Carbon dioxide vessel incidents, consequence models and experiments

Non-pipeline transport and international shipping of CO_2 workshop

Regulations, Safety and Risk session

Cardiff University, Wales, 25 March 2026

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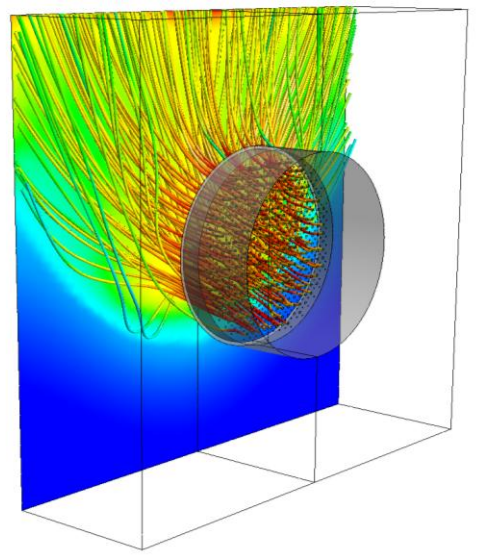
Overview

- Introduction to HSE
- Context: non-pipeline transport of CO_2
- Failure of vessels containing pressure-liquefied gases
- CO_2 vessel failure incidents
- Experiments
- Models
- Standards, guidelines, codes of practice and other helpful information
- Summary and next steps

Introduction to the Health and Safety Executive (HSE)

- HSE is the regulator for workplace health and safety in Great Britain
- Includes onshore/offshore pipelines, chemical/oil/gas infrastructure, offshore platforms
- Activities: evidence gathering, policy development, consultation, regulation, incident investigation, enforcement
- In 2025: 730,000 new cases of work-related ill health, 124 fatalities in workplace accidents*
- HSE has 3,000 total staff (FTE): £310M annual budget, 66% from Government

- HSE Science and Research Centre, Buxton, UK
- 400 staff, 550-acre test site
- Scientific support to HSE and other Government departments
- “Shared research” or joint-industry projects co-funded by HSE
- Bespoke consultancy on a commercial basis



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* Source: https://www.hse.gov.uk/statistics/assets/docs/hssh2425.pdf

Context: Potential growth in shipping of CO_2

Global CCS Institute: forecast growth in worldwide CO_2 shipping from current level of 0.5 million tonnes per annum (Mtpa), Nov 2025

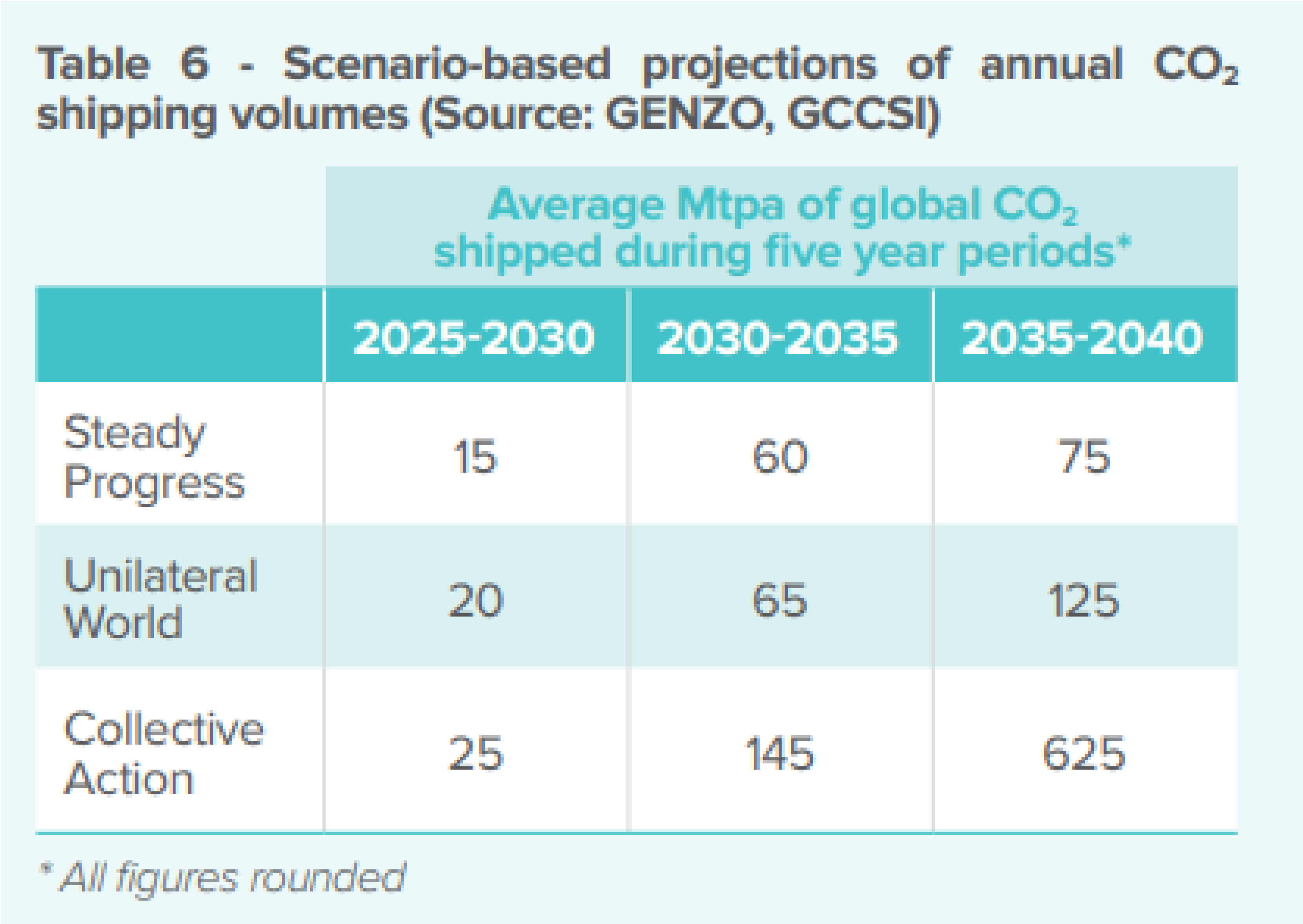
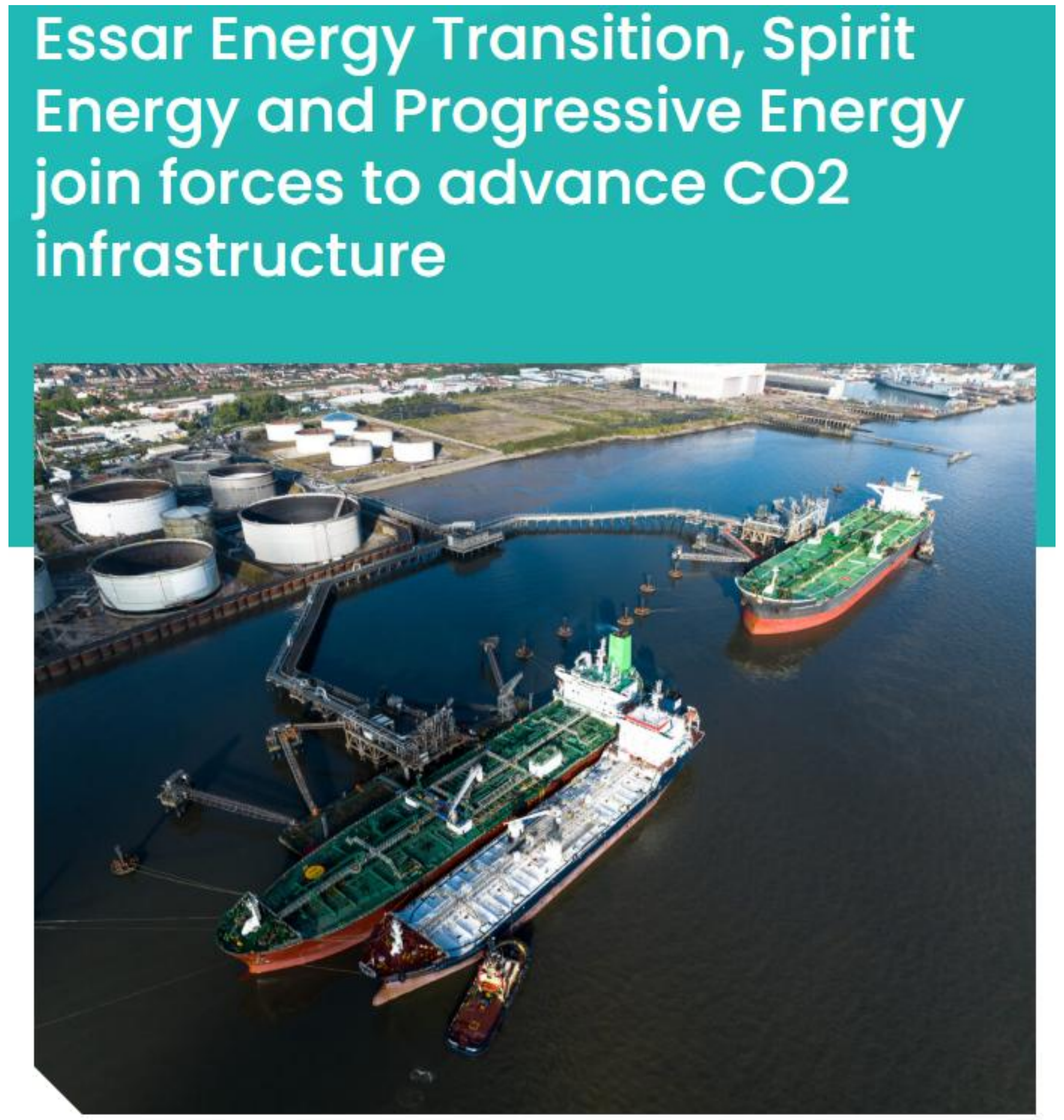


Table 6 - Scenario-based projections of annual CO_2 shipping volumes (Source: GENZO, GCCSI)

	Average Mtpa of global CO_2 shipped during five year periods*		
	2025-2030	2030-2035	2035-2040
Steady Progress	15	60	75
Unilateral World	20	65	125
Collective Action	25	145	625

* *All figures rounded*

https://www.globalccsinstitute.com/wp-content/uploads/2025/11/Global-CCS-Institute-Needs-Opportunities-and-Prospects-for-CO2-Shipping-in-CCS-Projects.pdf



Essar Energy Transition, Spirit Energy and Progressive Energy join forces to advance CO2 infrastructure

https://www.stanlowterminals.co.uk/essar-energy-transition-spirit-energy-and-progressive-energy-join-forces-to-advance-co2-infrastructure/

Home › United Kingdom › Immingham Port › UK to Build CO2 Terminal at Immingham in CCS Transport-Storage Network

United Kingdom Immingham Port News Ports

UK to Build CO2 Terminal at Immingham in CCS Transport-Storage Network

By **portnews** - October 24, 2022 133 0

Immingham is the UK's largest port by volume and well positioned to be part of the CCS network (ABP)

https://www.worldports.org/uk-to-build-co2-terminal-at-immingham-in-ccs-transport-storage-network/

Context: Onshore temporary storage of CO_2

Liquid CO_2 at saturation conditions

Temperature	Density
0 °C	925 kg/m^3
-25 °C	1054 kg/m^3
-45 °C	1136 kg/m^3

https://encyclopedia.airliquide.com/carbon-dioxide

Øygarden, Norway (Northern Lights Project)

- Onshore storage, 12 × 700 m^3 tanks (Phase 1), further 9 tanks (Phase 2)
- Ship capacity: 7,500 m^3 (2 × 3,750 m^3 tanks), future capacity 12,000 m^3

https://norlights.com/news/northern-lights-expansion-of-phase-2-new-storage-tanks-arrived/

Esbjerg, Denmark (Greensand Project)

- Onshore storage, 6 × 1,000 te tanks
- Ship capacity: 5,000 m^3 (8 tanks)

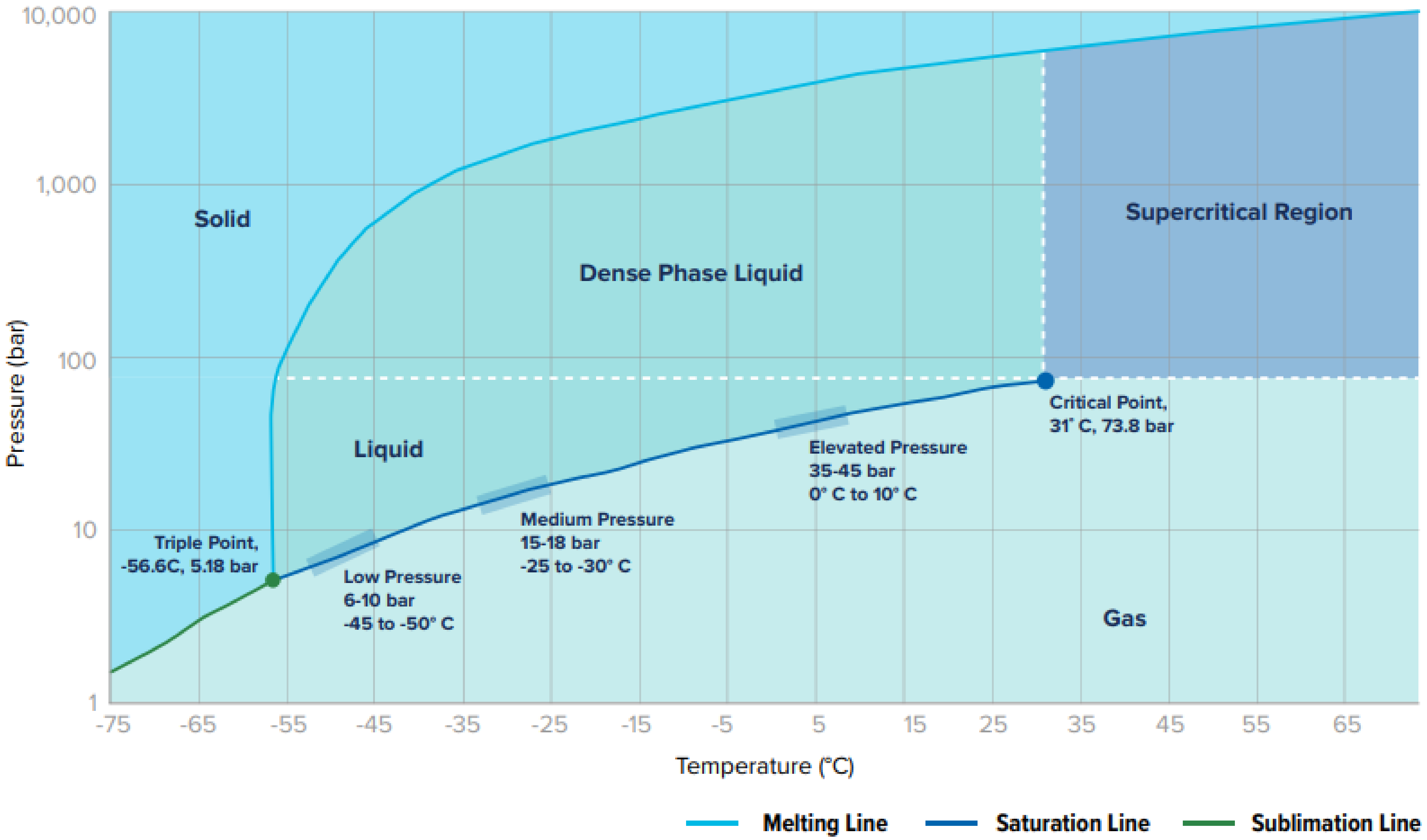
https://knowledge.energyinst.org/new-energy-world/article?id=139606

https://www.wagenborg.com/news/final-co2-tanks-installed-on-carbon-destroyer-1-in-delfzijl

https://www.ineos.com/inch-magazine/articles/issue-30/carbon-destroyer-1-launches-as-europes-first-co2-storage-ship/

Storage conditions: pressure and temperature

Figure 1 - Pressure and temperature balance for CO_2 vessels (Advancements in CCS technologies and costs, GCCSI)



https://www.globalccsinstitute.com/wp-content/uploads/2025/11/Global-CCS-Institute-Needs-Opportunities-and-Prospects-for-CO2-Shipping-in-CCS-Projects.pdf

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Failure of vessels containing pressure-liquefied gases (e.g., CO_2)

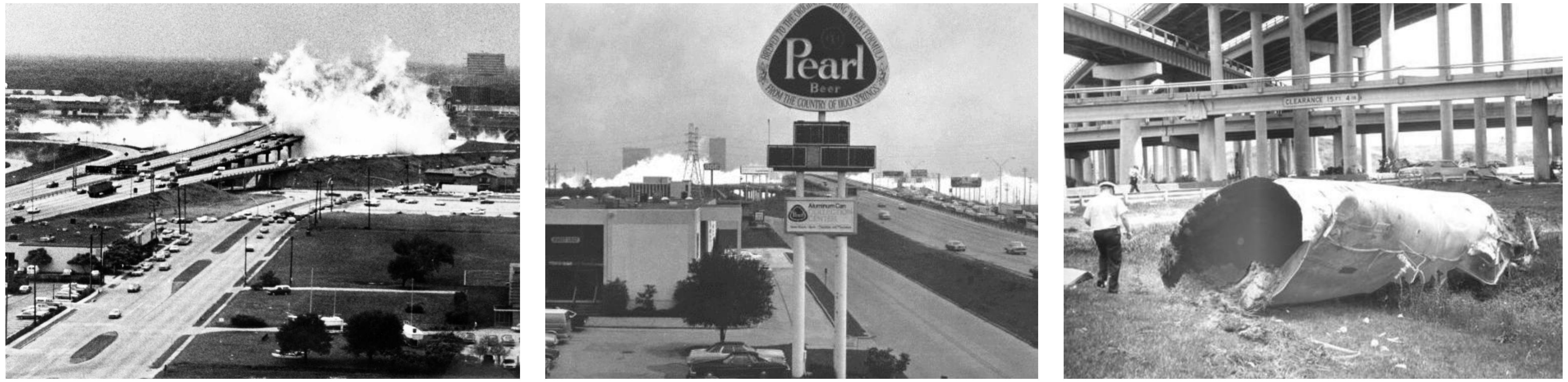
- **Hole in storage vessel** produces a two-phase jet and a dispersing cloud of toxic CO_2

Photos of CO_2 jet experiments at INERIS, https://ineris.hal.science/ineris-00973714/document

https://doi.org/10.1016/j.jlp.2014.09.014

- **Catastrophic vessel failure** produces:
  - Blast effect (pressure wave) due to rapid phase-transition from liquid into vapour, i.e., BLEVE
  - Expanding cloud of droplets and vapour, producing a dispersing cloud of toxic CO_2

} Primary focus of this talk



Photos of **ammonia** road tanker catastrophic vessel failure in Houston, Texas (1976)
Ammonia and CO_2 are both transported as pressure-liquefied gases

Photograph taken by Texas Air Control Board

https://www.houstonchronicle.com/news/houston-texas/houston/article/In-1976-an-ammonia-truck-disaster-claimed-the-12906732.php

What is a BLEVE?

- Boiling Liquid Expanding Vapour Explosion (BLEVE)
- Steps involved:
  1. Vessel containing pressure-liquefied gas ruptures
     - Due to over-pressurization (e.g., loss of cooling, fire engulfment), missile hit, material fatigue, corrosion etc.
  2. Instantaneous loss in pressure: liquid now in “metastable” superheated state
  3. Liquid instantaneously transforms into vapour, expanding in volume by factor of 100s or 1000s, producing a powerful blast wave
  4. Fragments of the vessel are projected outwards at high velocity
  5. The rapidly expanding cloud of vapour mixes with air
     - For flammable substances (e.g., LPG) if this cloud ignites, there can be a fireball
     - For non-flammable substances (e.g., CO_2), the plume disperses in the atmosphere

Causes of 88 major BLEVEs occurring from 1926 to 2007

Fire	36%
Mechanical damage	22%
Overfilling	20%
Runaway reactions	12%
Overheating	6%
Vapour space contamination	2%
Mechanical failure	2%

Source: Abbasi & Abbasi (2007)
http://dx.doi.org/10.1016/j.jhazmat.2006.09.056

CO_2 vessel failure incidents (Slide 1 of 3)

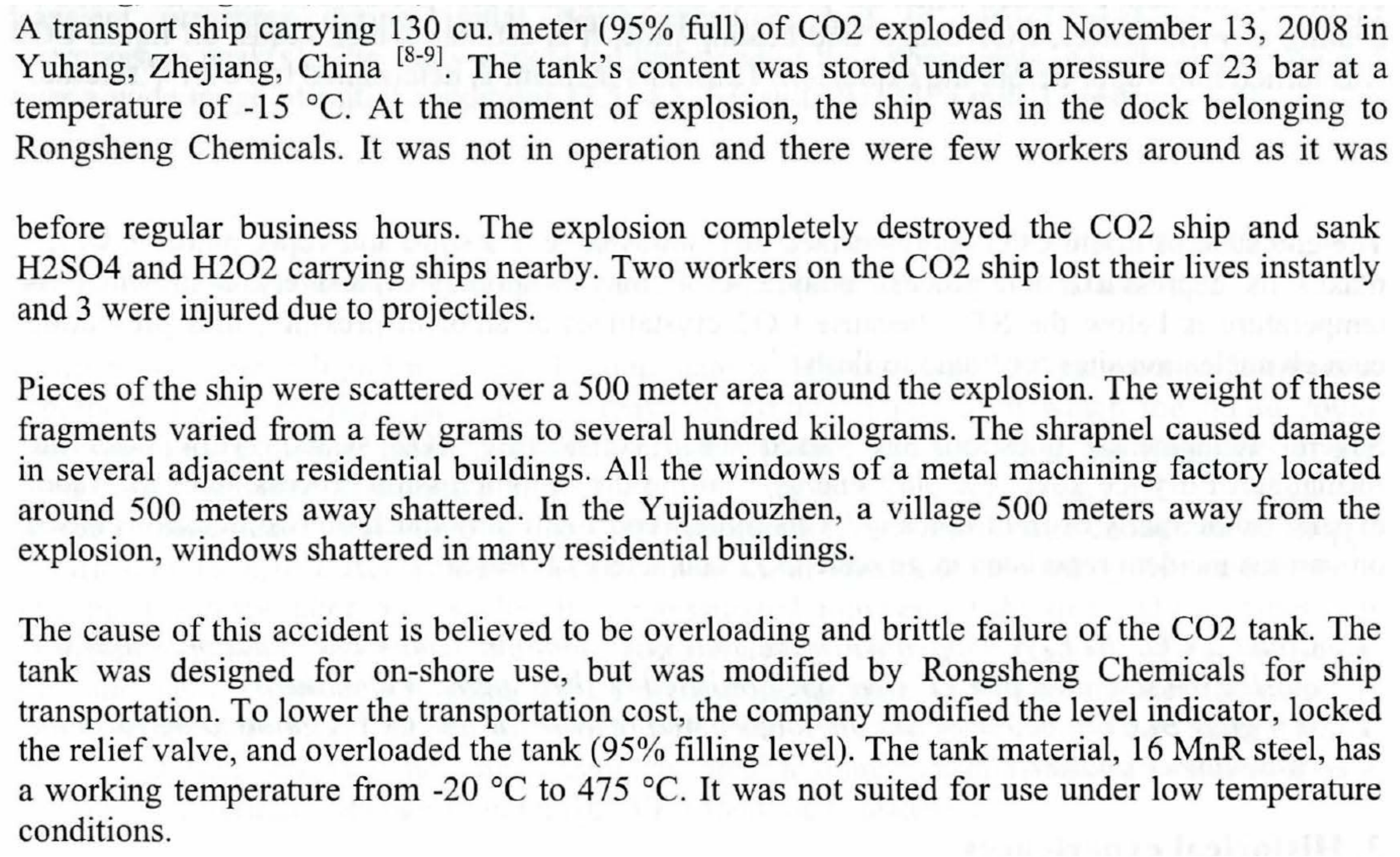
- **Repcelak, Hungary (1969)**: Two CO_2 vessels exploded in rapid succession and third vessel rocketed from foundations (domino effects). Cause: probably overfilling. Fragments scattered to 400 m radius
- **Fukushima, Japan (1969)**: CO_2 storage tank exploded, windows broken to 500 m radius. Cause: heater left on, safety valves closed due to repairs
- **Haltern, Germany (1975)**: CO_2 railcar failure during shunting. Fragments flung 300 m, 1 fatality. Cause: brittle failure
- **Worms, Germany (1988)**: 30 te CO_2 vessel failure, heater failed “on”, pressure relief valves iced-up, 3 fatalities, 8 injured

https://www.icheme.org/media/5385/lpb_issu e125p003.pdf
https://doi.org/10.1002/prs.680130405

https://doi.org/10.1016/j.engfailanal.2013.12.006
http://dx.doi.org/10.4028/www.scientific.net/MSF.689.461

CO_2 vessel failure incidents (Slide 2 of 3)

- **Yuhang, Hangzhou, China (2008)**



A transport ship carrying 130 cu. meter (95% full) of CO2 exploded on November 13, 2008 in Yuhang, Zhejiang, China [8-9]. The tank's content was stored under a pressure of 23 bar at a temperature of -15 °C. At the moment of explosion, the ship was in the dock belonging to Rongsheng Chemicals. It was not in operation and there were few workers around as it was

before regular business hours. The explosion completely destroyed the CO2 ship and sank H2SO4 and H2O2 carrying ships nearby. Two workers on the CO2 ship lost their lives instantly and 3 were injured due to projectiles.

Pieces of the ship were scattered over a 500 meter area around the explosion. The weight of these fragments varied from a few grams to several hundred kilograms. The shrapnel caused damage in several adjacent residential buildings. All the windows of a metal machining factory located around 500 meters away shattered. In the Yujiadouzhen, a village 500 meters away from the explosion, windows shattered in many residential buildings.

The cause of this accident is believed to be overloading and brittle failure of the CO2 tank. The tank was designed for on-shore use, but was modified by Rongsheng Chemicals for ship transportation. To lower the transportation cost, the company modified the level indicator, locked the relief valve, and overloaded the tank (95% filling level). The tank material, 16 MnR steel, has a working temperature from -20 °C to 475 °C. It was not suited for use under low temperature conditions.

- Ship with 130 m^3 CO_2 vessel failed
- Explosion destroyed ship and sank two nearby ships
- 2 fatalities and 3 or 4 injured
- Fragments of ship flung 500 m
- Buildings damaged, glass broken to a distance of 500 m
- Causes:
  - Vessel level indicator modified
  - Pressure relief valve locked
  - Vessel over-pressurized
  - Steel vessel may have been embrittled

Zhang Y., Schork J., and Ludwig K. (2013) Revisiting the conditions for a CO2 tank explosion, AIChE 9th Global Congress on Process Safety, San Antonio, Texas, 28 April – 1 May 2013, http://dx.doi.org/10.4028/www.scientific.net/MSF.689.461

Li W., Di G. and Wang R. (2011) The cause analysis of a liquid CO_2 tank explosions on a ship, Materials Science Forum, 689, p461-467, http://dx.doi.org/10.4028/www.scientific.net/MSF.689.461

CO_2 vessel failure incidents (Slide 3 of 3)

- **Further incidents**

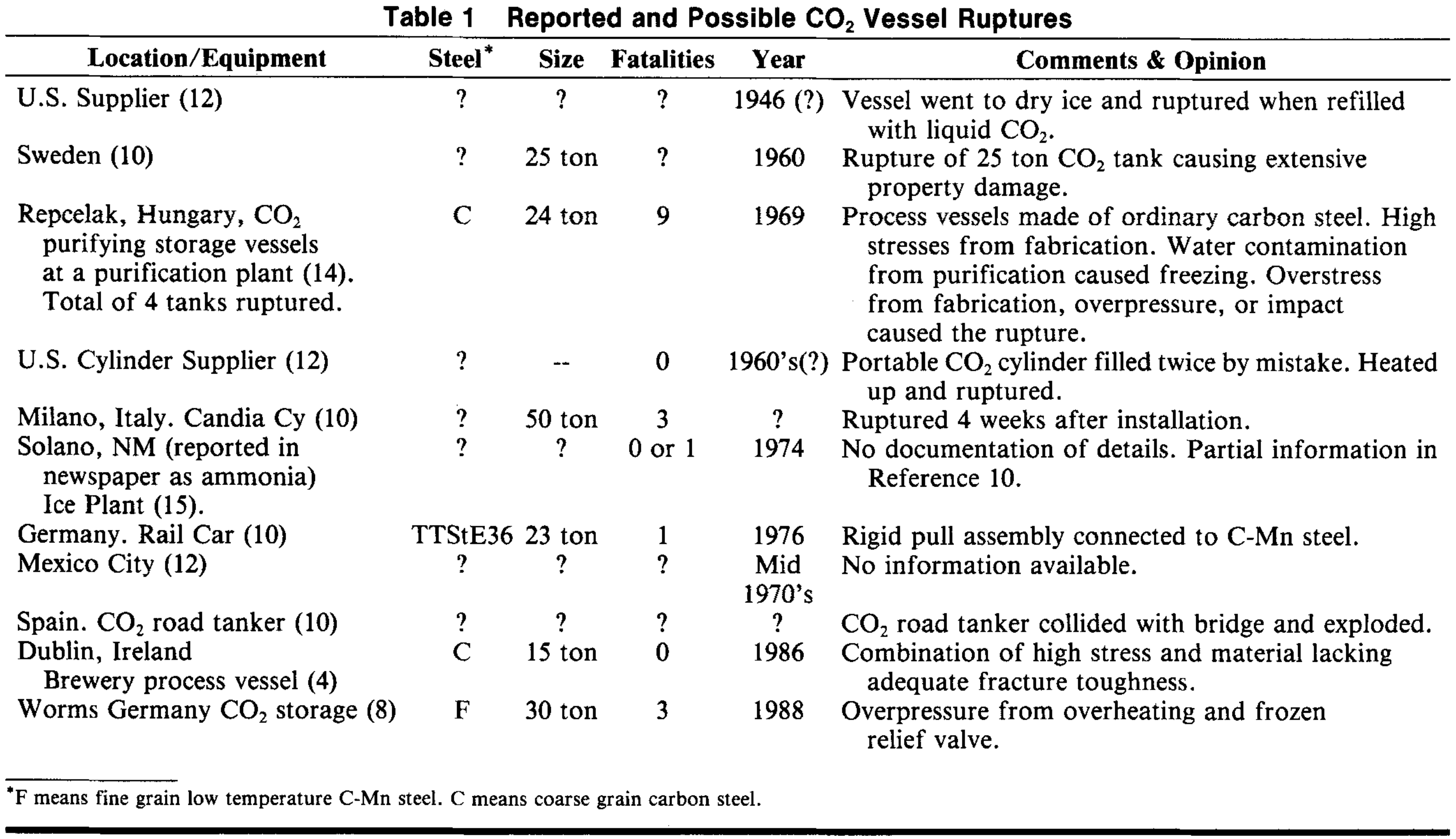


Table 1 Reported and Possible CO_2 Vessel Ruptures

Location/Equipment	Steel*	Size	Fatalities	Year	Comments & Opinion
U.S. Supplier (12)	?	?	?	1946 (?)	Vessel went to dry ice and ruptured when refilled with liquid CO_2.
Sweden (10)	?	25 ton	?	1960	Rupture of 25 ton CO_2 tank causing extensive property damage.
Repcelak, Hungary, CO_2 purifying storage vessels at a purification plant (14). Total of 4 tanks ruptured.	C	24 ton	9	1969	Process vessels made of ordinary carbon steel. High stresses from fabrication. Water contamination from purification caused freezing. Overstress from fabrication, overpressure, or impact caused the rupture.
U.S. Cylinder Supplier (12)	?	--	0	1960's(?)	Portable CO_2 cylinder filled twice by mistake. Heated up and ruptured.
Milano, Italy. Candia Cy (10)	?	50 ton	3	?	Ruptured 4 weeks after installation.
Solano, NM (reported in newspaper as ammonia) Ice Plant (15).	?	?	0 or 1	1974	No documentation of details. Partial information in Reference 10.
Germany. Rail Car (10)	TTStE36	23 ton	1	1976	Rigid pull assembly connected to C-Mn steel.
Mexico City (12)	?	?	?	Mid 1970's	No information available.
Spain. CO_2 road tanker (10)	?	?	?	?	CO_2 road tanker collided with bridge and exploded.
Dublin, Ireland Brewery process vessel (4)	C	15 ton	0	1986	Combination of high stress and material lacking adequate fracture toughness.
Worms Germany CO_2 storage (8)	F	30 ton	3	1988	Overpressure from overheating and frozen relief valve.

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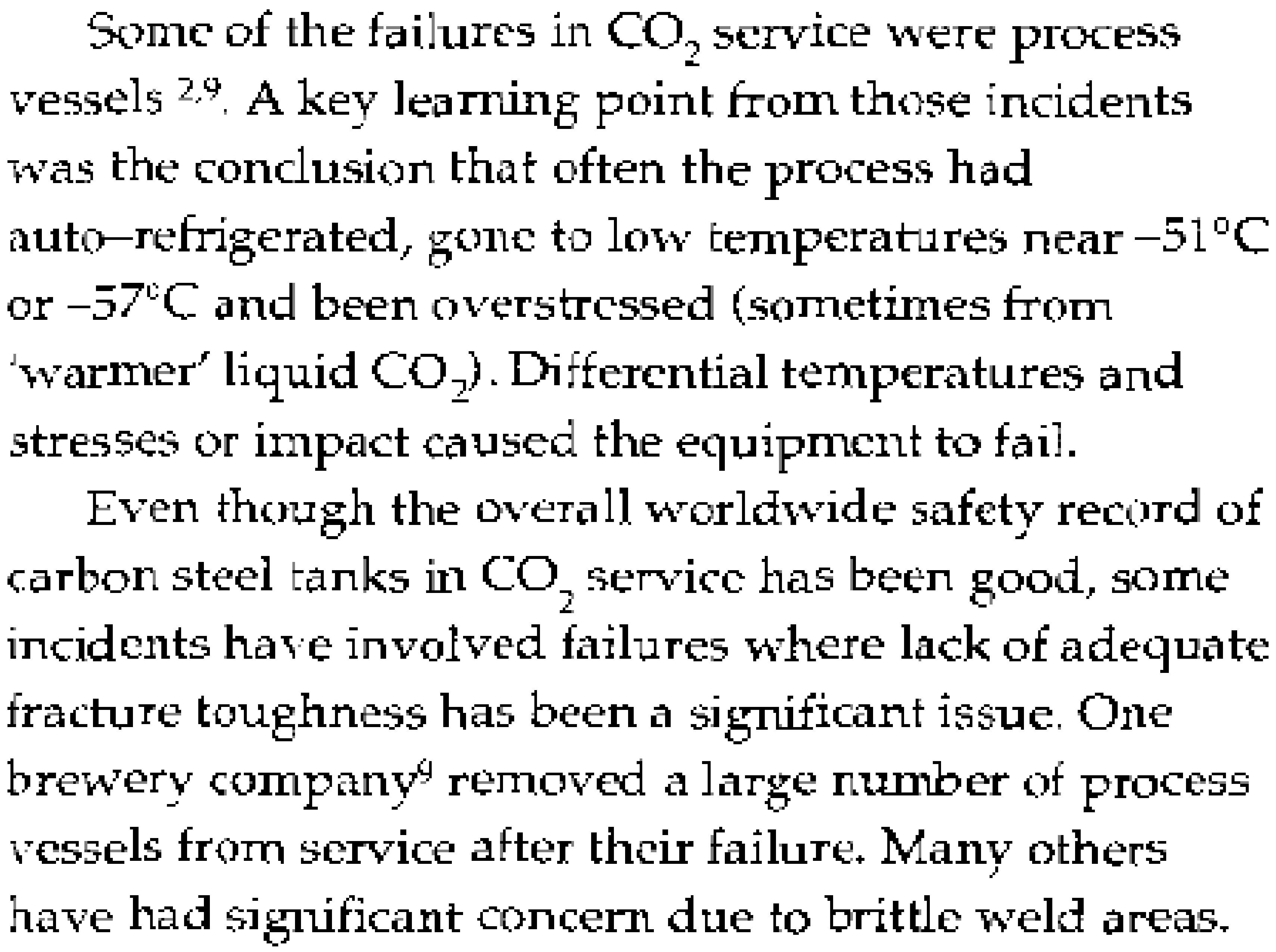
*F means fine grain low temperature C-Mn steel. C means coarse grain carbon steel.



Some of the failures in CO_2 service were process vessels [2,9]. A key learning point from those incidents was the conclusion that often the process had auto–refrigerated, gone to low temperatures near –51°C or –57°C and been overstressed (sometimes from 'warmer' liquid CO_2). Differential temperatures and stresses or impact caused the equipment to fail.

Even though the overall worldwide safety record of carbon steel tanks in CO_2 service has been good, some incidents have involved failures where lack of adequate fracture toughness has been a significant issue. One brewery company[9] removed a large number of process vessels from service after their failure. Many others have had significant concern due to brittle weld areas.

https://www.icheme.org/media/5385/lpb_issue125p003.pdf
https://doi.org/10.1002/prs.680130405

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Catastrophic vessel failure experiments

Authors	Substance	Inventory	Notes	Validation
Hess *et al*. (1974)			Qualitative data	
Hardee and Lee (1975)	Propane	422 kg	"Relatively small" hole size. Details of experiments missing from paper (e.g., actual hole size)	1
Maurer *et al*. (1977)	Propylene	0.124 – 452 kg	Uncertainty in initial conditions: pressure was well above saturated vapour pressure. Cloud ignited at 0.5 seconds	1, 2
Hasegawa and Sato (1977)	N-Pentane	0.31 – 6.2 kg	Glass sphere ruptured and ignited. Main focus was fireballs	
Bettis (1987)	Refrigerant R11	3.2 litres	Hemispheres pulled apart, produced planar radial jet	
Hardy (1990)	R11 and R114	3.2 and 0.4 litres	Hemispheres pulled apart, produced planar radial jet	
Pettitt (1990)	R11, R113 and R114.	1 litre	Glass spheres shattered, produced spherical cloud. Cloud radius measured only to 0.4 m	1, 2
Johnson and Pritchard (1991)	Butane and propane	1 – 2 te	Vessels failed and ignited, primarily to study fireball behaviour	
Bettis and Jagger (1992)	R11	20 litre, 1 – 10 kg	Data analysed by Webber *et al*. (1992) SRD/HSE R584	1
Schmidli *et al*. (1992), Schmidli (1993)	Propane, butane R12 and R114	0.1, 1 and 2 litres	Glass spheres shattered. Mostly qualitative data. Cloud radius recorded for 2 litre propane tests	1, 2
Birk *et al*. (2007)	Propane	0.4 m^3 and 2 m^3	Blast wave measurements, no dispersion measurements	
Van der Voort *et al*. (2013)	**CO_2**	40 litre	Linear shaped charges used to rupture vessels, blast wave measurements, no dispersion measurements	
Hansen (2018), and Ibrahim *et al*. (2023)	**CO_2**	0.03 and 0.2 litre	P-T measurements inside vessel, high-speed video, blast wave measurements, no dispersion measurements	

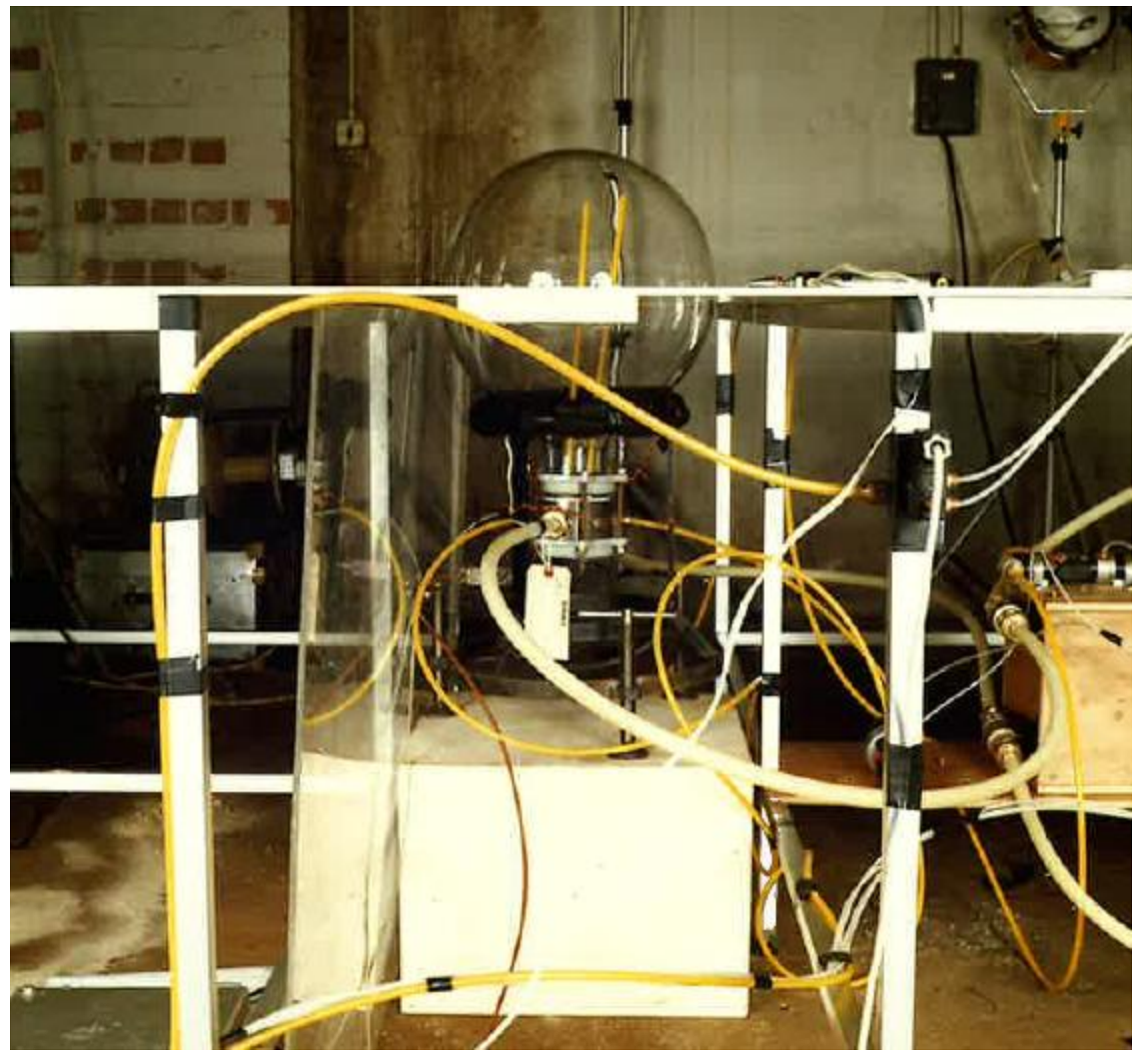
← See next slides

← See next slides

1 = Used to validate ACE model used by HSE ; 2 = Used to validate DNV PHAST INEX model

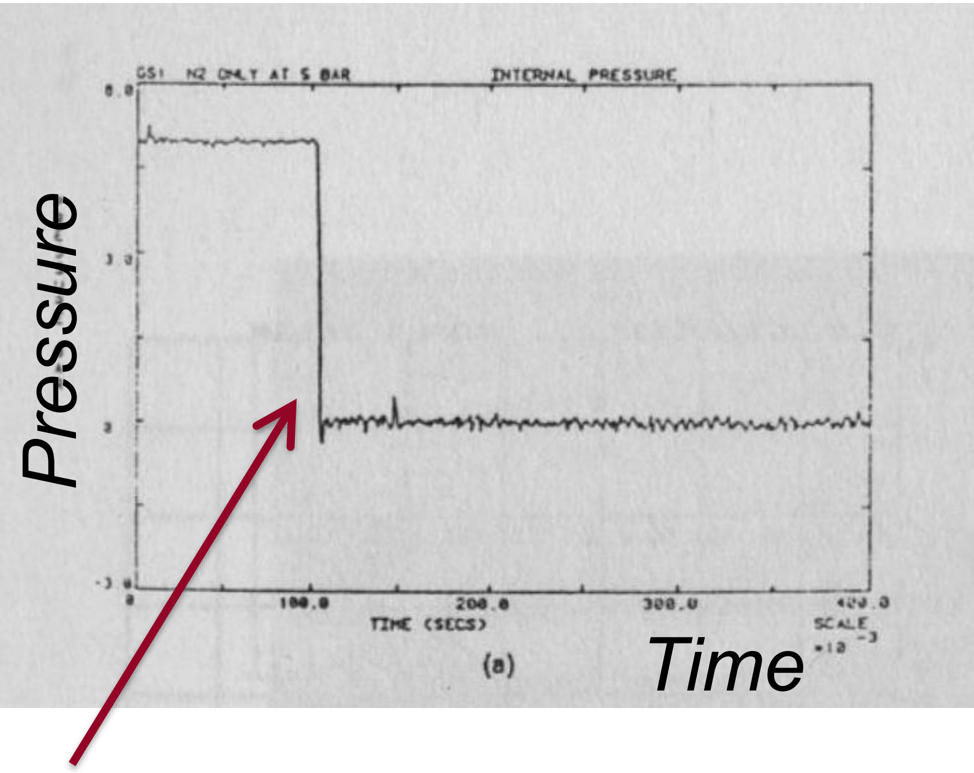
Bettis and Jagger (1992) experiments

- 0.4 m diameter, 20 litre glass sphere filled with nitrogen gas or pressure-liquefied refrigerant R11 (50% fill), vessel failed by external impact
- Additional tests with 0.42 m cylinder fitted with bursting disk and 50 mm square shock-tube



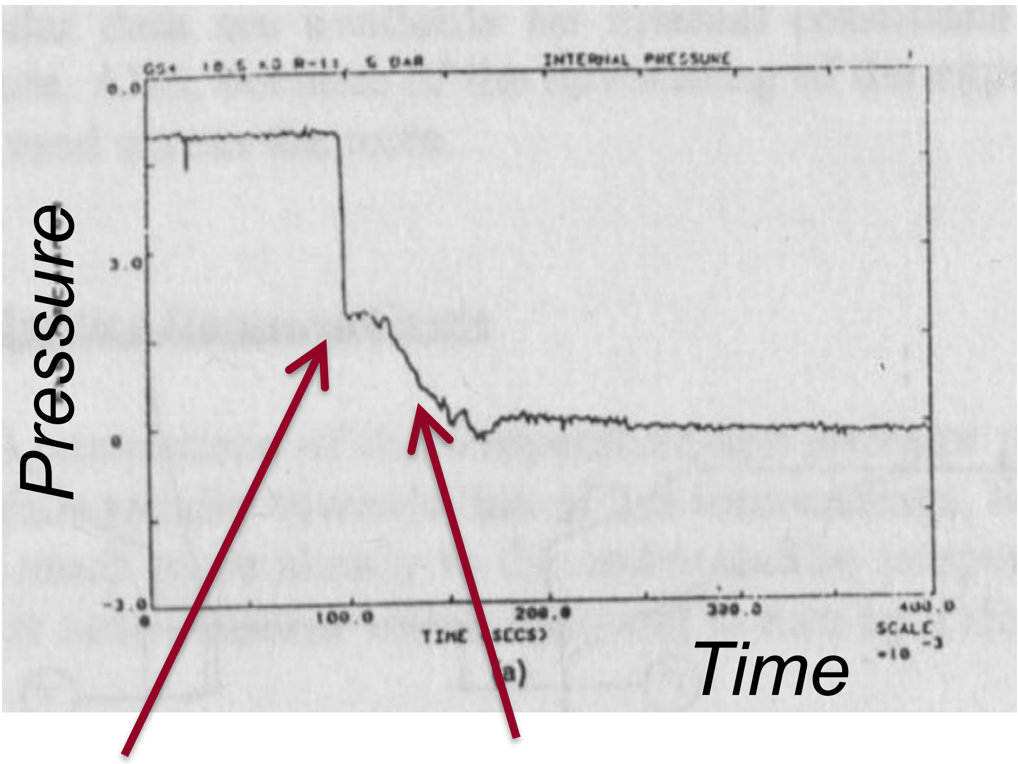
20 litre glass sphere experiments at HSE Science and Research Centre, Buxton, 1986-88

Nitrogen gas



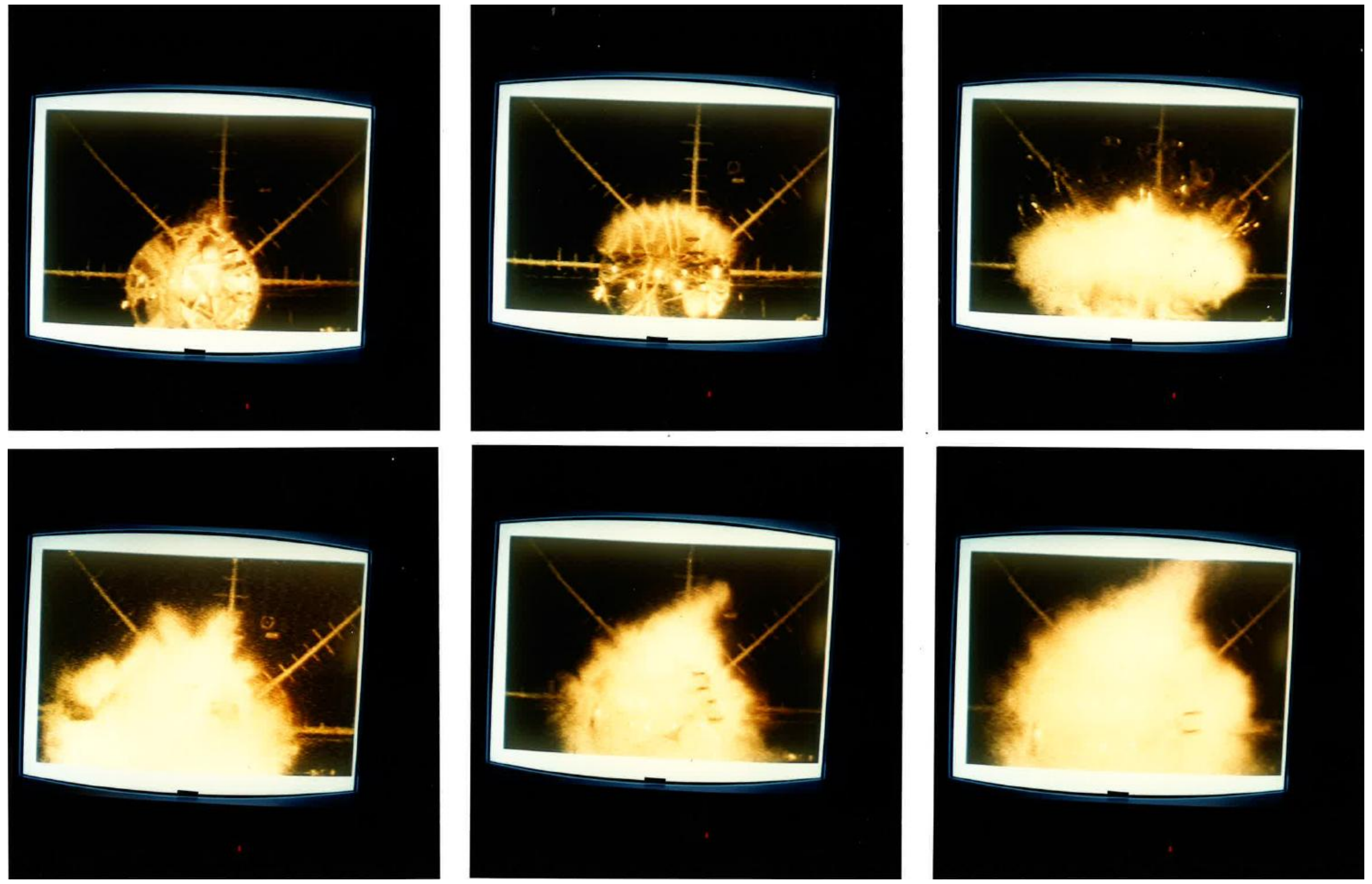
Pressure drops in 2 ms

R11 liquid



Initial rapid gas-phase expansion

Liquid boils



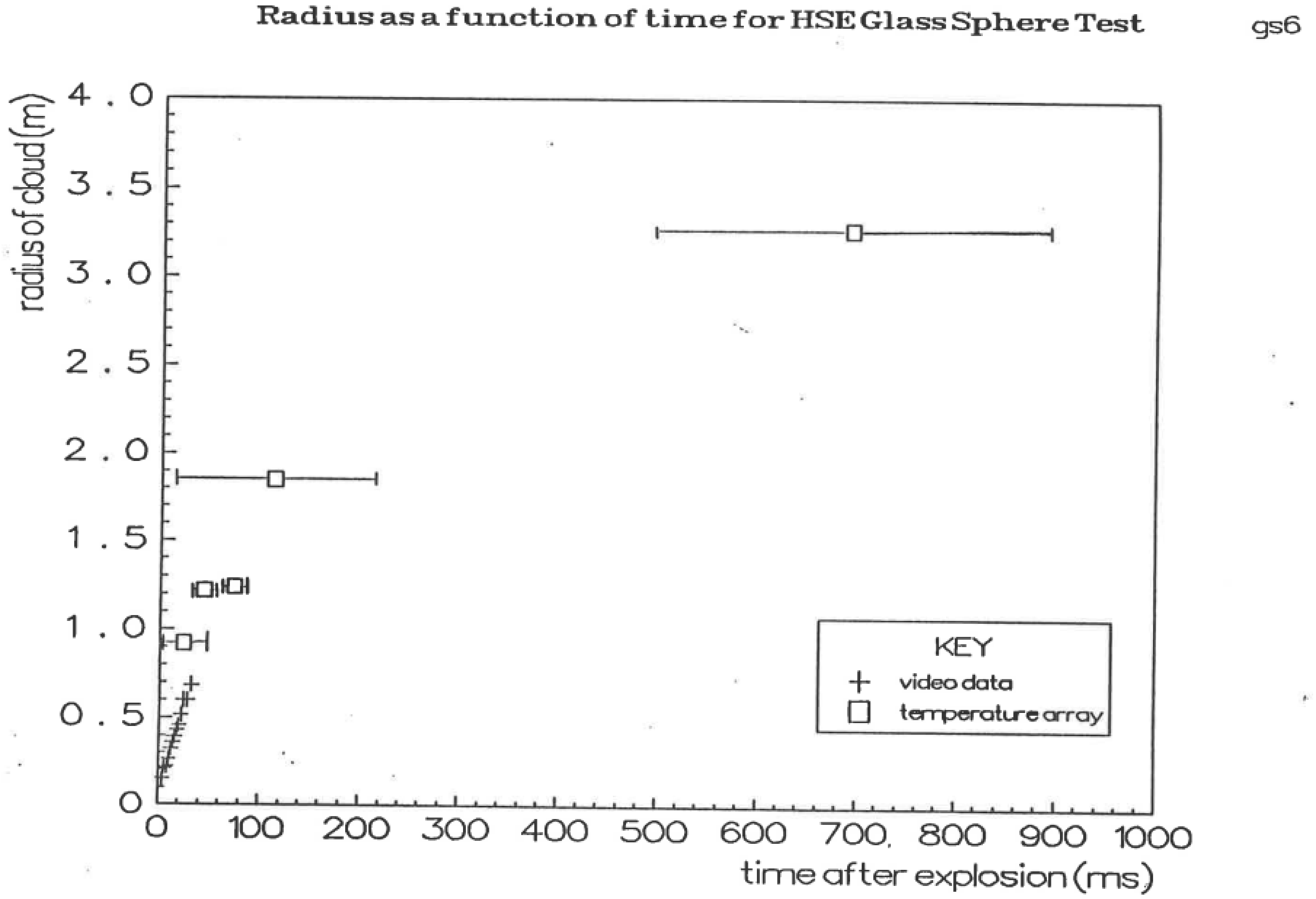
https://www.icheme.org/media/25274/major-hazards-onshore-and-offshore-icheme-symposium-series-130-1992-17-bettis.pdf

Bettis and Jagger (1992) experiments

Fire Section
EFL Buxton

Cloud Expansion
Experiments

Summer 1987



Measured expansion rate of the cloud is used to validate models

Webber *et al*. (1992) SRD/HSE R584
https://admlc.com/safety-and-reliability-directorate-srd-series-reports/

Maurer *et al*. (1977) experiments

- Propylene vessels ranging in size from 40 mm to 700 mm diameter
- Heated to between 50 – 80 °C (saturation pressure 22 – 39 bar)
- Then failed at 60 bar, using either a lance or explosive charge
- Temperature at time of failure was not reported, i.e., initial conditions were uncertain
- Cloud ignited after delay of 0.5 s
- Releases were pressurised above saturation conditions, therefore were likely to produce faster initial expansion and less rainout than at typical (saturated) storage conditions

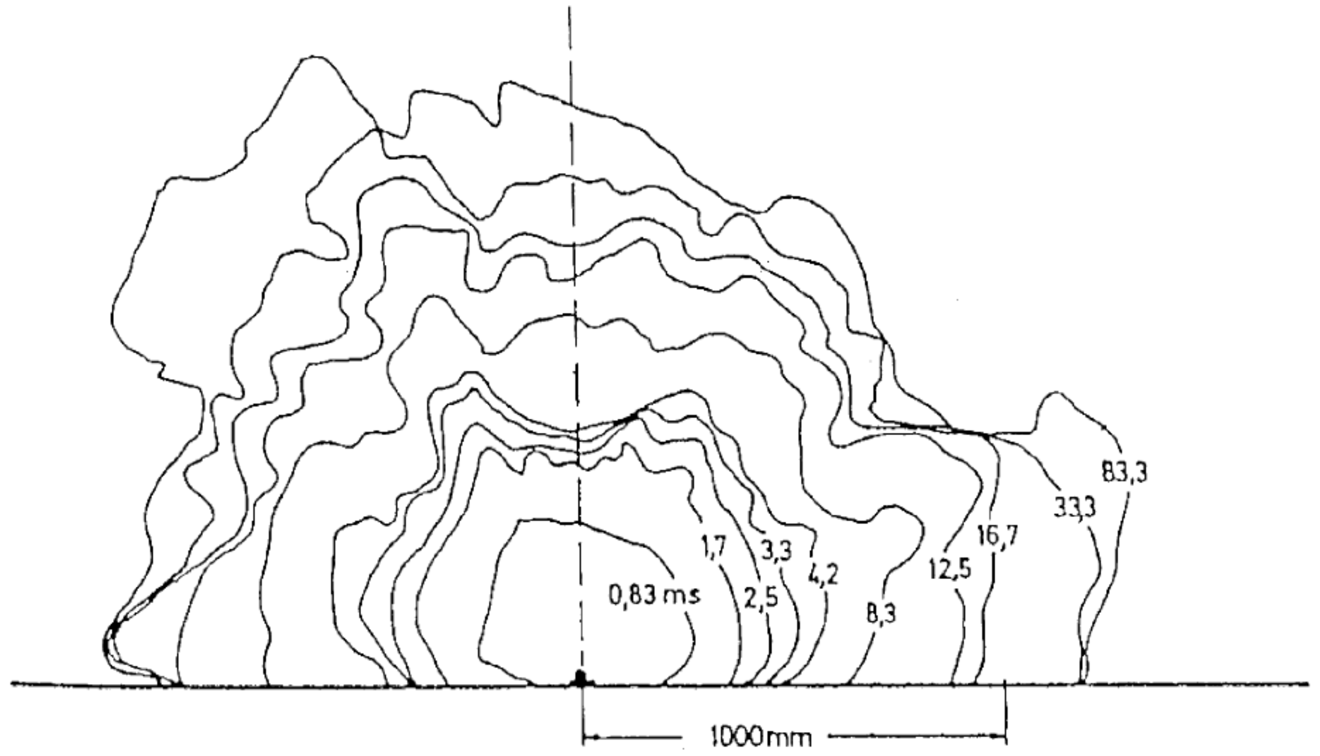
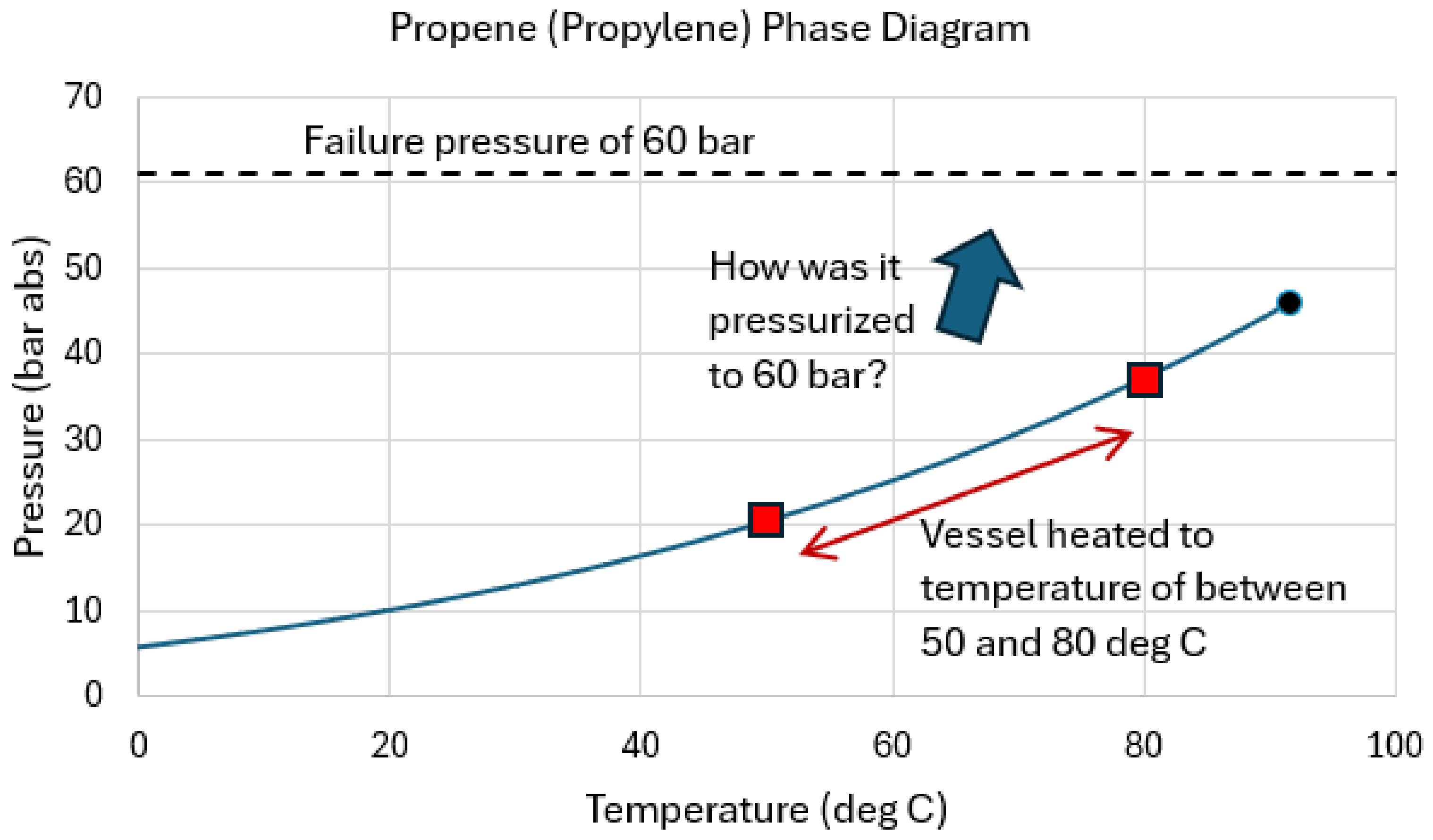


Fig. 11. Explosion phase of propylene release ($M = 0.124$ kg) from the small scale experiments of Maurer et al.

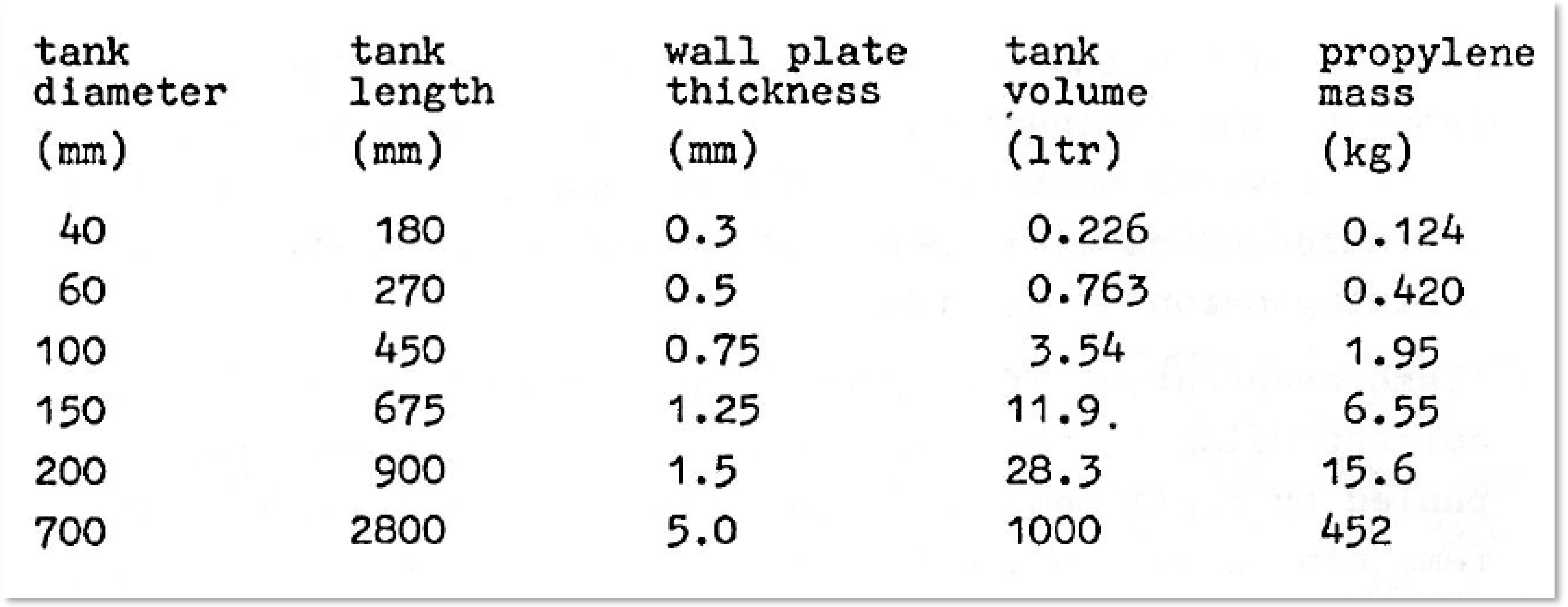
https://doi.org/10.1016/S0304-3894(01)00284-9


Propene (Propylene) Phase Diagram

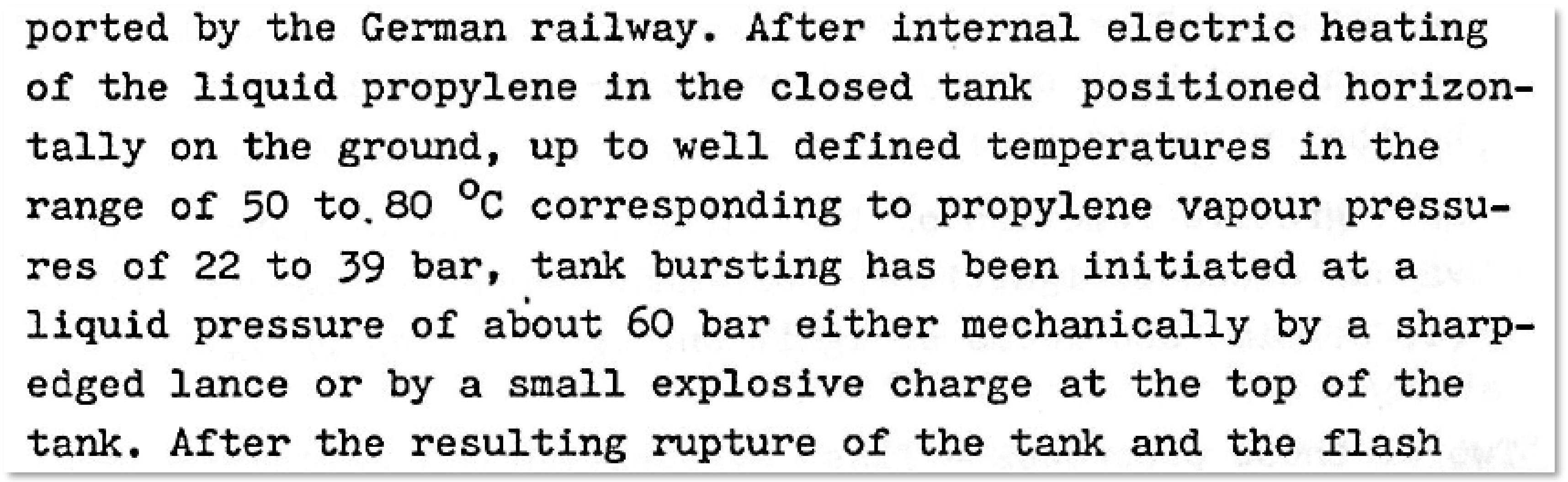
Failure pressure of 60 bar

How was it pressurized to 60 bar?

Vessel heated to temperature of between 50 and 80 deg C



tank diameter (mm)	tank length (mm)	wall plate thickness (mm)	tank volume (ltr)	propylene mass (kg)
40	180	0.3	0.226	0.124
60	270	0.5	0.763	0.420
100	450	0.75	3.54	1.95
150	675	1.25	11.9	6.55
200	900	1.5	28.3	15.6
700	2800	5.0	1000	452



ported by the German railway. After internal electric heating of the liquid propylene in the closed tank positioned horizontally on the ground, up to well defined temperatures in the range of 50 to 80 °C corresponding to propylene vapour pressures of 22 to 39 bar, tank bursting has been initiated at a liquid pressure of about 60 bar either mechanically by a sharp-edged lance or by a small explosive charge at the top of the tank. After the resulting rupture of the tank and the flash

Maurer, B., Hess, K., Giesbrecht H. and Leuckel, W., (1977), "Modelling of vapour cloud dispersion and deflagration after bursting of tanks filled with liquefied Gas", Int. Loss Prevention Symposium, Heidelberg, Germany.

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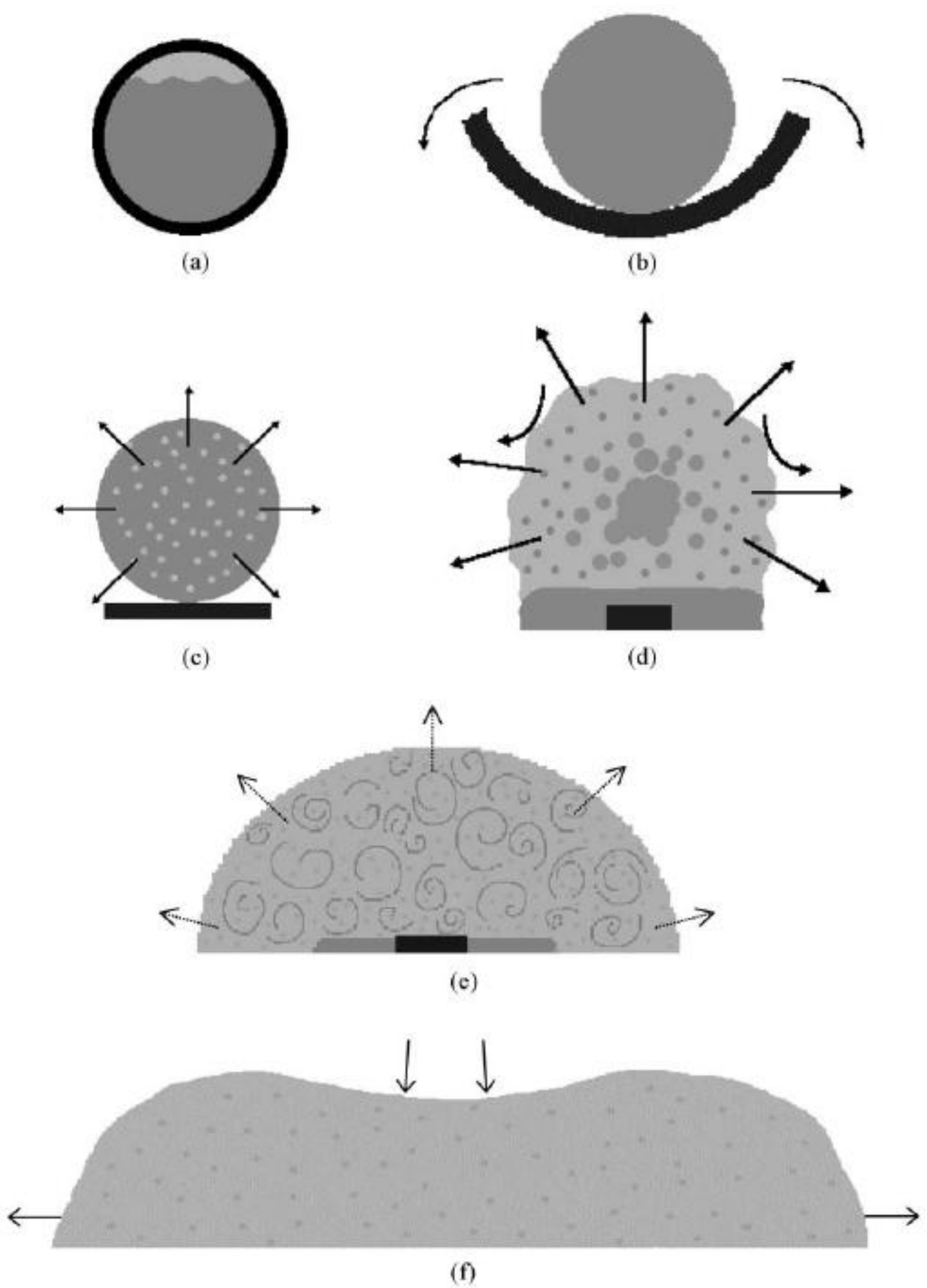
Dispersion Source Model: ACE (Airborne Concentration Estimate)

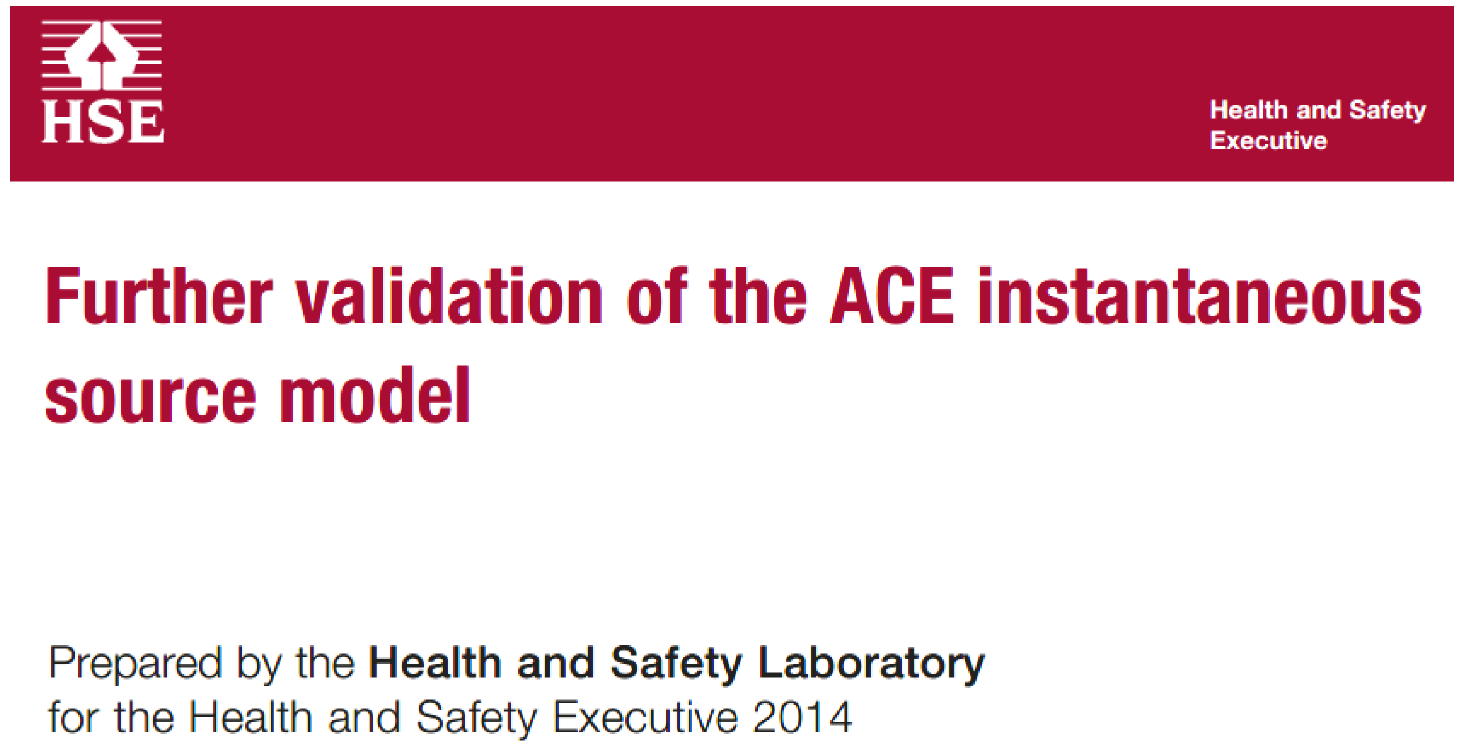


- Integral model developed by W.S.Atkins for HSE
- Two modelled phases
  - Initial explosive growth, liquid flashes into aerosol
  - Turbulent entrainment of air, aerosol evaporates
- Two release configurations: downward release and omni-directional (with more rainout in the downward configuration)
- Model parameters informed by results of CFD model, Johnson & Pritchard and other experiments
- Model outputs: cloud size, composition (aerosol and vapour) and temperature, initial liquid pool
- Predicted cloud radius compared to data from experiments:
  - Hardee and Lee (1975), orifice in the side of a propane tank
  - Maurer *et al*. (1977), 0.124 kg of propylene
  - Pettitt (1990), glass vessel containing 0.74 kg of Freon-11

https://doi.org/10.1016/S0304-3894(01)00284-9

https://webarchive.nationalarchives.gov.uk/ukgwa/20230103125624mp_/https://www.hse.gov.uk/research/crr_pdf/1999/crr99250.pdf

Dispersion source model: ACE (Airborne Concentration Estimate)



HSE Health and Safety Executive

Further validation of the ACE instantaneous source model

Prepared by the **Health and Safety Laboratory** for the Health and Safety Executive 2014

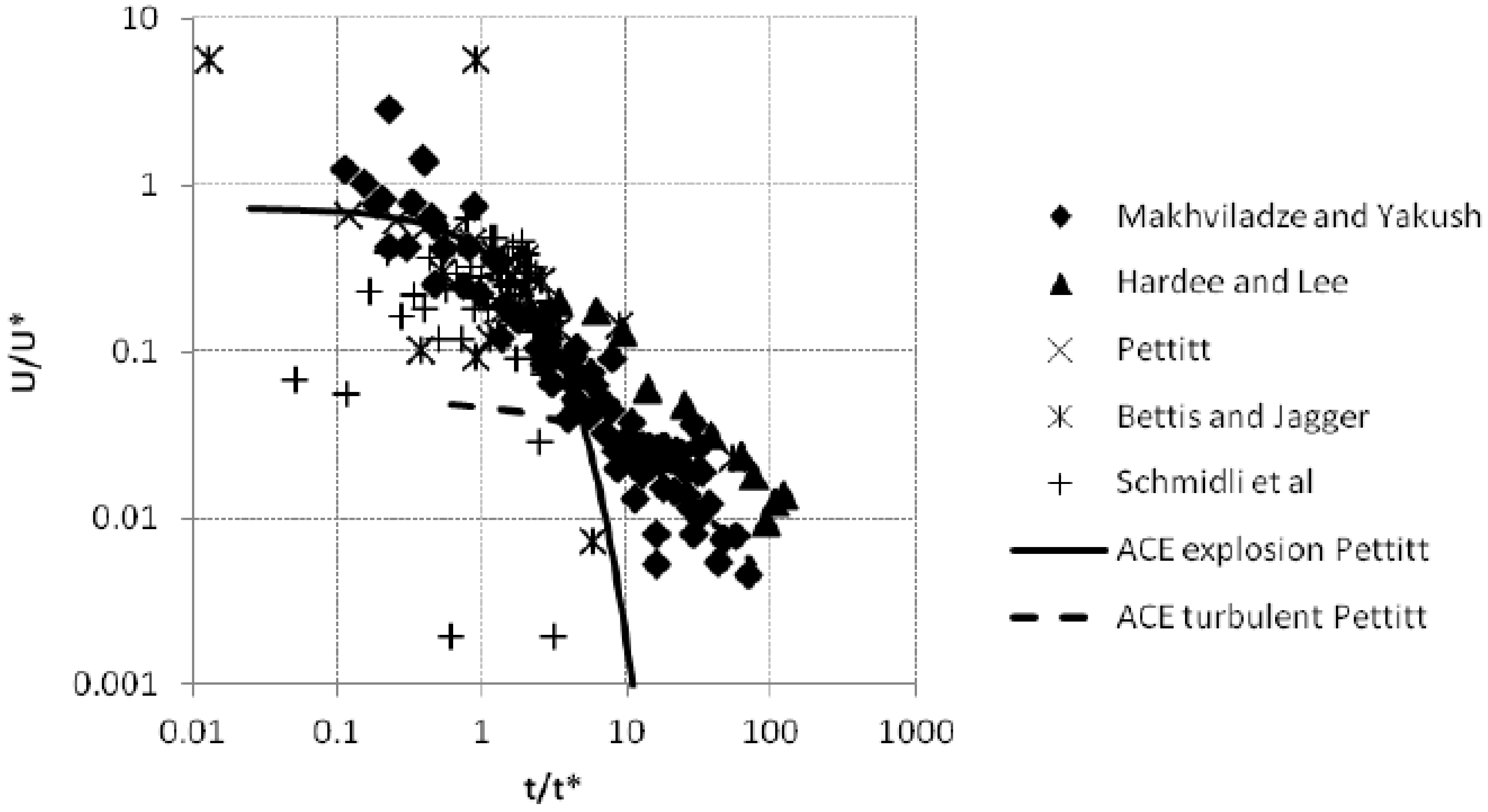
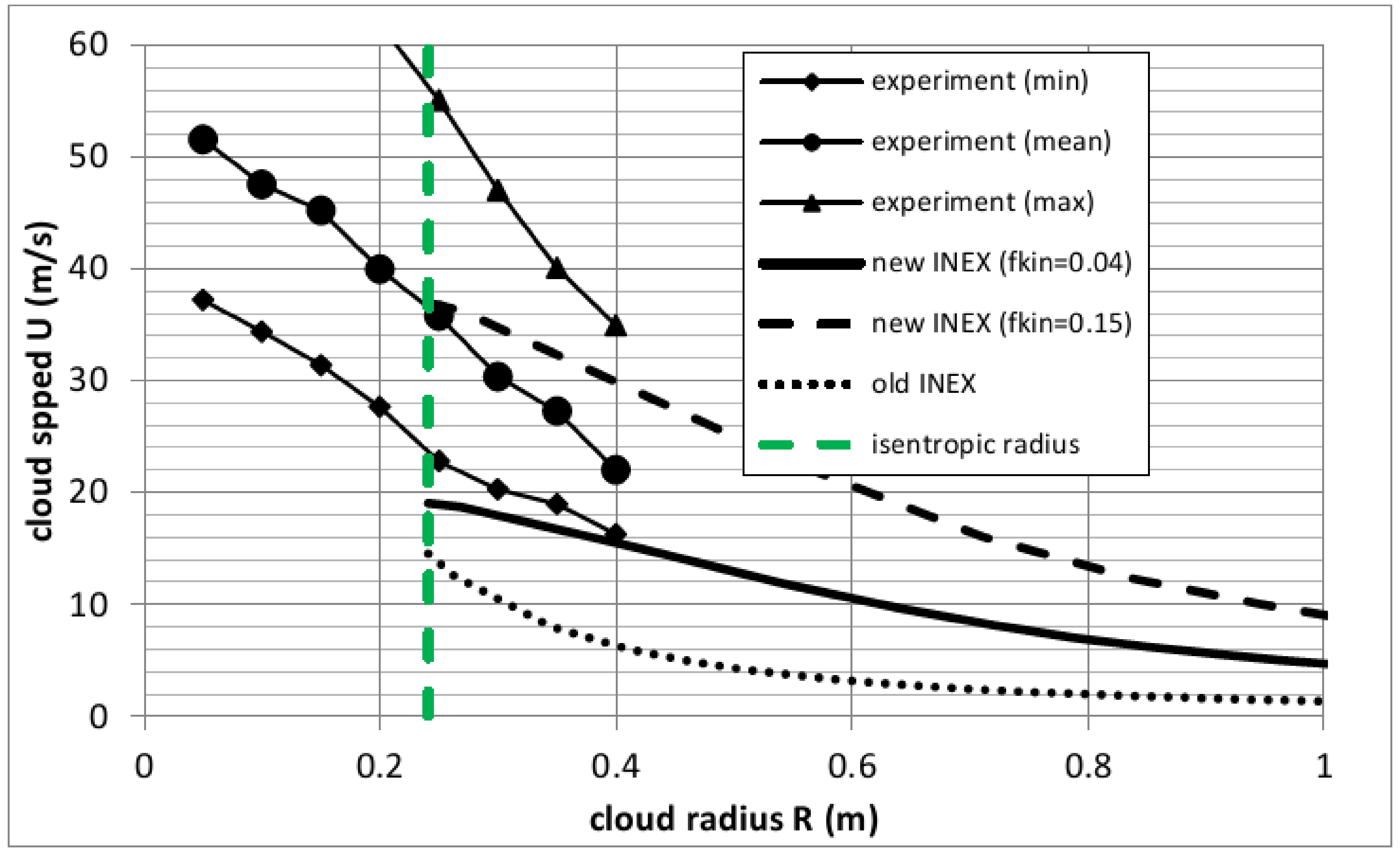


Figure 24 ACE predictions of Pettitt (1990) plotted against all data

- Further validation of ACE
  - Predicted expansion velocities compared to measurements
- Additional datasets were examined
  - Maurer et al. (1977), 0.124 – 452 kg of propylene
  - Bettis and Jagger (1992), 1 – 10 kg of R11
  - Schmidli *et al*. (1992), 2 litres of propane
- Final cloud radii predicted by ACE were generally in line with those observed

https://webarchive.nationalarchives.gov.uk/ukgwa/20230103160604/https://www.hse.gov.uk/research/rrhtm/rr1028.htm

Dispersion source model: INEX (INstantaneous Expansion Model)



(b) INEX speed U versus cloud radius R [old model; new model (f_{kin}=0.05, and f_{fin}=0.30)]

Figure 15. **Pettitt experiment (Freon 11, 100% fill, 410kPa) - INEX cloud speed validation[31]**

- DNV PHAST is probably the most widely-used consequence model for process safety in UK/Europe
- Dutch Environmental Regulation requires DNV SAFETI-NL to be used for assessing external safety risks in the Netherlands (this uses PHAST)
- PHAST uses INEX model for catastrophic vessel failures
- Two-phase INEX is validated against:
  - Maurer *et al*. (1977), 0.124 – 452 kg of propylene
  - Pettitt (1990), 1 litre of R11
  - Schmidli *et al*. (1992) 0.1, 1 and 2 litres of propane, butane R12 and R114

http://dx.doi.org/10.3303/CET1648028

https://mysoftware.dnv.com/download/public/phast/technical_documentation/05_dispersion/udm/theory/UDM%20INEX%20Theory_Validation.pdf

CO_2 BLEVE blast overpressure model: TNO

- TNO developed a numerical model for BLEVEs that calculates the gas dynamics for explosive evaporation of pressure-liquefied gas in ruptured vessels
- Assumes thermodynamic equilibrium at the interface between liquid and vapour
- Expansion process controlled by the inertia of the developing vapour and the surrounding atmosphere
- Heat needed for the evaporation is extracted uniformly from the liquid
- Involves solution of the Euler equations
- Assumptions are conservative/cautious (e.g., no energy losses from accelerating fragments of vessel)
- Model predictions presented in the form of blast curves of overpressure and impulse as a function of radial distance from the vessel
- See Van den Berg (2008) and Van den Voort *et al*. (2013)
  http://dx.doi.org/10.1002/prs.10252 http://dx.doi.org/10.1016/j.jlp.2013.02.016

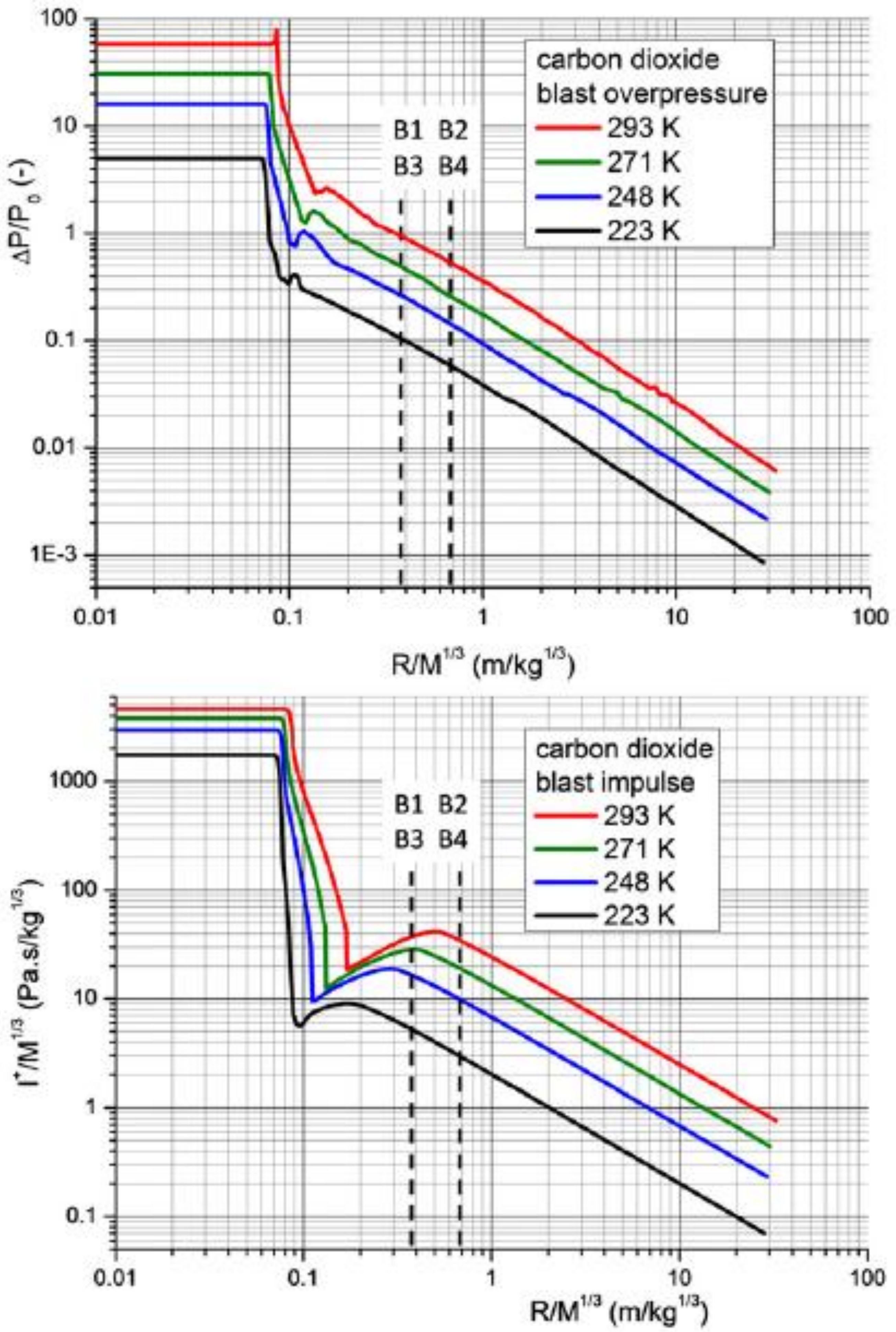
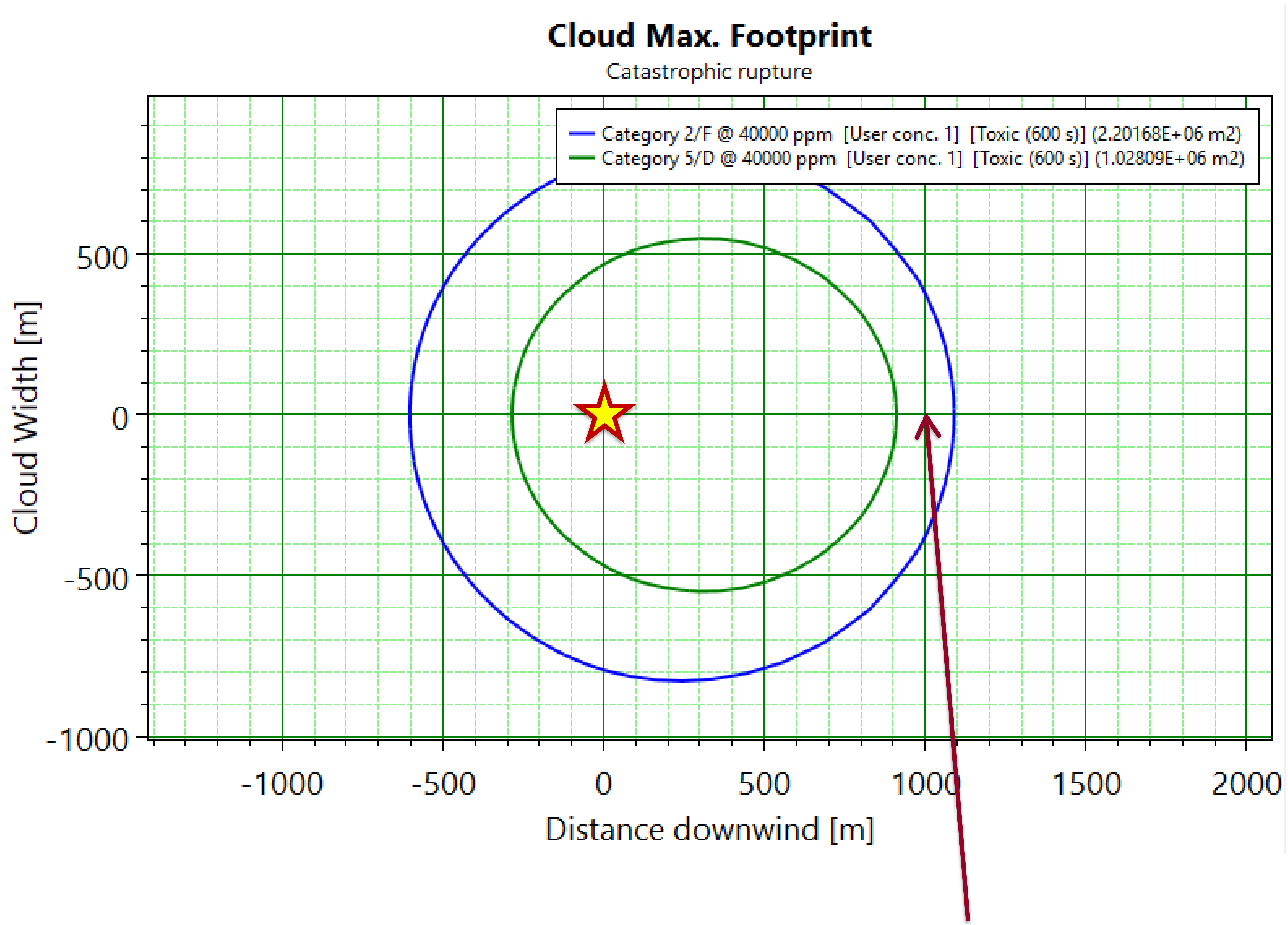


Fig. 2. Blast charts for the explosive evaporation of liquid CO_2 calculated analogous to Van den Berg (2008). Non-dimensionalised peak overpressure and scaled impulse versus scaled distance. The distance and impulse have been scaled with the liquid mass *M* to the power 1/3. Graphs are given for four relevant temperatures within the range of future storage conditions. The location of the pressure transducers B1 through B4 applied in the experiments is also shown.

Example calculation using INEX dispersion source model

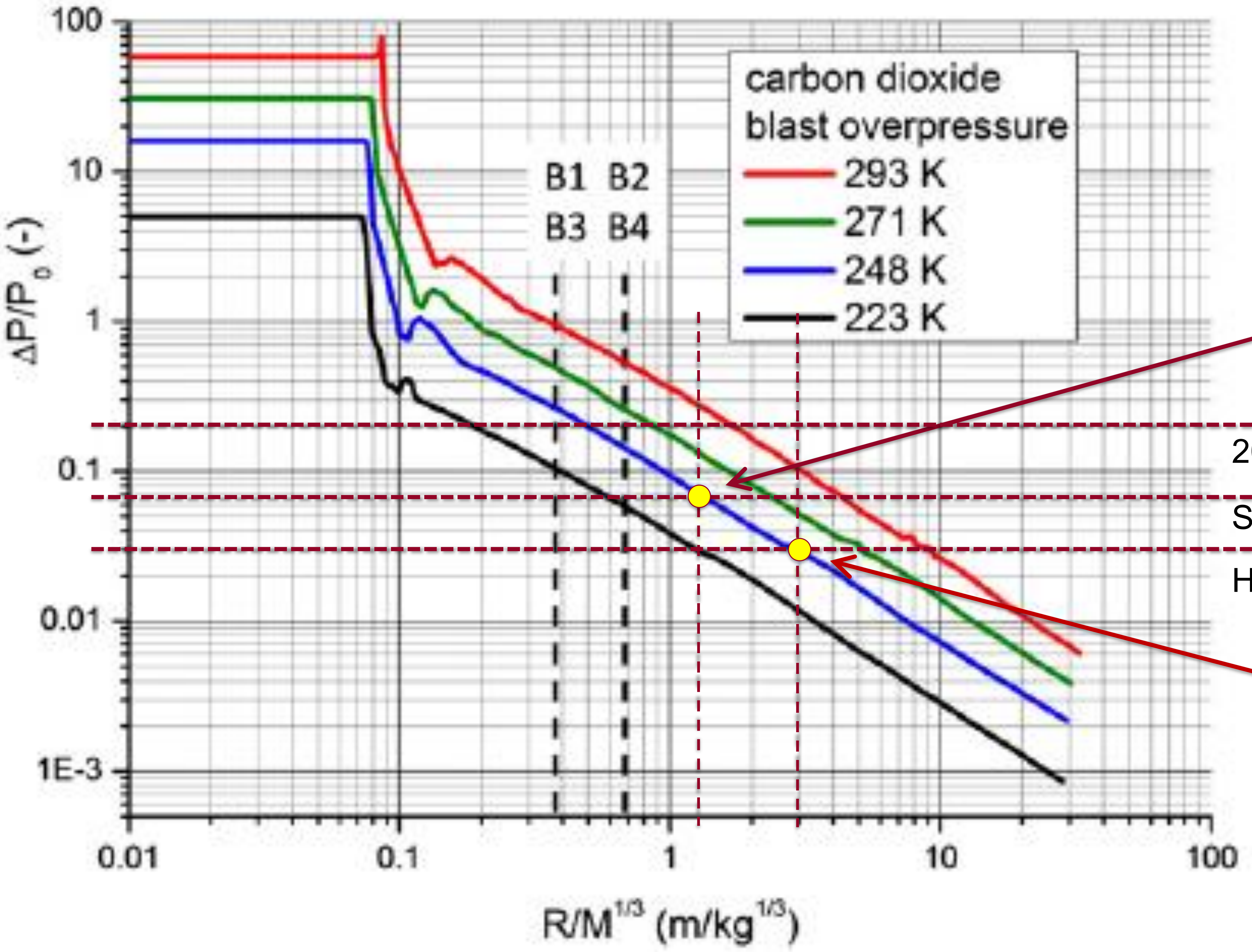
- Sample PHAST INEX simulation
  - 1000 te CO_2 vessel inventory
  - Initial temperature = -25°C
  - Initial pressure = saturation
  - Weather conditions (2/F and 5/D)
    - Wind speed = 2 m/s or 5 m/s
    - Stability = Pasquill Class D or F
  - Footprint shows distance to harm threshold of Immediately Dangerous to Life and Health (IDLH) = 4% v/v CO_2

https://www.cdc.gov/niosh/idlh/124389.html



- Immediately Dangerous to Life and Health (IDLH) threshold is reached at a distance of approximately 1 km downwind from the 1000 te vessel
- How does this compare to BLEVE blast hazard range?

Example calculation using TNO blast chart for CO_2 BLEVE



20% fatalities inside buildings, threshold for domino effects

Significant building damage, >90% window glass breakage, lacerations

Harm inside buildings from broken glass windows

Source: Van den Voort *et al*. (2013) http://dx.doi.org/10.1016/j.jlp.2013.02.016

CO_2 vessel conditions

- Refrigerated storage at -25°C (248 K)
- Vessel size M = 1000 te = 10^6 kg

Damage: Partial demolition of buildings, >90% window glass breakage, lacerations (0.07 bar)

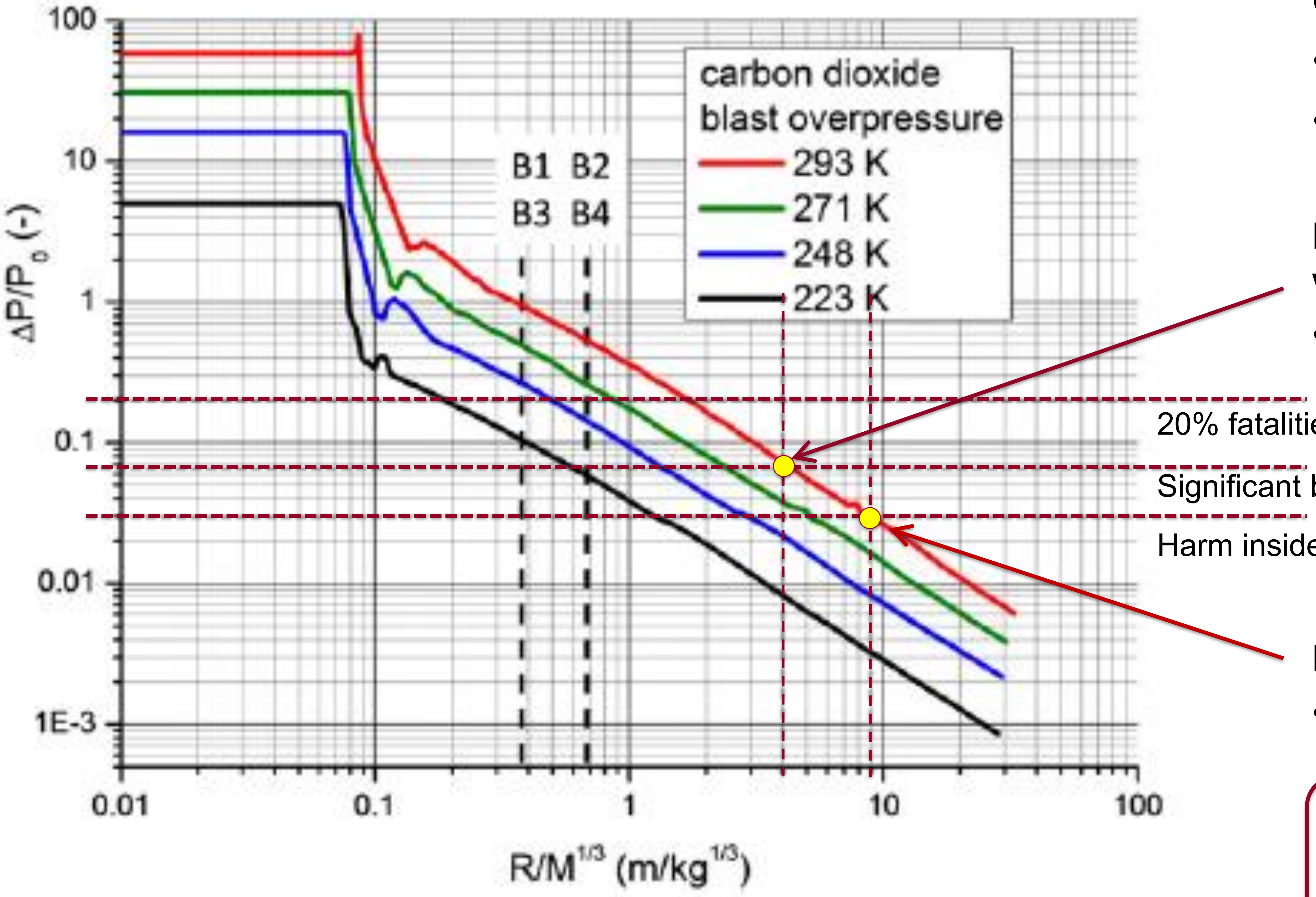
- Radius $R = 1.2M^{1/3} = 1.2(100) = 120\ m$

Damage: harm from broken glass windows (0.03 bar)

- Radius $R = 3M^{1/3} = 3(100) = 300\ m$

Conclusion: toxic dispersion hazard appears to extend further than the blast hazard for this 1000 te vessel

What if the 1000 te CO_2 vessel loses cooling and it fails at 20°C?



20% fatalities inside buildings, threshold for domino effects

Significant building damage, >90% window glass breakage, lacerations

Harm inside buildings from broken glass windows

Source: Van den Voort *et al*. (2013) http://dx.doi.org/10.1016/j.jlp.2013.02.016

CO_2 vessel conditions

- Vessel fails at 20°C (293 K)
- Vessel size M = 1000 te = 10^6 kg

Damage: Partial demolition of buildings, >90% window glass breakage, lacerations (0.07 bar)

- Radius $R = 4M^{1/3} = 4(100) = 400\ m$

Damage: Harm from broken glass windows (0.03 bar)

- Radius $R = 9M^{1/3} = 9(100) = 900\ m$

Conclusion: toxic dispersion hazard and blast hazard distances are similar for this 1000 te vessel

Overview

- Introduction to HSE
- Context: non-pipeline transport of CO_2
- Failure of vessels containing pressure-liquefied gases
- CO_2 vessel failure incidents
- Experiments
- Models
- Standards, guidelines, codes of practice and other helpful information
- Summary and next steps

Standards, guidelines, codes of practice and other helpful information

- Health and Safety Executive (HSE)
  - https://www.hse.gov.uk/carboncapture/carbondioxide.htm
- Compressed Gas Association (CGA)
  - https://www.cganet.com/carbon-dioxide-safety/
- European Industrial Gas Association (EIGA)
  - SI 28 / 20 - Operation of Carbon Dioxide Road Tankers and Equipment while Loading and Unloading
  - DOC 56 / 21 - Guide for the Delivery of Bulk Carbon Dioxide
  - DOC 66 / 22 - Refrigerated CO2 Storage at Users' Premises
  - SI 24 / 24 - Carbon Dioxide Physiological Hazards -“Not just an asphyxiant!”
- British Compressed Gas Association (BCGA)
  - CP26 Bulk liquid carbon dioxide storage at users’ premises
  - CP42 Implementation of EIGA Carbon Dioxide Standards
- Energy Institute
  - https://www.energyinst.org/technical/publications/sectors/ccus/good-plant-design-and-operation-for-onshore-and-offshore-carbon-capture-installations-and-pipelines
- DNV
  - Mapping of potential HSE issues related to large-scale capture, transport and storage of CO_2 https://kudos.dfo.no/dokument/9797/mapping-of-potential-hse-issues-related-to-large-scale-capture,-transport-and-storage-of-co2

This list is not exhaustive

Summary

- CO_2 BLEVE incidents with ~130 m^3 vessels have previously caused damage at 500 m
- Consequence models predict harm from 1000 te tanks to reach around 1 km
- Validation of these consequence models is very limited
- PHAST INEX dispersion source model has been validated using:
  - Pettit (1990) and Schmidli *et al*. (1992) data with a max vessel size of 2 litres ← Factor of a million times smaller than planned 1000 te CO_2 vessels
  - One larger-scale dataset (Maurer *et al*., 1977), which used up to 452 kg of propylene, but there are uncertainties in the initial conditions, and the vapour cloud was ignited
  - These tests were for refrigerants/butane/propane, but CO_2 phase behaviour is different (dry ice)
- TNO BLEVE blast model validated using 40 litre CO_2 vessel rupture experiments

Conclusion: there is a need for further, larger-scale CO_2 catastrophic vessel failure experiments

Next steps

HSE is planning a workshop at its Science and Research Centre in Buxton to discuss the scope of a possible future **joint-industry project on CO_2 vessel failure**

Aims:

- Undertake experiments to better understand CO_2 BLEVEs and produce validation data
  - Lab-scale tests at the University of South-Eastern Norway
  - Small-scale tests at HSE, Buxton
  - Large-scale tests at DNV, Spadeadam
  - Detailed analysis using multiphase non-equilibrium CFD model at SINTEF Energy, Norway
- Develop and validate models for CO_2 catastrophic vessel failure
  - BLEVE blast models
  - Atmospheric dispersion source models
- Review approaches for risk assessment of CO_2 storage vessels

- Date to be confirmed
- If you are interested: please contact: Simon.Gant@hse.gov.uk Hans.Skarsvag@sintef.no

Daniel.Allason@dnv.com Knut.Vagsather@usn.no

Thank you

Any questions?

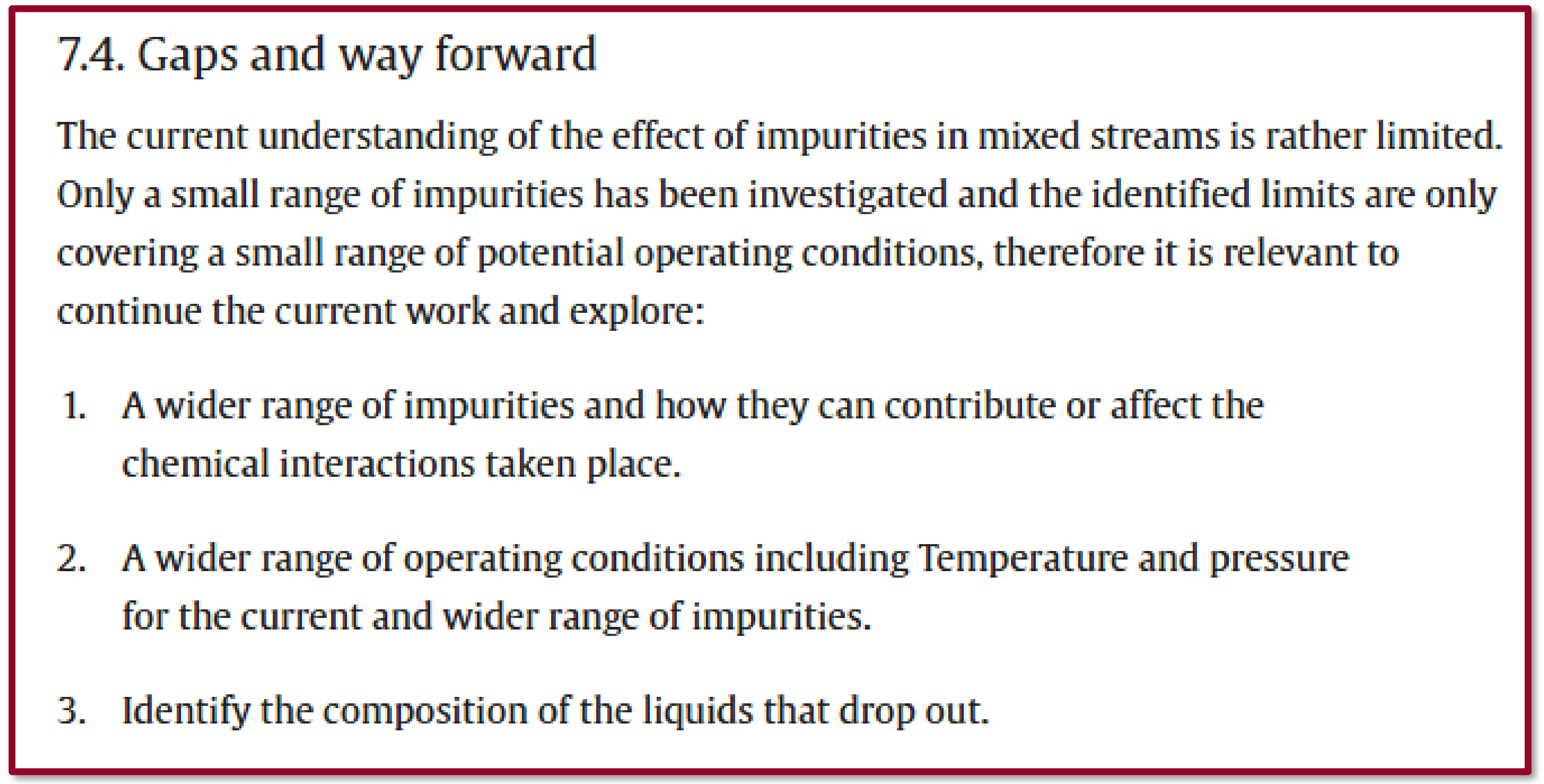
simon.gant@hse.gov.uk

- Disclaimer: the contents of this presentation, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy
- To review HSE areas of research interest, search here: https://ari.org.uk/ or https://int.octopus.ac/

Additional material

CO_2 corrosion, failure rates and risk assessment

- CO_2 stream contains range of impurities from capture plants
  - E.g., refineries, cement plants, waste-to-energy plants
- Impurities can react in mixed CO_2 streams to form tertiary compounds, which may be corrosive
- Research is still in progress to understand chemical reactions and corrosion rates
  - E.g., From Sonke *et al*., (2024) Shell, IFE, Total Energies, Equinor study https://doi.org/10.1016/j.ijggc.2024.104075



7.4. Gaps and way forward

The current understanding of the effect of impurities in mixed streams is rather limited. Only a small range of impurities has been investigated and the identified limits are only covering a small range of potential operating conditions, therefore it is relevant to continue the current work and explore:

1. A wider range of impurities and how they can contribute or affect the chemical interactions taken place.
2. A wider range of operating conditions including Temperature and pressure for the current and wider range of impurities.
3. Identify the composition of the liquids that drop out.

- Process upsets in gas-conditioning can also potentially cause exceedance of impurity levels
- How should this be taken into account in selecting CO_2 vessel failure rates, for risk assessment?

CO_2 vessel failure incidents: Haltern, Germany (1976)

https://doi.org/10.1016/j.engfailanal.2013.12.006

- CO_2 railcar failed catastrophically during shunting
- Fragments of vessel flung 300 m damaged a nearby building
- One fatality
- No indication of defect before incident, such as fatigue crack or leak
- Analysis indicated the crack probably initiated in the heat-affected zone in one of the welds
- Steel shell had insufficient toughness to arrest crack growth
- Similar previous incident in Essen Nord in 1975 led to leak but not catastrophic failure (crack was arrested)
- Haltern incident led revised technical regulations:
  - Implementation of toughness testing and acceptance guidelines
  - Inspection (non-destructive testing) of welds

CO_2 vessel failure incidents: Worms, Germany (1988)

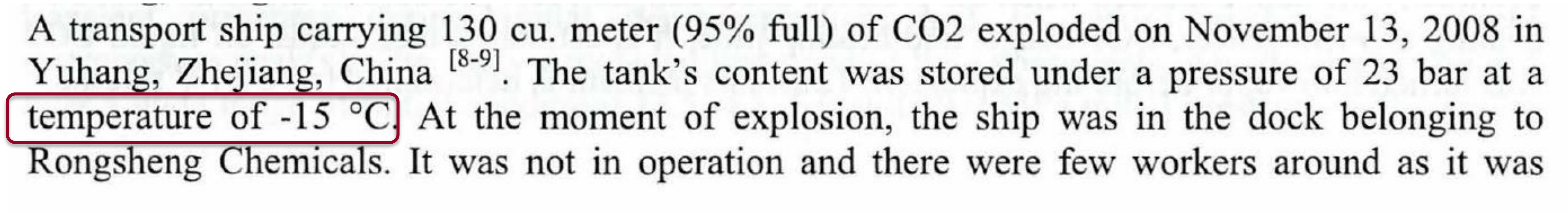
- Most costly incident of Procter and Gamble in 150-year history
- 30 t, 2.6 m diameter, 6.45 m long steel tank failed catastrophically
- Large part of vessel rocketed 300 m into Rhine river
- Three fatalities and eight injured
- Five weeks prior to incident, a heater in the vessel failed “off” and temperatures fell to -60 °C, which may have initiated a crack, which subsequently grew from pressure-cycling and fatigue
- Probable cause of incident: heater control failed “on” leading to overpressure, pressure relief valves failed to operate due to icing, and there was no alarm to indicate overpressure
- Incident recommendations included:
  - Use of fine-grain, tough, low-temperature rated carbon steel for vessels
  - Use low-heat-input weld procedures
  - Careful operations to “thaw” tanks following low-temperature excursions
  - Avoid pressure-relief valves where standpipes/springs/seats can freeze
  - Use controls, interlocks and alarms for pressure and temperature

https://www.icheme.org/media/5385/lpb_issue125p003.pdf
https://doi.org/10.1002/prs.680130405

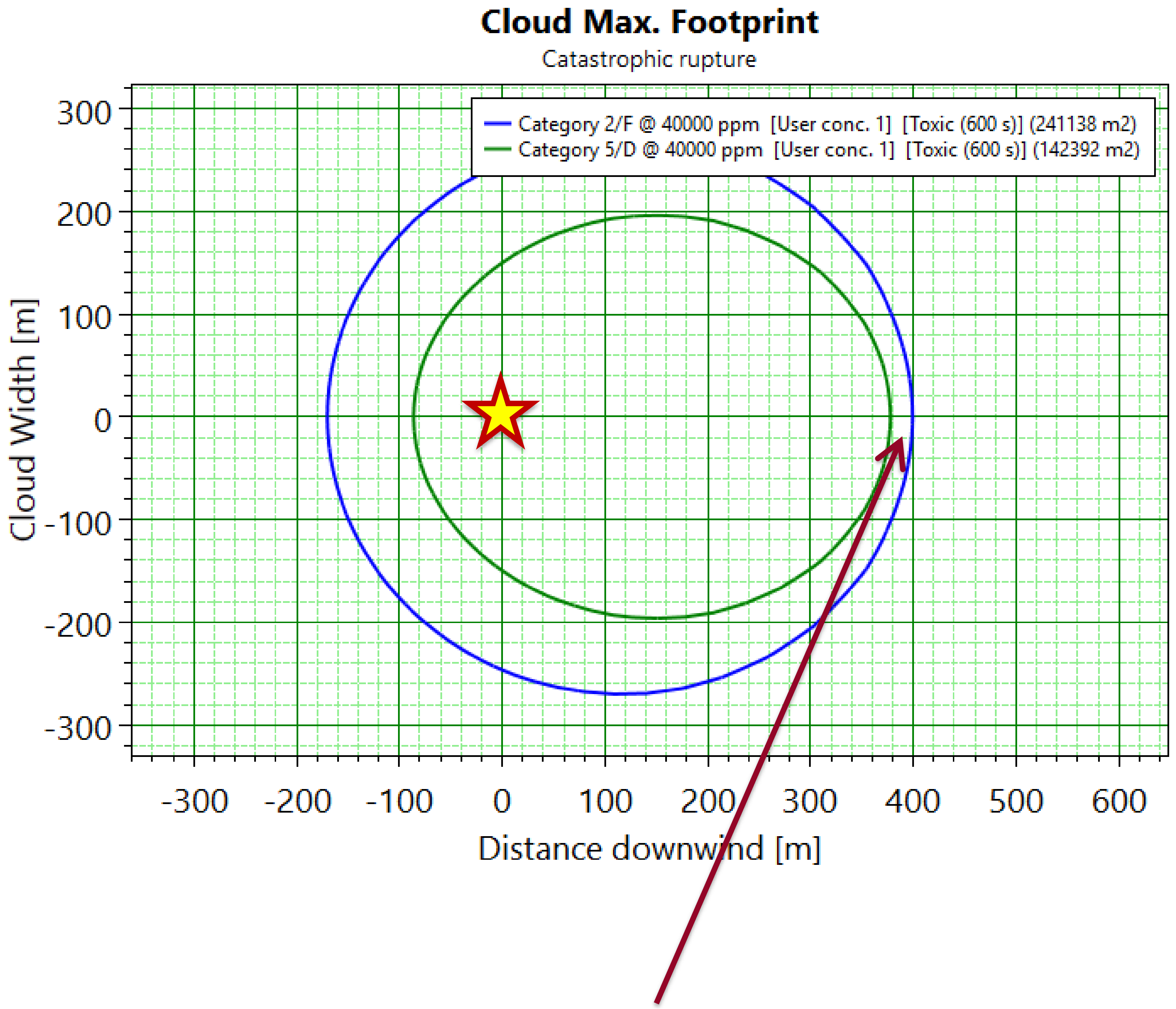
https://kudos.dfo.no/dokument/9797/mapping-of-potential-hse-issues-related-to-large-scale-capture,-transport-and-storage-of-co2

Toxic dispersion distance prediction for Yuhang, China (2008) incident

- Ship with **130 m^3 CO_2 vessel** failed catastrophically
- Explosion destroyed ship and sank two nearby ships
- 2 fatalities and 3 or 4 injured
- Fragments of ship flung 500 m
- Buildings damaged, glass broken to a distance of 500 m



A transport ship carrying 130 cu. meter (95% full) of CO2 exploded on November 13, 2008 in Yuhang, Zhejiang, China [8-9]. The tank's content was stored under a pressure of 23 bar at a temperature of -15 °C. At the moment of explosion, the ship was in the dock belonging to Rongsheng Chemicals. It was not in operation and there were few workers around as it was

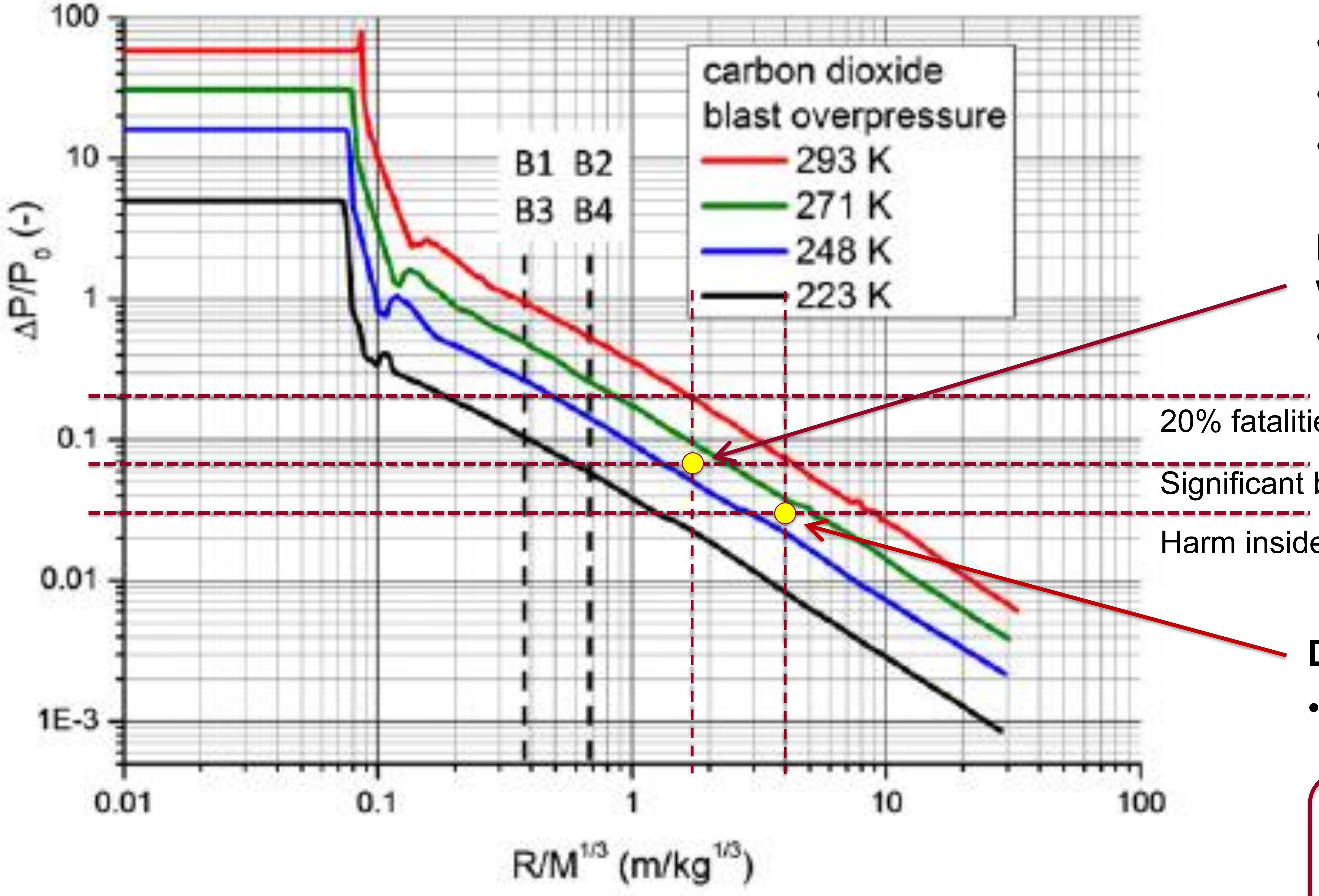


Zhang Y., Schork J., and Ludwig K. (2013) Revisiting the conditions for a CO2 tank explosion, AIChE 9th Global Congress on Process Safety, San Antonio, Texas, 28 April – 1 May 2013, http://dx.doi.org/10.4028/www.scientific.net/MSF.689.461

Li W., Di G. and Wang R. (2011) The cause analysis of a liquid CO_2 tank explosions on a ship, Materials Science Forum, 689, p461-467, http://dx.doi.org/10.4028/www.scientific.net/MSF.689.461

- IDLH toxic threshold is reached at a distance of approx. 400 m
- Observed BLEVE blast damage distance of 500 m in the incident appears to exceed the toxic dispersion hazard range for this 130 m^3 vessel

TNO blast prediction for for Yuhang, China (2008) incident



20% fatalities inside buildings, threshold for domino effects

Significant building damage, >90% window glass breakage, lacerations

Harm inside buildings from broken glass windows

CO_2 vessel conditions

- Refrigerated storage at -15°C (258 K)
- Vessel volume Vol = 130 m^3
- Vessel mass M = 131,000 kg

Damage: Partial demolition of buildings, >90% window glass breakage, lacerations (0.07 bar)

- Radius $R = 1.8M^{1/3} = 1.8(51) = 91\ m$

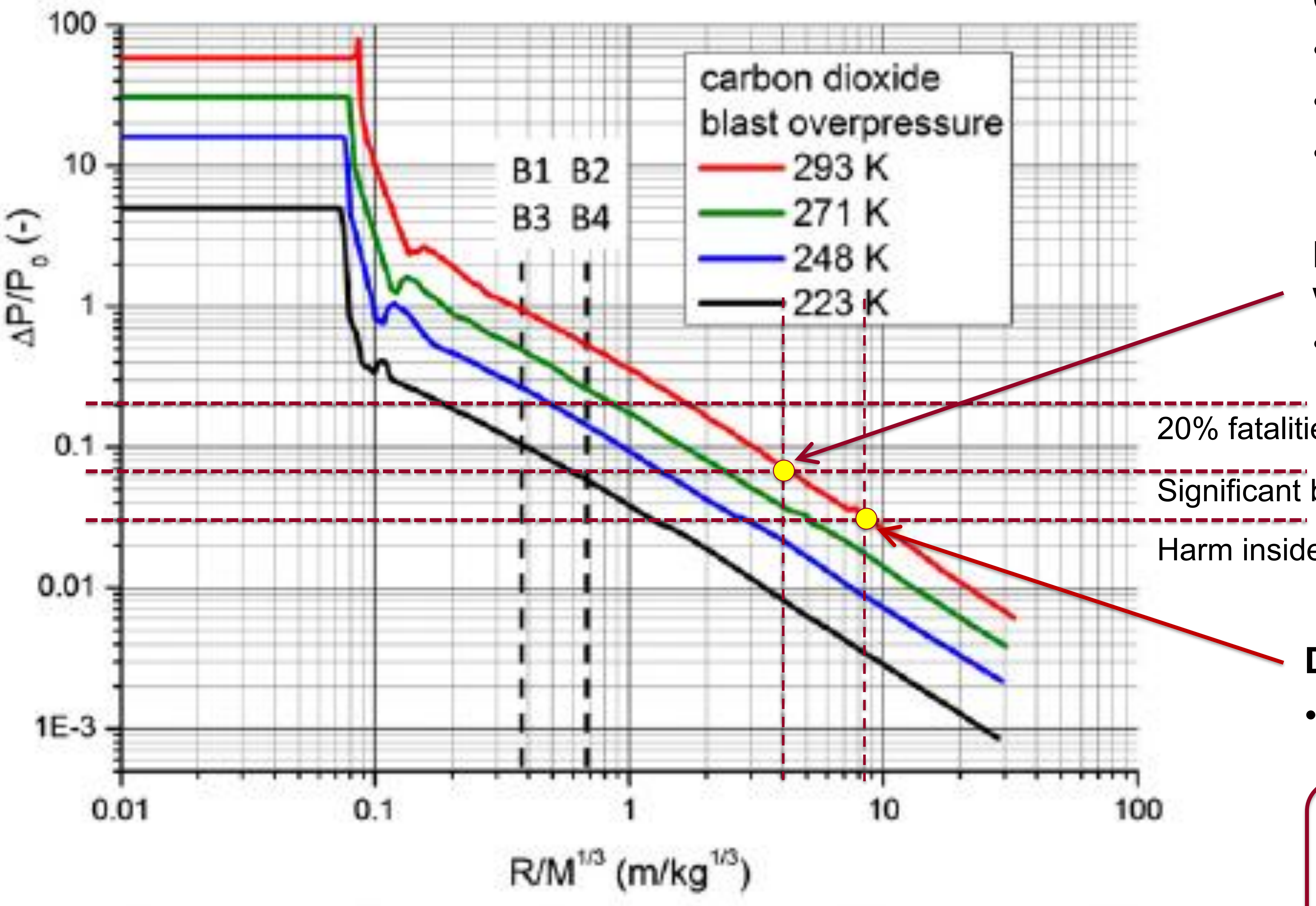
Damage: Harm from broken glass windows (0.03 bar)

- Radius $R = 4M^{1/3} = 4(51) = 203\ m$

Conclusion: Model predicts blast damage at 203 m, compared to observed damage at 500 m in incident

Source: Van den Voort *et al*. (2013) http://dx.doi.org/10.1016/j.jlp.2013.02.016

What if vessel failed at 20 °C in Yuhang, China (2008) incident?



20% fatalities inside buildings, threshold for domino effects

Significant building damage, >90% window glass breakage, lacerations

Harm inside buildings from broken glass windows

Source: Van den Voort *et al*. (2013) http://dx.doi.org/10.1016/j.jlp.2013.02.016

CO_2 vessel conditions

- What if vessel was at 20°C (293 K)
- Vessel volume Vol = 130 m^3
- Vessel mass M = 131,000 kg

Damage: Partial demolition of buildings, >90% window glass breakage, lacerations (0.07 bar)

- Radius $R = 4M^{1/3} = 4(51) = 203\ m$

Damage: Harm from broken glass windows (0.03 bar)

- Radius $R = 8.5M^{1/3} = 8.5(51) = 432\ m$

Conclusion: At higher temperature of 20°C, predicted blast damage radius is closer to observed damage in incident

Damage criteria from explosion overpressure

HSE: Offshore guidance (SPC30)	kPa	bar
1% level glass breakage	1.7	0.017
>90% level glass breakage and skin lacerations	7	0.070
20% fatality to people inside buildings	21	0.210

https://www.hse.gov.uk/foi/internalops/hid_circs/technical_osd/spc_tech_osd_30/

EIGA 75/21: Safety and Separation distances	kPa	bar
Harm inside buildings from broken glass windows	3	0.030
Harm from building damage, masonry collapse	7	0.070
Harm outside buildings from projectiles	10	0.100
Onset of damage to heavy machines, storage tanks, steel frame buildings etc	20	0.200

https://www.eiga.eu/uploads/documents/DOC075.pdf

French Ministry: damage effect thresholds	kPa	bar
Irreversible effects, glass breakage	2	0.020
Irreversible effects, significant danger to human life	5	0.050
First lethal effects, serious damage to structures	14	0.140
Significant lethal effects, threshold for domino effects	20	0.200

https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000000238461/

Summary used in graphs here as follows:

	kPa	bar
Harm inside buildings from broken glass windows	3	0.030
Partial demolition of buildings, >90% glass breakage, lacerations	7	0.070
20% fatalities inside buildings, threshold for domino effects	20	0.200

Immediately Dangerous to Life and Health (IDLH) toxic threshold

- Immediately Dangerous to Life and Health limits (IDLHs) are workplace exposure limits that are meant to protect workers when they are exposed to a toxic chemical in the course of their work.
- The US National Institute of Occupational Safety and Health (NIOSH) defines an immediately dangerous to life or health condition as a situation "that poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment"
- The IDLH limit represents the concentration of a chemical in the air to which healthy adult workers could be exposed (if their respirators fail) without suffering permanent or escape-impairing health effects.
- IDLH limits are derived by NIOSH based on animal and human data. Two factors are considered when establishing IDLH limits. Workers must be able to escape from the environment where they are exposed to hazardous chemicals without suffering (a) permanent health damage or (b) severe eye or respiratory tract irritation (or other conditions) that might impair their ability to escape.
- IDLH limits were created mainly to assist in making decisions regarding respirator use. Above the IDLH, only supplied air respirators should be used; below the IDLH, air purifying respirators may be used, if appropriate.
- Until 1994, an exposure duration of 30 minutes was associated with the IDLH. However, the current definition has no exposure duration associated with it; workers should not be in an IDLH environment for any length of time unless they are equipped and protected to be in that environment.

Excerpts taken directly from: https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/immediately-dangerous-life-health-limits-idlhs.html

Ibrahim *et al*. (2023) CO_2 experiments

- Extension of previous work by Hansen (2018) at University of South-Eastern Norway
- Studied Bottom Release (BR) from a 0.2 litre rectangular duct
  - Hansen (2018) previously studied Top Release (TR)
- Degree of superheating (DOS) in the BR tests was lower than in TR
  - E.g., DOS of 34% for BR compared to 68.4% for TR
- Pressure drop was 1.2–1.8 times faster during BR than TR tests, implying faster evaporation of the liquid
- Evaporation rate depends on whether the rupture area is below or above the liquid, which will probably affect blast strength and fragment formation
- No dispersion measurements

https://doi.org/10.1007/s42452-023-05469-7

Fig. 4 **a** Sketch of the test section showing the pressure transducer positions and the distance from the diaphragm position **b** photograph of the duct showing the positions of the shadowgraph lenses and pressure transducers