Simulation of Releases from CO_2 Transport Pipelines

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Tom Grieb, Michael Ungs, Kateryna Sayenko, Karen Summers, Bill Mills, Kay Johnson, Mark Rigby, Steve Gherini, Sujoy Roy and Bob Johns

TETRA TECH

CO_2 Pipeline Characteristics

Carbon sequestration in geologic formations involves the capture, transport and injection of CO_2. The environmental risks from CO_2 transportation have been assumed to be small relative to the geological hazards and risks of CO_2 releases and leakage associated with the capture and sequestration steps. This perception is based, in part, on the routine use of pipelines for long-distance transport of natural gas and liquids, such as crude oil, fuel oil, condensate, and gasoline. However, previous studies have shown that releases caused by outside forces, corrosion and other pipe failures can be expected during the lifetime of the CO_2 pipelines. The large volumes of CO_2 that are involved in carbon capture and storage require the transport of the CO_2 as a supercritical fluid, typically at pressures between 75 and 200 bar. The potential human health risks associated with pipeline releases of CO_2 and other sequestered gases such as hydrogen sulfide (H_2S) has recently been evaluated in detail at four sites within the U.S. that we evaluated as part of the risk assessment for the FutureGen Project (DOE, 2007).

A new pipe-walking algorithm was developed to estimate the expected number of individuals affected by pipeline releases at specified intervals along the length of the pipeline. Site-specific data on wind speed, wind stability, population densities as well as thermal dynamic properties and dispersion characteristics of the transported gases are incorporated in the analysis. Simulated dispersion patterns of the released gases were combined with toxicity information to estimate potential human health risks.

Figure 1. CO_2 release from pipeline

Failure Rate Frequencies for Pipelines and Injection Wells

Failure rates for the key release scenarios that were simulated were estimated from historical operational data from existing operating sites and data on pipeline transport of captured gases.

The CO_2 pipeline failure frequency was calculated based on data contained in the on-line library of the Office of Pipeline Safety (http://ops.dot.gov/stats/IA98.htm). Accident data from 1994-2006 indicated that 31 accidents occurred during this time period. The two accidents with the largest CO_2 releases (4000 barrels and 7408 barrels) were rupture type releases.

The failure rate of an injection well during operation was estimated as 2.02×10^{-5} per well per year based on experience with natural gas injection wells from an IEA GHG Study (Papa et al., 2006).

Table 1. Failure rate frequencies for pipelines and injection wells

Parameter	Jewett, TX	Odessa, TX	Mattoon, IL	Tuscola, IL
Pipeline Length, km	84	99	0.8	18
Frequency of Failure by Rupture per year	0.005	0.0059	5.0E-05	0.002
Probability of at least one failure over lifetime	0.22	0.25	0.002	0.05
Number of Injection Wells	1	10	1	1
Frequency of Failure per year	2.02E-05	2.02E-04	2.02E-05	2.02E-05
Incidents of Failure in 50 years	1.01E-03	1.01E-02	1.01E-03	1.01E-03

Estimation of CO_2 Phases in the Environment after Pipeline Release

It is assumed that CO_2 leaks from a pipeline under adiabatic, isenthalpic conditions (Walas, 1985). This is the also known as a Joule-Thompson expansion of the fluid. Also assumed is that since the pipeline fluid is over 99 percent CO_2 that behavior of the fluid mixture can be estimated based upon that of the pure single component CO_2.

Initial pipeline pressure and temperature in the pipeline (2,200 psi and 90 degrees F) are above the critical point values for CO_2 (see figure). CO_2 in the pipeline would be a dense fluid rather than a vapor or liquid. For the constant enthalpy expansion of the pipeline CO_2 to atmospheric conditions (14.7 psia), the resulting CO_2 will exist as both solid and vapor phases. The fraction of the mixture that will be released as vapor, was estimated to be roughly 74 percent. The estimated solid fraction of the released mixture is 26 percent.

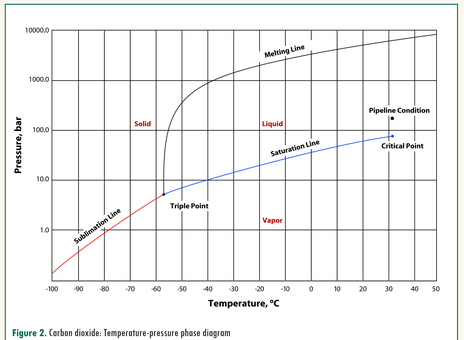

Figure 2. Carbon dioxide: Temperature-pressure phase diagram

Methodology

There are five main steps in the new pipe-walking algorithm

1. **Summarize Meteorological Conditions that Affect Plume Transport**. Recent meteorological data (wind speed and direction) are used to characterize atmospheric conditions at each site. Wind direction data are divided up into 16 wind directions from which wind blows (e.g., S, SSW, SW, WSW) and wind speed and atmospheric stability conditions are divided up into 7 categories (e.g., category F2 means Pasquill stability F and 2 meters per second wind speed). The proportion of time over a year in each of 112 atmospheric states (combinations of 16 directions and 7 stability categories) was defined. The wind rose information for one of the FutureGen sites is provided in Table 2.

2. **Simulate the Area Potentially Affected by a Pipeline Release.** The SLAB model (Ermak, 1990), developed to simulate denser-than-air gas releases for both horizontal jet and vertically elevated jet scenarios, was run to determine the potential impact zone for each of the 112 defined atmospheric states. For each simulated pipeline release type, the gaseous impact zone or footprint was determined for five concentration levels corresponding to selected health-effect levels for 15-minute exposure durations: 0.51 ppmv H_2S, 27 ppmv H_2S, 50 ppmv H_2S, 30,000 ppmv CO_2, and 40,000 ppmv CO_2.

3. **Estimate Population Affected for Each Atmospheric State.** The polygon representing the surface area A(i) of the ith predicted impact zone defined in Step 2 for each of the 112 atmospheric states was superimposed onto a map containing the digitized census-tract data. The total affected population in the ith impact zone (p_i) was estimated as the sum of the products of the area of each kth unique sub-portion of the impact zone ($A(i)_k$) and the corresponding population density (ρ_k):

$$p_i = \sum_{k=1}^{m} \rho_k A(i)_k \qquad \text{(Eq 1)}$$

$$A(i) = \sum_{k=1}^{m} A(i)_k \qquad \text{(Eq 2)}$$

where: m equals the number of distinct census tracts that are intersected by the ith atmospheric state. A simple schematic demonstrating this calculation is shown in Figure 3.

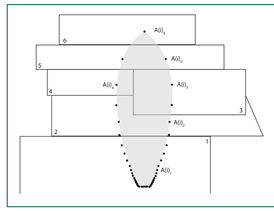

Figure 3. Intersection of the ith impact zone A(i) intersecting six census tracts, which have population densities $\rho_1,\ldots,\rho_6$. The intersected sub-portion of the impact zone area with census tracts are labeled $A(i)_1,\ldots,A(i)_6$.

4. **Determine the Total Number of Individuals Potentially Affected at the Specified Release Points.** The affected population in each of the ith impact zones (p_i) was next multiplied by the proportion of the time (relative importance) in each of the ith atmospheric states (Atm_i) over a period of one year. Since Atm_i for all 112 atmospheric states sums to 1, the sum of these products provides the expected number of affected individuals at the lth selected point along the pipeline (P_l):

$$P_l = \sum_{i=1}^{112} p_i \, Atm_i \qquad \text{(Eq 3)}$$

$$\sum_{i=1}^{112} Atm_i = 1 \qquad \text{(Eq 4)}$$

or combining Equations 1 and 3:

$$P_l = \sum_{i=1}^{112} Atm_i \sum_{k=1}^{m} \rho_k A(i)_k \qquad \text{(Eq 5)}$$

The above process is repeated for each concentration threshold, for each type of accident scenario, and for each chemical of concern.

The calculations were also performed at different spacing distances along the pipeline. It was found by trial and error that there was no significant change in the predicted concentrations when using a 300 meter spacing along the pipeline.

5. **Characterize the Potential Exposure Along the Entire Pipeline.** By automating the analysis, the routine simulates the release of CO_2 and H_2S at points every 300 m above the entire route of the pipeline. The analysis of potential exposure to released gases calculates P_l, the expected number of affected individuals at the lth selected point.

Table 2. Wind rose data for Jewett, TX site based on combined data from Waco and Huntsville Regional Airports from Jan 1, 2005 through Dec 31, 2005 (FutureGen Alliance, 2006). The table shows the percent of time per year that wind blows from one of sixteen directions and with one of seven wind-speed stability categories. The Pasquill stability categories are shown along the top line of the table. Values are based on the corresponding wind-speed and the assumption of moderate insolation (Turner, 1994, page 2-7). For example, category B03 means a 3 m/sec wind with a Pasquill stability class B, etc.

	F02	A01	A02	B03	B04	C06	D08
From	Calm (%)	2.6 to 3.09 mph(%)	3.09 to 5.14 mph (%)	5.14 to 8.23 mph (%)	8.23 to 10.8 mph (%)	10.8 to 15 mph (%)	>=15mph (%)
S	1.3	1.1125	1.3125	5.625	4.875	4.875	3.375
SSW	1.3	0.5625	0.5625	2.25	0.75	0.75	0.375
SW	1.3	0.1875	0.375	0.5625	0.5625	0.375	0
WSW	1.3	0.0375	0.1125	0.75	0.075	0.15	0
W	1.3	0.1875	0.375	1.125	0.1875	0.1875	0
WNW	1.3	0	0.1875	0.5625	0.375	0.375	0.375
NW	1.3	0.1875	0.375	1.3125	0.375	0.375	0
NNW	1.3	0.375	0.375	1.5	0.75	0.75	0.75
N	1.3	0.75	0.5625	2.625	1.5	1.5	1.3125
NNE	1.3	0.1875	0.1875	1.125	0.375	0.375	0.1875
NE	1.3	0.075	0.375	1.125	0.1875	0.225	0
ENE	1.3	0.5625	0.75	1.3125	0.15	0.225	0
E	1.3	1.3125	1.3125	1.3125	0.375	0	0
ESE	1.3	0.1875	0.375	1.125	0.375	0.375	0
SE	1.3	0	0.75	1.875	0.75	0.5625	0.1875
SSE	1.3	0.75	0.75	3.75	2.625	2.25	1.875

Findings

Figure 4 and Table 3 present the estimates of the number of individuals potentially experiencing adverse health effects from exposures to H_2S concentrations (0.51 ppmv) at all four FutureGen sites. For example at the Jewett site, along much of the pipeline (50 Km out of the total length of 95 Km), less than 10 individuals would be expected to be exposed to H_2S above 0.51 ppmv from a pipeline rupture. At about 60 Km, the potentially exposed population increases to greater than 30 and up to 63 individuals. The same results for the Tuscola site show that fewer than 10 individuals would be expected to be exposed over the entire length of the pipeline. The maximum number of exposed individuals would occur over a 3 km segment of the entire 18 Km Tuscola pipeline.

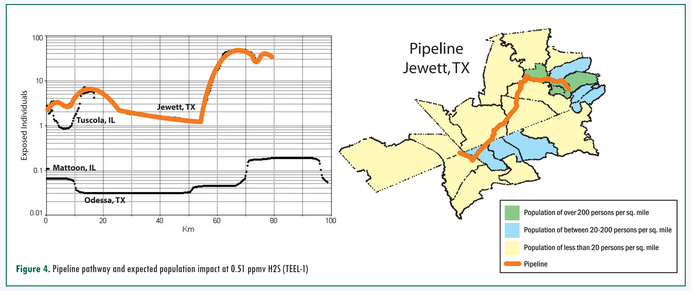

Figure 4. Pipeline pathway and expected population impact at 0.51 ppmv H2S (TEEL-1)

Table 3. Pipeline Lenghts (km) Corresponding to Expected Number of Individuals in Offsite Population Potentially Exposed to 0.51 ppmv Concentrations of H_2S (Adverse Effects) by Pipeline Rupture.

Number of Individuals Potentially Affected	Length of Pipeline Effect (km)			
	Mattoon	Tuscola	Jewett	Odessa
<1	0.8	4.2	0	99
1-10		13.5	59	
11-20		—	2.4	—
21-30	—	—	1.2	—
31-40	—	—	5.1	—
41-50	—	—	9.6	—
51-60	—	—	2.7	—
Total Pipeline Length (km)	0.8	17.7	80	99

Summary

Previous studies have shown that releases caused by outside forces, corrosion and other pipe failures can be expected during the lifetime of a pipeline (Gale and Davison, 2004). A new pipe-walking algorithm was developed that incorporates site-specific data on wind speed, atmospheric stability, population densities as well as the thermal dynamic properties and dispersion characteristics of the transported gases, to estimate the potential risk to nearby populations from an accidental release of CO_2 and other gases from pipelines.

Due to the sparse populations in the areas around the proposed pipelines of the FutureGen sites, the likelihood of health effects to offsite populations from the CO_2 concentrations predicted for a pipeline rupture was low, since the CO_2 concentrations more than 250 m from the release points are less than a level (30,000 ppmv) below which there would be only mild or transient health effects. If a pipeline rupture occurred within populated areas, the impact zone with predicted H_2S concentrations at a level [Protective Action Criteria (PAC)-2 of 27 ppmv], where there could be more than transient health effects, was predicted to extend to distances of up to several hundred meters, while the zone with H_2S concentrations causing mild transient effects (PAC-1 of 0.51 ppmv) could extend out to distances of up to several kilometers.

Figure 5. FutureGen sites simulated

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