RISK ASSESSMENT METHODOLOGIES FOR CO_2 TRANSPORTATION WITHIN GCS PROJECTS

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INTRODUCTION

Pipeline transportation of fluids is a proven technology for moving large quantities of liquids and gases (e.g., hydrocarbons, hazardous liquids, hydrogen) over large and small distances.

The potential introduction of large-scale Geologic Carbon Sequestration (GCS) as a means of reducing greenhouse gas emissions will require the ability to transport massive amounts of carbon dioxide (CO_2), safely and economically.

About 1.5 billion tons of CO_2 are produced annually in the United States from coal-fired power plants.

The existing U.S. CO_2 pipeline infrastructure transports approximately 45 Mt of CO_2 per year over 3,500 miles of pipe for enhanced oil recovery (EOR). For comparison, the existing U.S. natural gas pipeline network transports 455 Mt per year of natural gas over 300,000 miles of interstate and intrastate pipes (McCoy, 2009).

The length of pipeline needed to transport CO_2 will be in the range of 15,000-66,000 miles by 2030.

Based on models of costs for transmission lines, CO_2 pipelines, and fuel transportation, it is always preferable to locate a CCS power facility nearest the electric load (i.e. electricity end-users), reducing the losses and costs of bulk electricity transmission (Newcomer and Apt, 2008). Therefore, densely inhabited areas will not be avoidable when deciding the route of CO_2 pipelines.

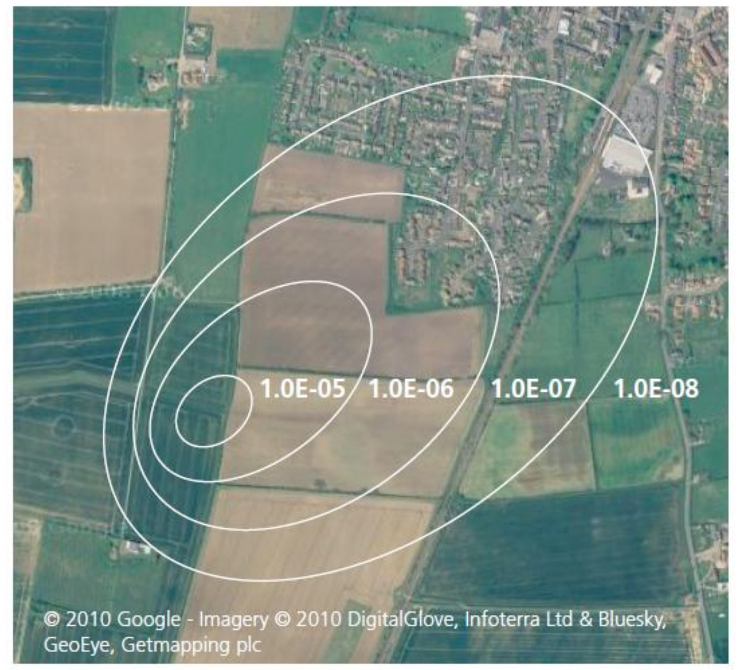
Major fluids transportation infrastructure in the USA

PIPELINE	Owner/Operator	Length (mi)	Length (km)	Diameter (in)	Estimated Max Flow Capacity (MMcfpd)	Estimated Max Flow Capacity (million tons/yr)	Location
Adair	Apache	15	24	4	47	1.0	TX
Anton Irish	Oxy	40	64	8	77	1.6	TX
Beaver Creek	Devon	85	137				WY
Borger, TX to Camrick, OK	Chaparral Energy	86	138	4	47	1.0	TX, OK
Bravo	Oxy Permian	218	351	20	331	7.0	NM, TX
Centerline	Kinder Morgan	113	182	16	204	4.3	TX
Central Basin	Kinder Morgan	143	230	16	204	4.3	TX
Chaparral	Chaparral Energy	23	37	6	60	1.3	OK
Choctaw (aka NEJD)	Denbury Onshore, LLC	183	294	20	331	7.0	MS, LA
Comanche Creek (currently inactive)	PetroSource	120	193	6	60	1.3	TX
Cordona Lake	XTO	7	11	6	60	1.3	TX
Cortez	Kinder Morgan	502	808	30	1117	23.6	TX
Delta	Denbury Onshore, LLC	108	174	24	538	11.4	MS, LA
Dollarhide	Chevron	23	37	8	77	1.6	TX
El Mar	Kinder Morgan	35	56	6	60	1.3	TX
Enid-Purdy (Central Oklahoma)	Merit	117	188	8	77	1.6	OK
Este I to Welch, TX	ExxonMobil, et al	40	64	14	160	3.4	TX
Este II to Salt Creek Field	ExxonMobil	45	72	12	125	2.6	TX
Ford	Kinder Morgan	12	19	4	47	1.0	TX
Free State	Denbury Onshore, LLC	86	138	20	331	7.0	MS
Green Line I	Denbury Green Pipeline LLC	274	441	24	850	18.0	LA
Joffre Viking	Penn West Petroleum, Ltd	8	13	6	60	1.3	Alberta
Llaro	Trinity CO_2	53	85	12-8	77	1.6	NM
Lost Soldier/Werrz	Merit	29	47				WY
Mabee Lateral	Chevron	18	29	10	98	2.1	TX
McElmo Creek	Kinder Morgan	40	64	8	77	1.6	CO, UT
Means	ExxonMobil	35	56	12	125	2.6	TX
Monell	Anadarko			8	77	1.6	WY
North Ward Estes	Whiting	26	42	12	125	2.6	TX
North Cowden	Oxy Permian	8	13	8	77	1.6	TX
Pecos County	Kinder Morgan	26	42	8	77	1.6	TX
Powder River Basin CO_2 PL	Anadarko	125	201	16	204	4.3	WY
Raven Ridge	Chevron	160	257	16	204	4.3	WY, CO
Rosebud	Hess						NM
Sheep Mountain	Oxy Permian	408	656	24	538	11.4	TX
Shute Creek	ExxonMobil	30	48	30	1117	23.6	WY
Slaughter	Oxy Permian	35	56	12	125	2.6	TX
Sonat (reconditioned natural gas)	Denbury Onshore, LLC	50	80	18	150	3.2	MS
TransPetco	TransPetco	110	177	8	77	1.6	TX, OK
W. Texas	Trinity CO_2	60	97	12-8	77	1.6	TX, NM
Wellman	PetroSource	26	42	6	60	1.3	TX
White Frost	Core Energy, LLC	11	18	6	60	1.3	MI
Wyoming CO_2	ExxonMobil	112	180	20-16	204	4.3	WY
Canyon Reef Carriers	Kinder Morgan	139	224	16	204	4.3	TX
Dakota Gasification (Souris Valley)	Dakota Gasification	204	328	14-12	125	2.6	ND, Sask
Pikes Peak	SandRidge	40	64	8	77	1.6	TX
Val Verde	SandRidge	83	134	10	98	2.1	TX

Existing major CO_2 transportation pipelines in the U.S.A.; US CO_2 infrastructure will have to be expanded to be comparable in size to natural gas and oil pipeline systems.

QUANTITATIVE RISK ASSESSMENTS (QRAs)

Transportation safety is paramount and health, safety and environmental (HSE) risk needs to be assessed prior to and during the operational phase of CO_2 transport. Failures can be due to pipeline damage, corrosion, and leaks, which are reasonably rare events. There were 12 accidents in 3,500 miles of CO_2 pipelines between 1986 and 2008 and no human injuries or fatalities (Parfomak and Folger, 2008). By contrast, there were 5,610 accidents causing 107 fatalities and 520 injuries related to natural gas and hazardous liquid pipelines (a category that does not include CO_2 pipelines) during the same period in the U.S..

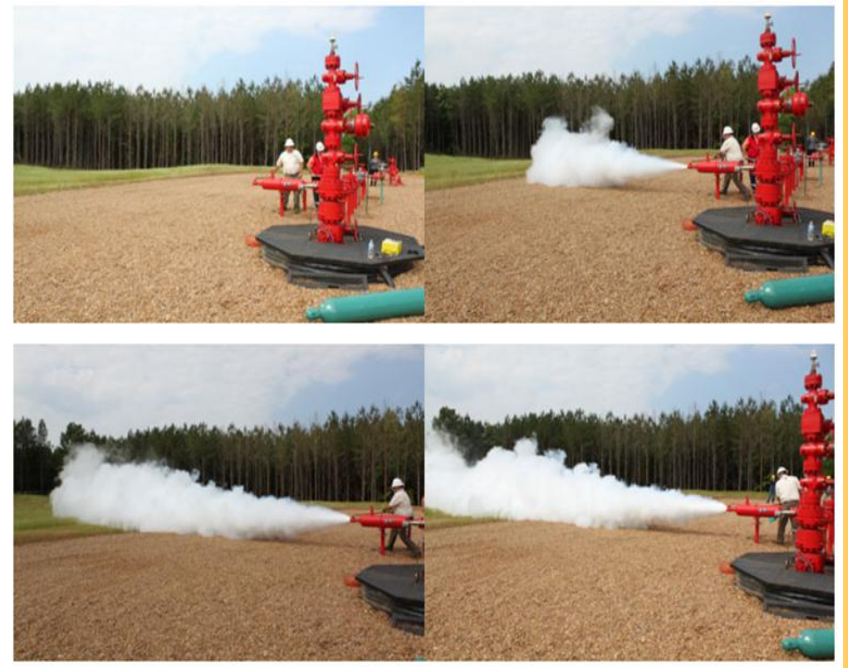


Above. Individual RA for a fictional proposed chemical plant near a populated area

Risk involved in the transportation of a toxic gas is assessed by evaluating the area influenced by high concentrations of the gas after a leak.

In the last decade several studies considered potential atmospheric dispersion of CO_2 leaked from CCS transportation facilities (e.g. Cameron-Cole, 2005; Vendrig et al., 2003), drawing RAs based on Gaussian/dense-gas simulations.

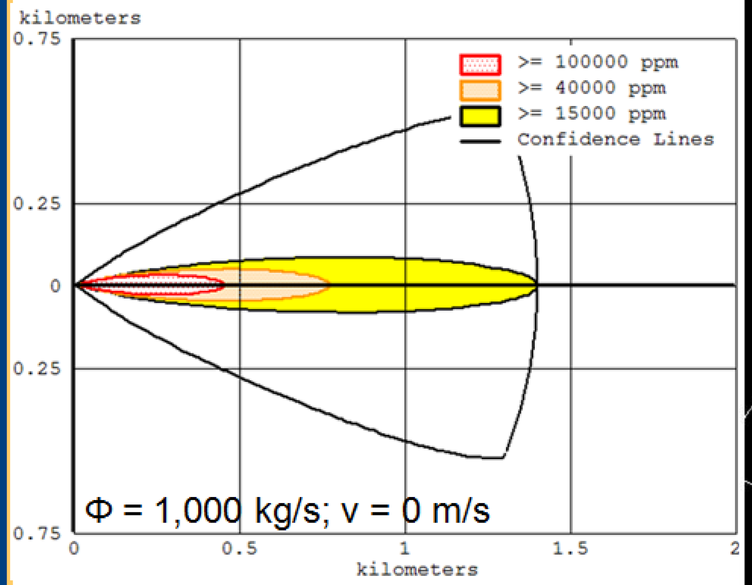
Below. Controlled release of CO_2 from a HP facility (Cranfield, MS). White color due to H_2O condensation

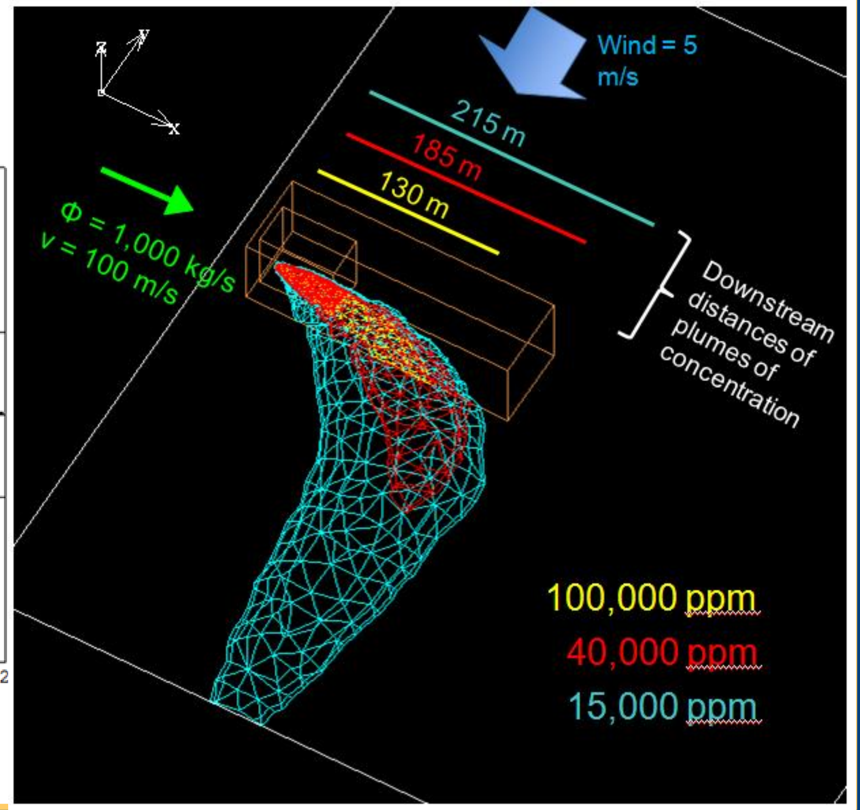


The high momentum of the jet release could not be modeled properly.

The high velocity of the release causes initial dilution of CO_2, due to resistance of static air. The utilization of Gaussian models could highly overestimate the actual risk involved in piping the gas.

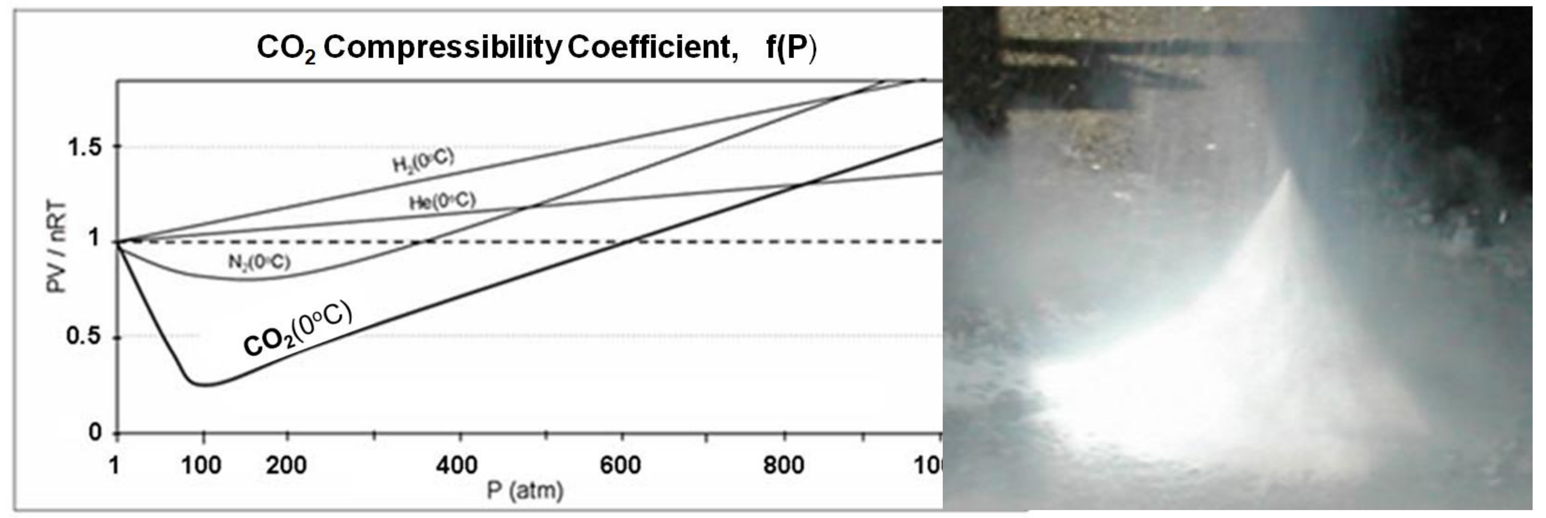
Below, a comparison between Gaussian and CFD modeling for wind = 5 m/s. Note the difference in downwind lengths of differently concentrated plumes. The CFD code used is Fluidyn-PANACHE v. 4.0.7





Above and right. Comparison between Gaussian and CFD atm. dispersion modeling

JOULE-THOMSON EFFECT



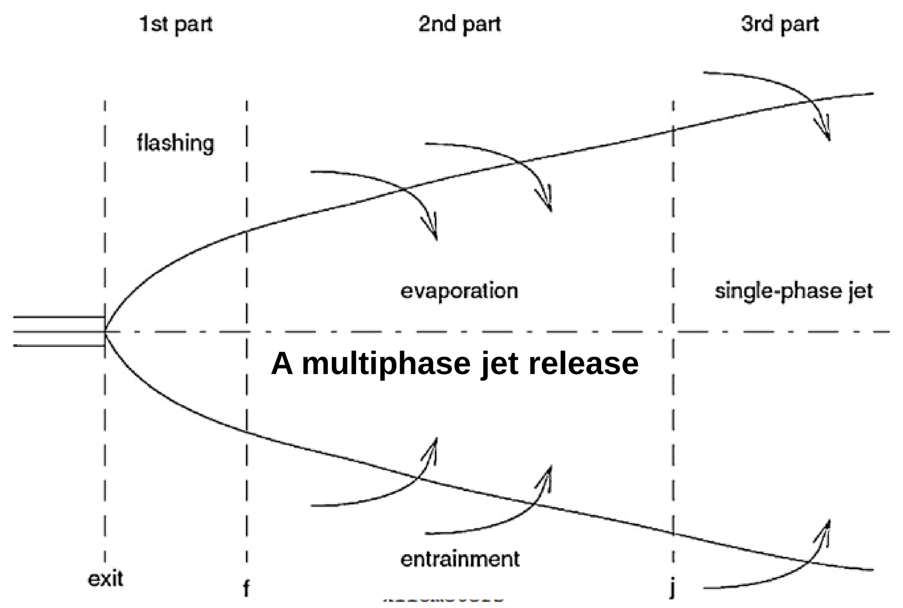
Left, Compressibility Coefficient for some real gases. Right, the formation of a bank of solid CO_2 (dry ice, T < -78ºC) after a sudden P drop, for a downward direction (Mazzoldi et al., 2007)

CO_2 cannot be modeled as an ideal gas. Thus its compressibility coefficient, PV / nRT, deviates from unity and varies with pressure. Above is depicted its variation at different P. Deflections of PV/nRT from unity are due to molecular interactions, particularly, CO_2 presents attractive intermolecular forces at high pressure. When the gas is forced to expand (due to e.g. P drop) its molecules will have to do work against these forces, lowering the T of the fluid .

The Joule-Thomson equation relates the temperature and pressure changes for real gases: $\Delta T = \varphi * \Delta P$; φ is the J-T coefficient. For CO_2 the value of the J-T coefficient was found experimentally: $\varphi_{CO2} = 1.3$ K atm^{-1}.

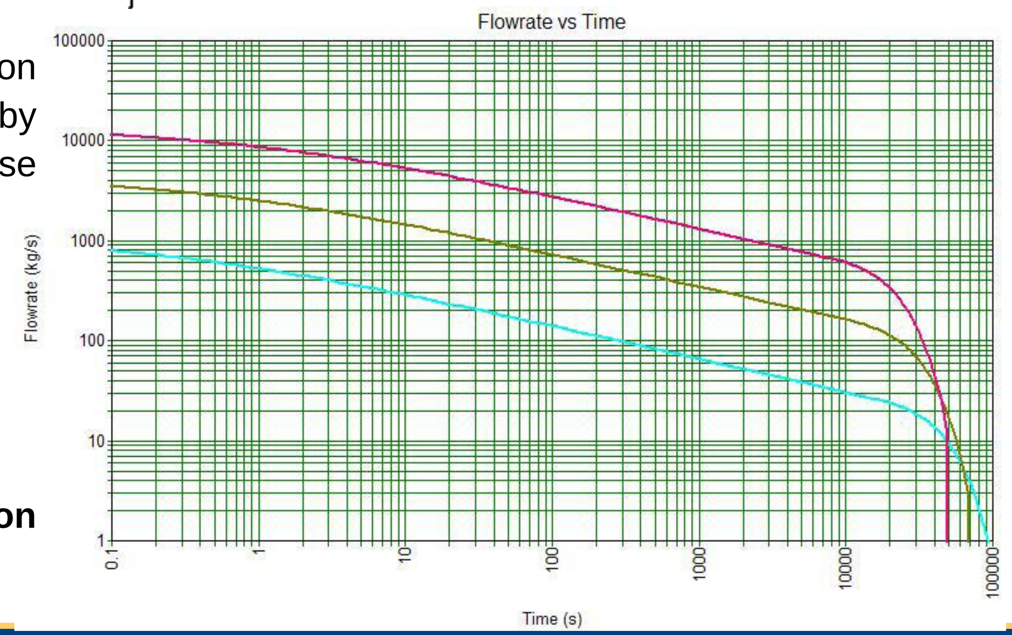
MULTI-PHASE JET RELEASE

Multiphase effects are observed in CO_2 releases as consequence of P drops.



A real-fluid non-isentropic decompression model (Picard and Bishnoi, 1988) will be used to evaluate the transient real gas release rate from HP pipeline full-bore leaks. The use of perfect-gas theory can result in the transient release rate being underestimated by 30% to 45%, and the total amount of fluid released, underestimated by 50%.

Below, transient release rates



CO_2 release rates from leaks on HP facilities will be dictated by 'source-term parameters'. These can be summarized as:

- **Pipeline internal P**;
- **Pipeline diameter (2r)**;
- **Leak 2r (here, = pipe 2r)**;
- **Pipeline length**;
- **ESD' frequency and activation timing**

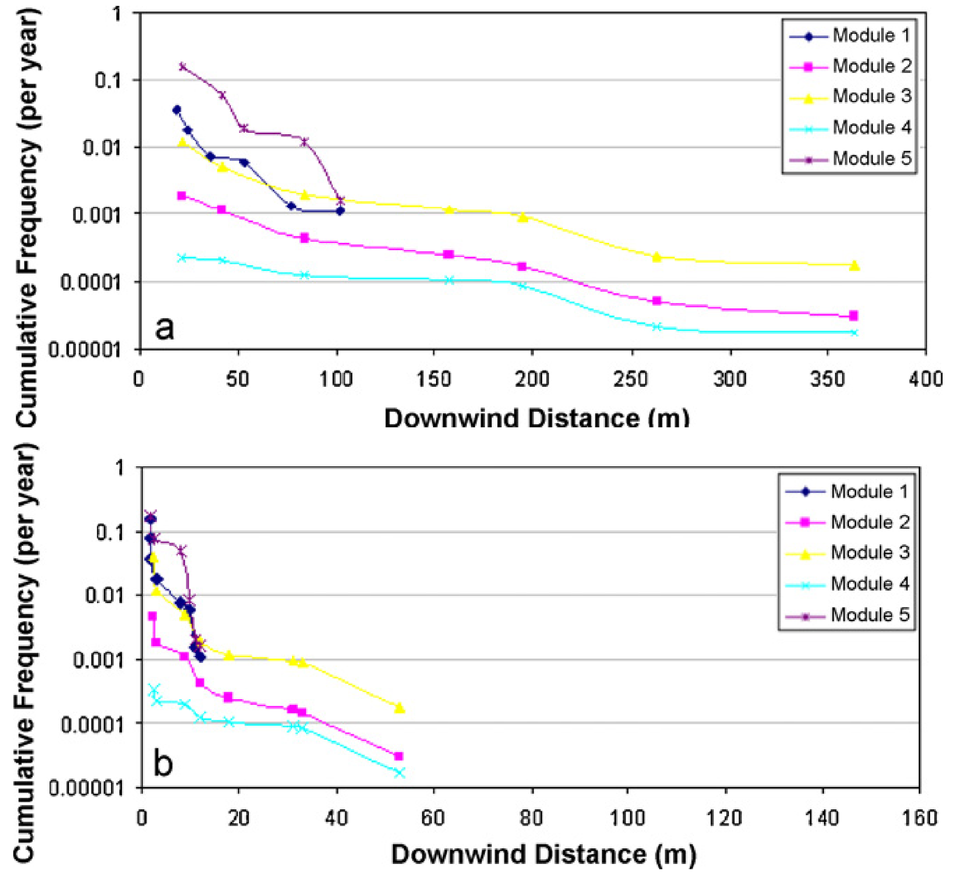
CFD RAs DRAFTING & SAFETY DISTANCES CALCULATION

The HSE risk involved in transporting CO_2 is represented by the potential for accidental leakage and the expected consequences for humans and the environment.

Risk of fatality is estimated by multiplying the area covered by specific concentrations of gas (e.g. 100,000 ppm or 250,000 ppm) by the average density of humans present in the area by the time–frequency of the failure that produced the plume.

Accounting for a high-speed source term (jet-mixing effect' dilution) gives lower areal coverage for toxic plumes of concentrated CO_2. Below are shown downwind lengths of 100,000 ppm concentration of CO_2 plumes leaked from different modules of a transportation system, calculated with a Gaussian model, ALOHA 5.4, and CFD, PANACHE (Mazzoldi et al. 2011).

Based on Gaussian results, the E.U. drafted a RA on CO_2 transportation (E.U. 2008), that calculated an expected death rate of about 5 persons per year by 2030, over European territories. Their results were very similar to ALOHA's, as shown in the figure.



100,000 ppm downwind distances for Gaussian, a), (0 m/s releases) and CFD, b) (50 m/c releases) dispersion models

Conservatively, in many risk assessments the lethal concentration of CO_2 has been considered to be 100,000 ppm, although the gas is lethal only after more then 10 minutes of uninterrupted inhalation.

Accounting for the jet-release and in order to estimate safety distances (perpendicular to the pipe) from CO_2 facilities, the next step will be the downstream modeling of 250,000 ppm concentration (fatal after a few breath), after calculating transient release rates for different pipeline geometries and source-term parameters, using the Picard decompression model.

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