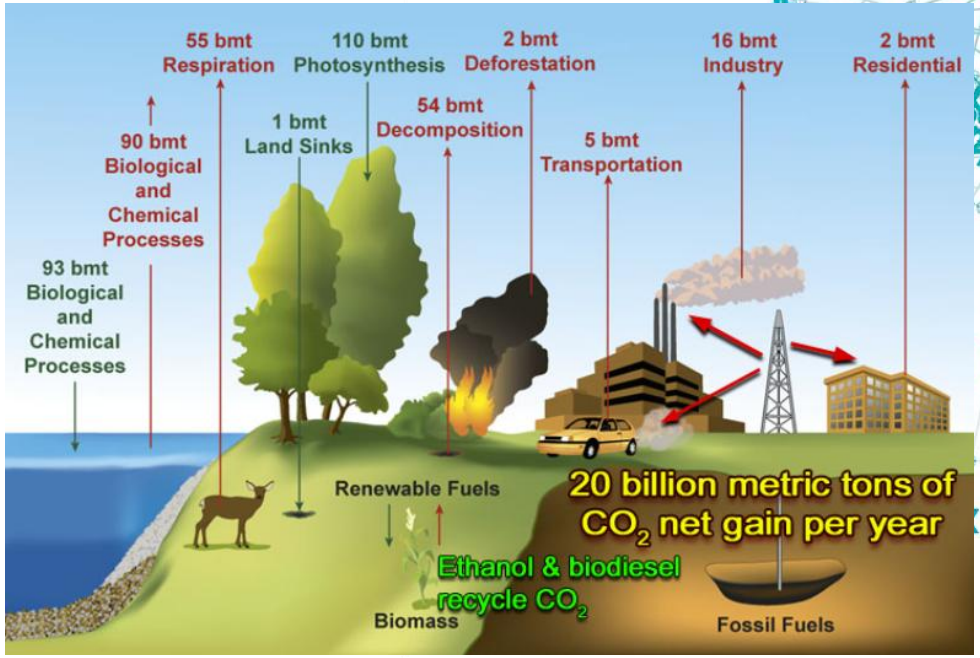
CO_2 sources

- Naturally occurring
- Man-made emissions
- Carbon Capture & Storage



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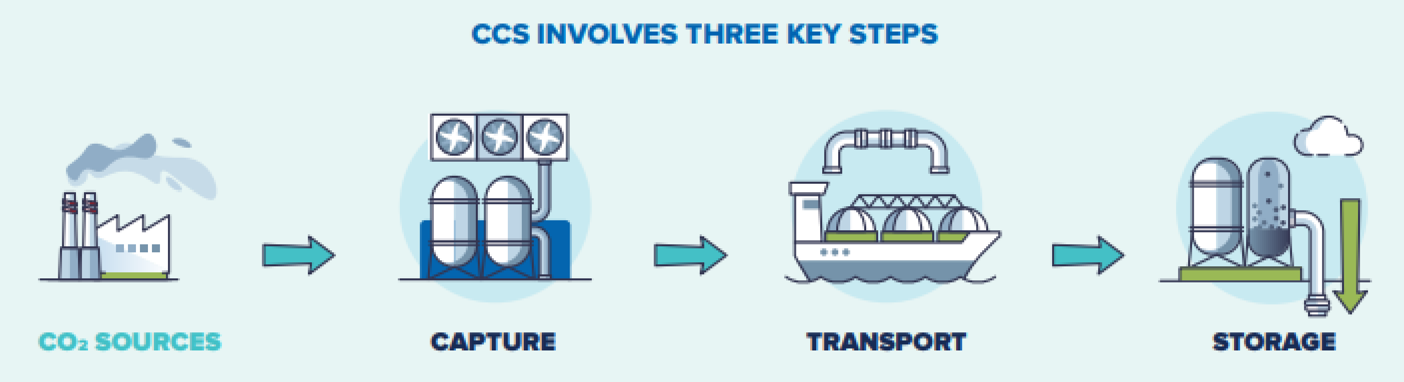

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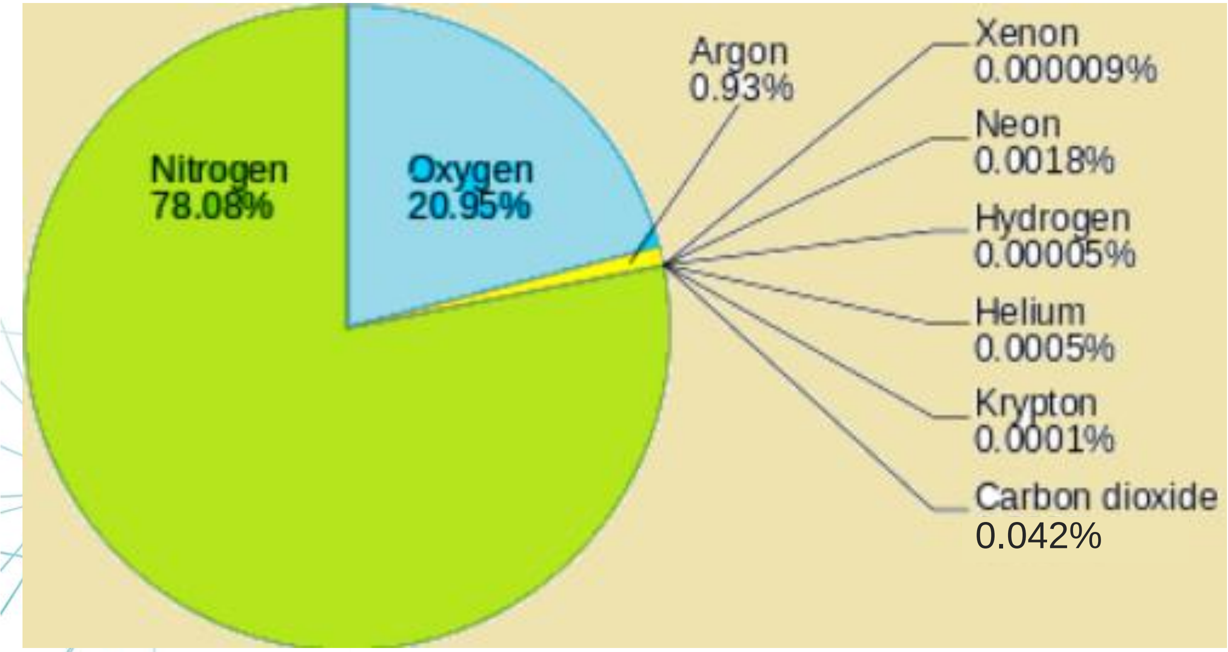
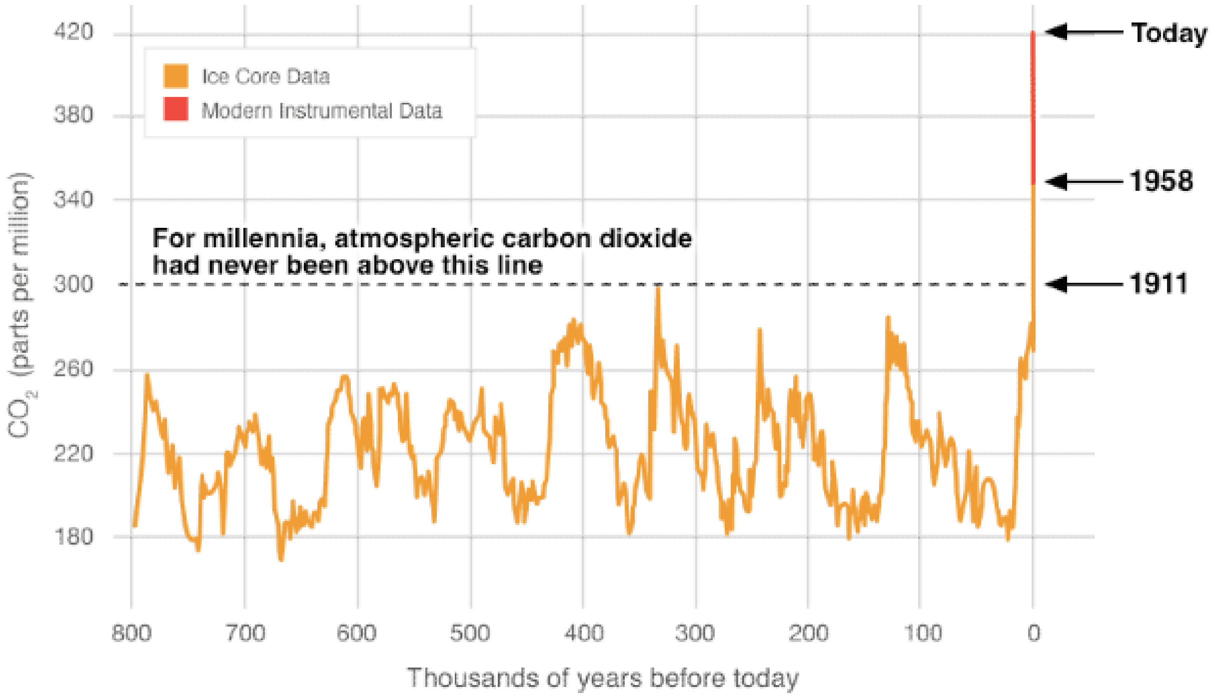
CO_2 in atmosphere

How much CO_2 is there in the atmosphere?



PROXY (INDIRECT) MEASUREMENTS

Data source: Reconstruction from ice cores.
Credit: NOAA



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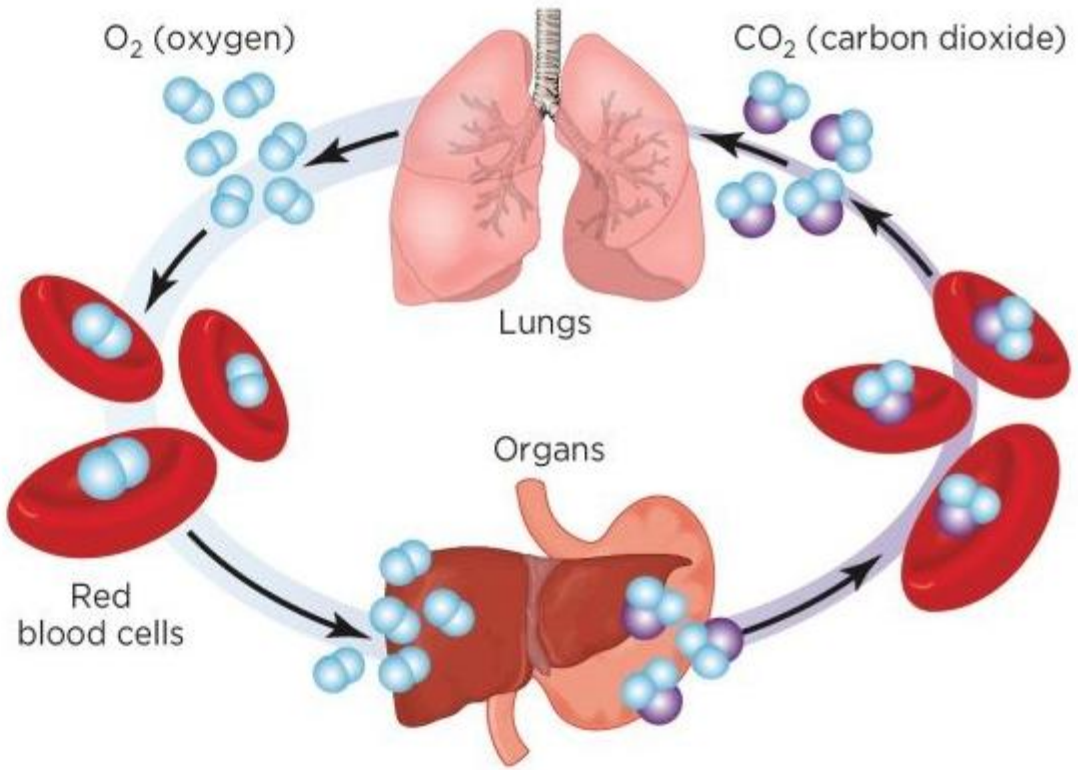
CO_2 in human body



How much CO_2 do we breathe out?

Exhaled air ~4% CO_2, 100 x inhaled

CO_2 challenges - CO_2 toxicity

- Many decisions in design & ER based on effect on people
- Various views exist on ‘tolerable’ levels of CO_2 exposure
- Too conservative assumptions may lead to overdesign

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CO_2 challenges - CO_2 toxicity

Examples:

Dutch regulator (RIVM) summary of CO_2 hazards:
20220608-carbon dioxide-INHOUDELIJK VASTGESTELD | RIVM

Concentration CO_2 (ppm)	Concentration CO_2 (Vol%)	Concentration CO_2 (mg/m³)	Remarks
45000	4.5	823500	Reduced concentration capability after more than 8 hours exposure, adaptation possible
55000	5.5	100650	Breathing difficulty, headache and increased heart rate after 1 hour
65000	6.5	118950	Dizziness, and confusion after 15 minutes exposure
70000	7.0	128100	Anxiety caused by breathing difficulty effects becoming severe after 6 minutes exposure
100 000	10	183000	Approaches threshold of unconsciousness in 30 minutes
120 000	12	219600	Threshold of unconsciousness reached in 5 minutes
150 000	15	274500	Exposure limit 1 minutes
200 000	20	366000	Unconsciousness occurs in less than 1 minute

NASA Technical Memorandum 103832: **Individuals have tolerated levels of up to 5% for *'days to weeks'***

Summary

Physiologic responses to elevated CO_2 levels are dependent on the degree and duration of exposure. Exposure to CO_2 levels above 5% produces marked symptomology and cannot be tolerated for extended periods of time. Carbon dioxide levels between 3-5% produce symptoms of dyspnea, but individuals have tolerated these exposures for days to weeks. Exposure to CO_2 levels of 2-3% can be tolerated for weeks to months. Concentrations of CO_2 below 2% can be tolerated indefinitely.

'Carbon dioxide tolerability and toxicity in rat and man: A translational study' (Frontiers in Toxicology)

	CO_2 exposure level										
	6 %			*7.5 %*			*9 %*			*10 %*	*12 %*
Intended duration, minutes	***10***	***30***	***60***	***10***	***30***	***60***	***10***	***30***	***60***	***10***	***10***
Number participants	***6***	***6***	***6***	***6***	***6***	***6***	***6***	***6***	***6***	***10***	***2***
Completed regardless intended duration, No. (%)	18 (100)	12 (100)	6 (100)	18 (100)	12 (100)	6 (100)	12 (66.7)	4 (33.3)	1 (16.7)	3 (30)	0 (0)
Actual exposure duration, mean (SD)	10 (0)	30 (0)	60 (0)	10 (0)	30 (0)	60 (0)	10 (0)	15.7 (12.2)	22.2 (21.5)	7.1 (2.6)	6.5 (2.1)

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CO_2 toxicity - probit

Table of SLOT & SLOD values for CO_2 [IOGP 434-14]

Inhalation exposure time	SLOT: 1-5% Fatalities		SLOD: 50% Fatalities	
	CO_2 Concentration in air*		CO_2 Concentration in air*	
	%	ppm	%	ppm
60 min	6.3%	63 000 ppm	8.4%	84 000 ppm
30 min	6.9%	69 000 ppm	9.2%	92 000 ppm
20 min	7.2%	72 000 ppm	9.6%	96 000 ppm
10 min	7.9%	79 000 ppm	10.5%	105 000 ppm
5 min	8.6%	86 000 ppm	11.5%	115 000 ppm
1 min	10.5%	105 000 ppm	14%	140 000 ppm

There are three different ‘probit’ functions in the published/online literature:

1. Energy Institute: Y = -89.8+In((C^8)*t)
2. RIVM (referencing UK-HSE): Y = -90.8+1.01*In((C^8)*t)
3. IOGP Report 434-14: Y = -72.44+0.817*In((C^8)*t)

Y is then related to lethality by a standard formula: $\text{Lethality} = \left(-\text{erf}\left(\frac{5-Y}{\sqrt{2}}\right)+1\right)/2$

CO_2 toxicity - conclusions

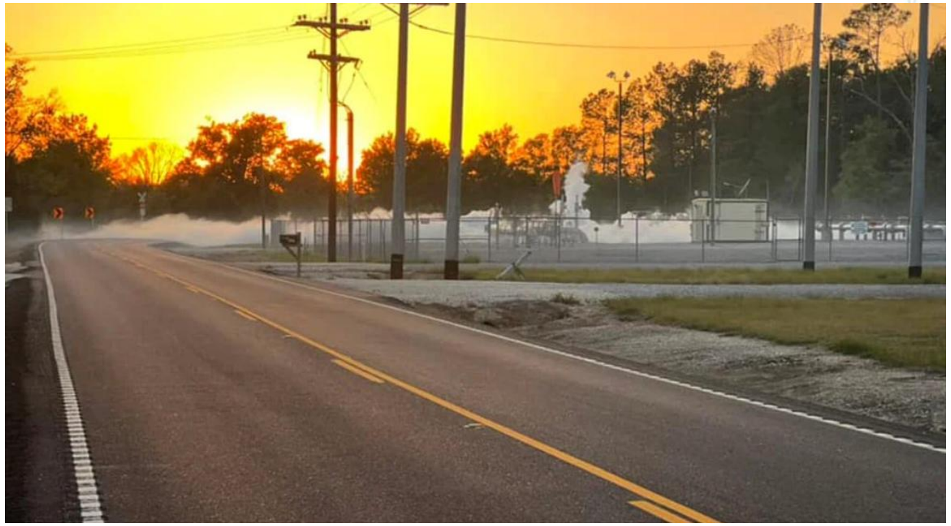
- We have evolved as humans to be able to easily withstand CO_2 concentrations up to 5%
- Guidance to date has been based on conservative assumptions in the face of limited scientific data
- Recent Human Vulnerability study provides clear evidence of subjects voluntarily withstanding CO_2 levels previously thought to be life-threatening
- As our understanding has developed, there is scope for reviewing human vulnerability / fatality functions

CO_2 challenges - CO_2 modelling

- Many decisions in design & ER based on effect on people & **asset**

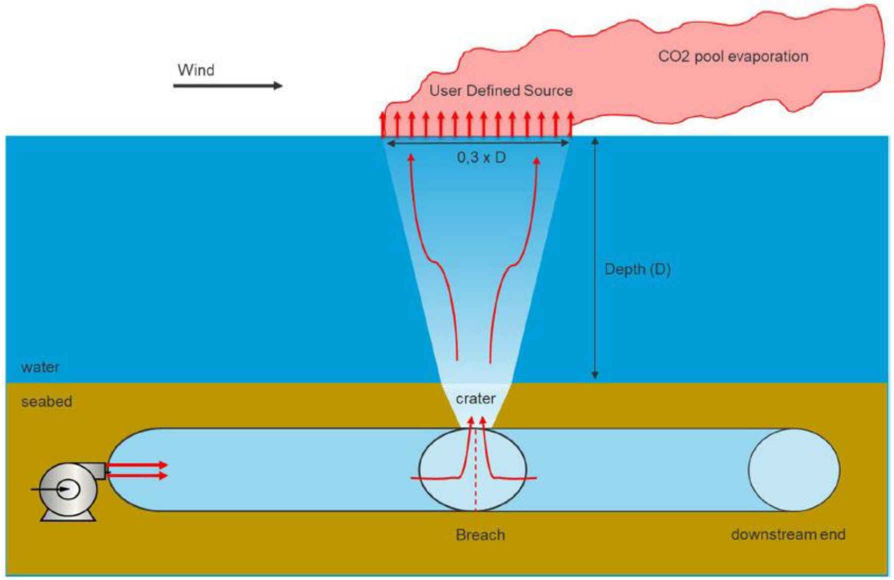
- Large uncertainty in modelling
  - Validation on limited data
  - Scalability

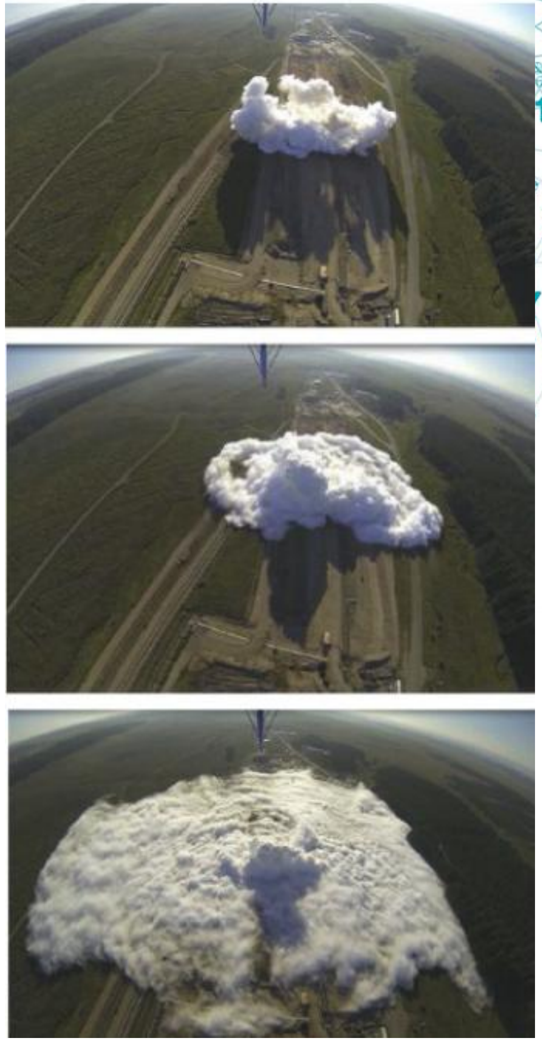
- Too conservative assumptions may lead to overdesign



CO_2 modelling

- Many “sub-models” available
  - Dense phase is either gas or liquid
  - “Gas Blanket” dispersion model (upwind)
  - Crater for underground pipeline
  - Underwater approach
  - Detailed knowlegde required for interpretation of results





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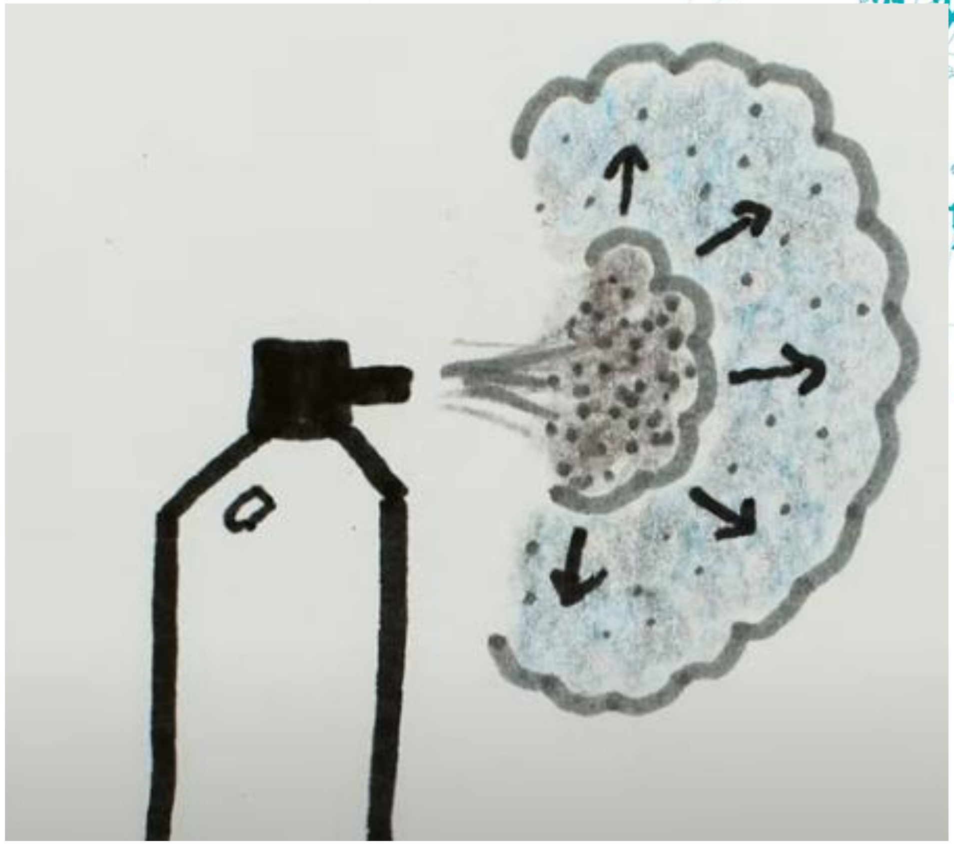
Cryogenic impact of CO_2

- Joule–Thomson (JT) effect
- Describes the temperature change of a gas or liquid when it expands through an orifice
- CO_2 has a strong JT effect causing very cold temperatures
- Released from dense & liquid phase -78°C + solid formation



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Cryogenic impact of CO_2

Cryogenic escalation

Leak in dense phase CO_2 system

Cold CO_2 jet impinging on structural member →

Cool down of structural member. Potential failure

Increased load / stress on other structural members →

Potential failure of platform

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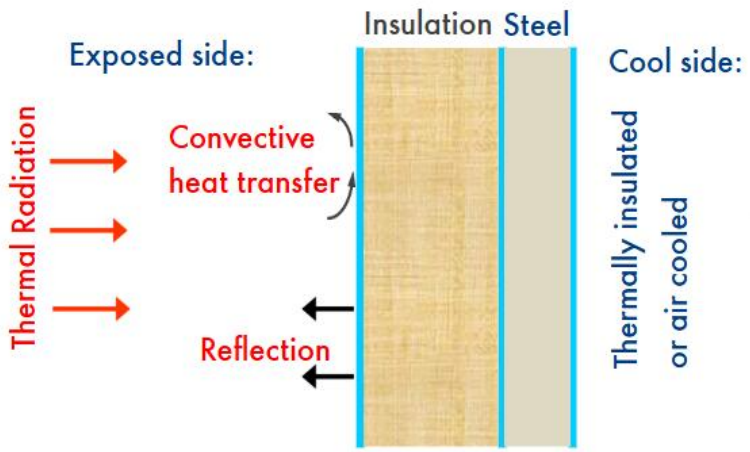
Cryogenic impact of CO_2

Cryogenic Risk Assessment

- Quantity the frequency of exceeding brittle fracture criteria for critical targets
- Temperature Rise models (e.g. in FRED) are established
- Cool down model uses same principles
- Embrittlement time based upon
  - Thickness receiving material
  - Plume temperature & width
  - CO_2 jet velocity
  - Exposed to gas or solid
- Important input to design



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CO_2 Challenges - ER

- ER Offshore
  - Typically based on O&G standards
  - Less familiar with heavy toxic gasses
  - Requires new philosophies

- ER Onshore
  - Similar to other heavy toxic gasses

ER Offshore

Which part of ER would you do **different** from traditional O&G?

- Detection
- Isolation / Blowdown
- Escape routes
- Muster area
- Evacuation
- PPE
- Ship Collision

- Noise, CO_2
- Yes & No
- Visibility
- Prevent impairment
- Going up
- Visibility, Cold
- Same as O&G

ER Onshore

Which part of ER would you do **different** from traditional O&G&C?

- Detection
- Isolation / Blowdown
- Muster area
- PPE
- BRA

- Noise, CO_2
- Yes & No
- Upwind dispersion
- Visibility, Cold
- Like heavy gas

- Cold dense plumes, slump into low areas
- Engines may stall
- Poor visibility may impair escape

Summary

- CO_2 is part of our daily life
  - Remember 0.04% versus 4% ☺
- Current probit can be considered conservative
- Consider the risk of cryogenic escalation
- Sensitivities of existing software models for CO_2
- Update of ER philosophy required for CO_2
- And many others which cannot be covered in half an hour

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Have a safe and secure day!

THANK YOU FOR YOUR ATTENTION

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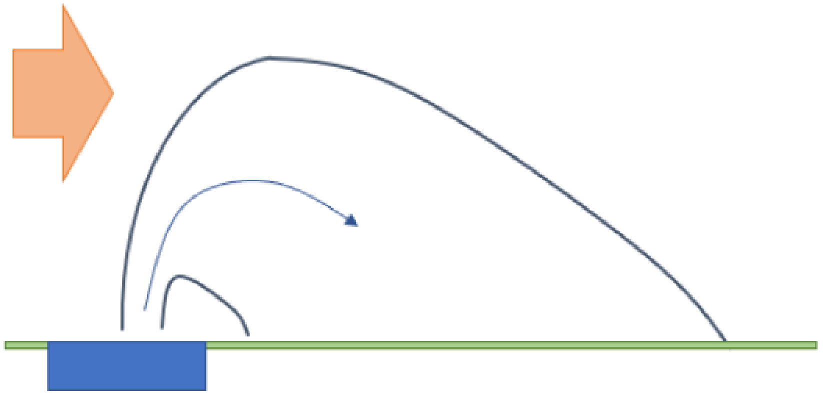
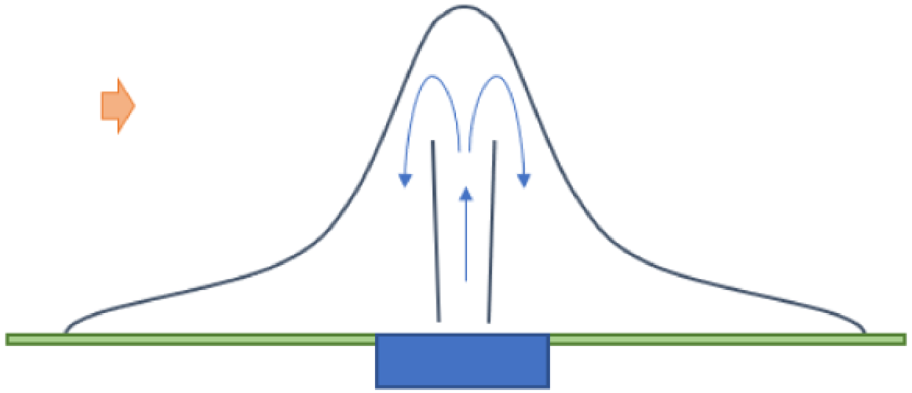
- High wind speed
  - Plume trajectory bent over by wind
  - No re-entrainment, no upwind spreading
  - Suitably handled by UDM

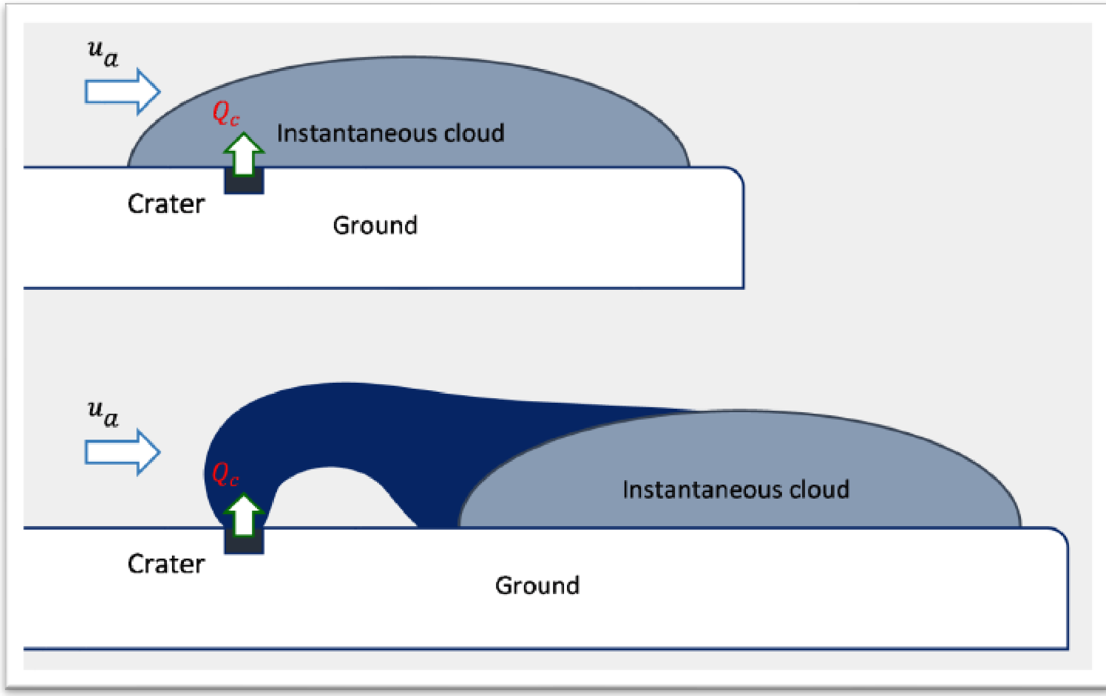


- Low wind speed
  - Low impact on trajectory, results in ‘fountain’ behaviour
  - Circular spreading at ground level
  - Not well handled by standard UDM



‘Gas Blanket’ model

- Requires the initial jet-based plume to touch down at > 45° impact angle (configurable)
- Represents the release as an instantaneous release
- Fed by a time-varying crater source
- Eventually the instantaneous cloud drifts and uncovers the crater
- Any remaining source treated as normal vertical jet



Gas blanket modelling