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Quantifying the potential exposure hazard due to energetic releases of CO_2 from a failed sequestration well

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Abstract

Wells are designed to bring fluids from depth to the earth's surface quickly. As such they are the most likely pathway for CO_2 to return to the surface in large quantities and present a hazard without adequate management. We surveyed oil industry experience of CO_2 well failures, and separately, calculated the maximal CO_2 flow rate from a 5000 ft depth supercritical CO_2 reservoir. The calculated maximum of 20,000 tonne/day was set by the sound speed and the seven-inch well casing diameter, and was greater than any observed event. We used this flux to simulate atmospheric releases and the associated hazard utilizing the National Atmospheric Release Advisory Center (NARAC) tools and real meteorology at a representative location in the High Plains of the United States. Three cases representing a maximum hazard day (quiet winds <1 m s^{-1} near the wellhead) and medium and minimal hazard days (average winds 3 m s-1 and 7 m s-1) were assessed. As expected for such large releases, there is a near-well hazard when there is little or no wind. In all three cases the hazardous Temporary Emergency Exposure Levels (TEEL) 2 or 3 only occurred within the first few hundreds of meters. Because the preliminary 3-D model runs may not have been run at high enough resolution to accurately simulate very small distances, we also used a simple Gaussian plume model to provide an upper bound on the distance at which hazardous conditions might exist. This extremely conservative model, which ignores inhomogeneity in the mean wind and turbulence fields, also predicts possible hazardous concentrations up to several hundred meters downwind from a maximal release.

Sequestration

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1. Introduction

Release to the atmosphere constitutes a significant safety concern in the handling of any large volume of gas. While there are established measures for evaluating the risk from chemical facilities and pipelines, the specific hazards

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associated with the geologic storage are only beginning to be addressed. Wells are designed to bring fluids from depth to the earth's surface quickly. As such they are the most likely pathway for CO_2 to return to the surface in large quantities and present a hazard without adequate management. In order to quantify the hazard, we constructed a hypothetical release scenario involving a supercritical CO_2 reservoir at 1500 m (5000 ft) depth at a site in the central plains of the United States where the states of Colorado, New Mexico, Oklahoma, and Kansas join. We chose a specific site (deliberately not identified in this publication) with flat terrain and reasonably good local meteorological data.

2. Energetic Releases – Well Failure

Release of carbon dioxide from the underground reservoir could occur by failure of an injection well or the failure of an improperly sealed or compromised well. In order to maintain operational integrity, deep wells are cased and cemented and, ultimately, plugged and abandoned (Jarrell *et al.* 2002). Despite the long, successful history of well engineering, there are many potential failure mechanisms that could potentially allow CO_2 to escape from deep reservoirs (Scherer *et al.* 2004, Gasda *et al.* 2006, Lewicki *et al.* 2007). Many conditions control the likelihood of well effectiveness, including the age and plugging mechanism, quality of completion, and post-closure history (Ide *et al.* 2006). Table 1.2 lists some well failures involving CO_2 for which there is documentation or first-hand information available. Several other examples are cited without name or location by Skinner (2003).

Table 1. Examples of CO_2 blow outs in the oil and energy extraction industries.

Location	**CO_2 release rate (original units)**	**CO_2 release rate (kg/sec)**	**Date**	**Reference**
Sheep Mt., CO	At least 200x10^6 scf/ day (2.5 x10^6 m^3/d)	120	March 17-April 3, 1982	Lynch *et al.* (1983, 1985) Holloway (2007)
Torre Alfina geothermal field, Italy	300 tons/hour	76	1973	Lewicki *et al.* (2007)
Travale geothermal field, Italy	450 t fluid/hr	113	Jan. 7, 1972	Geothermics Lewicki, *et al.* (2007)
Leroy Gas Storage Facility, WY	3e6 m3/year	0.2	1976-1981	Lewicki *et al.* (2007)
Edmund Trust #1-33 well, Kingfisher, OK	45 million cubic feet of gas/month	0.9	Dec. 2005-Jan. 2006	Lewicki *et al.* (2007)
Crystal Geyser, UT	2.6 to 5.8 kg/sec	2.6 to 5.8	Continuing	Gouveia and Friedmann (2006)

Well failures in a CO_2 field have some hazards common to any oil field blow out. A major exception is that CO_2 is not flammable or caustic. However, there is the suffocation hazard presented by large concentrations of CO_2 (IPCC 2005). Experience in the oil field (Skinner 2003) indicates that the CO_2 is not particularly hazardous in most instances because it vents high into the air where it mixes, ameliorating dangerous conditions at ground level.

In order to determine whether the release rates in Table 1 are representative of the worst case, we conducted a theoretical analysis of the possible release rate from cased wells open to deep reservoirs containing supercritical CO_2. The largest release would result from the complete removal of the wellhead leaving an open casing which would be a direct pathway to the CO_2 at depth. Such an accident could occur, for instance, if a bulldozer accidentally sheared off a well head. In such a case the amount of CO_2 released is a function of the pressure at depth, the size of the pipe, and to a lesser extent the friction and heat transfer in the pipe (the CO_2 naturally cools off as it expands, which reduces the pressure and driving force – heat from the walls of the pipe reduces that effect). The velocity of the gas leaving the top of the pipe is limited by the speed of sound. This allows us to calculate the maximum CO_2 that can be released.

Table 2. Calculated maximum CO_2 well failure mass flow rates.

	Release From 7 Inch ID Casing without Injection Tube		Release From 7 Inch ID Casing with 4 Inch OD Injection Tube	
Reservoir Depth (m)	Flow Rate (kg/s)	Flow rate (tonne/day)	Flow Rate (kg/s)	FlowRate (tonne/day)
1406	217	18,749	87	7,517
1488	224	19,354		
1535	225	19,440	91	7,862
1555	226	19,526		

The oil industry uses a variety of casing diameters. We calculated the possible release using two typical oil field configurations: a 7 inch ID casing with and without a concentric 4 inch OD injection tube. A range of depths (and therefore reservoir pressures) corresponding a site in the central plains of the United States was used. The resulting flows are somewhat higher than the estimated flows at the Sheep Mountain failure (the largest in Table 1) which is in accord with our conservative estimates of a completely open pipe. Any restriction (e.g., the injection tube) tends to reduce the velocity of the gas, and the overall flow rate.

In this scenario, the CO_2 was confined to the casing along the entire depth of the well bore. There was no structural failure of the casing and no fissures were created as a result of the failure. The flow was assumed to be one dimensional and steady with wall friction losses and heat transfer. The supercritical CO_2 pressure and temperature at the bottom of the casing were estimated for a given well depth based on a hydrostatic pressure assumption and a 25 K/km temperature gradient from the surface. Inherent in the steady flow assumption is that conditions of the CO_2 in the well do not change as the gas escapes through the bore. Instead of an equation of state, an interpolation of National Institute of Standards and Technology tables (NIST) provided CO_2 properties (density, viscosity, specific heat, enthalpy, and sound speed) as a function of temperature and pressure. With the tabulated data, the calculation allowed for phase changes, but was limited to a single phase at each depth due to the one-dimensional approximation.

The one-dimensional equations describing mass, momentum, and energy transport were numerically integrated from the given conditions at the bottom of the bore to the surface. Since the velocity at the well depth was unknown, the calculation began with an initial estimate and proceeded to determine the pressure, temperature, and velocity at points along the bore. If the surface CO_2 pressure at the top of the bore was less than atmospheric or the exit velocity was slower than the sound speed, the initial velocity was increased and this process was iterated until either the pressure continuity or sonic flow condition was satisfied. The mass flow rate was determined using the velocity that satisfies these bore exit conditions.

Momentum losses due to wall shear stress were incorporated with a friction factor that depended on local CO_2 properties, velocity, and casing wall roughness (0.046 mm) along the bore (White, 1986). The rate of heat transfer from the casing wall to the CO_2 was incorporated into the energy equation and was proportional to the temperature difference between the wall and CO_2. To simplify the calculation, an analogy between the heat transfer coefficient and friction factor was assumed (Shapiro 1953). Since the coupling is only one-way, the casing wall acted as a heat bath with a depth dependent temperature corresponding to the geological gradient of 25 K/km.

3. Atmospheric Hazard Assessment

In order to evaluate the maximum hazard represented by a well failure, we evaluated the historical meteorology in the vicinity of our hypothetical site over the last 11 years and chose three cases: a maximum hazard day (quiet winds), a medium hazard day (average winds) and a typical windy day which presents minimal hazard. The maximum hazard occurs in still conditions because the carbon dioxide is not diluted as it blows downwind, but accumulates in the vicinity of the wellhead. We then selected actual days from last year representing these conditions and used the National Atmospheric Advisory Release Capability (NARAC) facilities at LLNL to evaluate the consequences of the maximal release.

The National Atmospheric Release Advisory Center (NARAC) provides tools and services that map the spread of hazardous material accidentally or intentionally released into the atmosphere. Located at the Lawrence Livermore National Laboratory (LLNL), NARAC is a national support and resource center for planning, preparedness, real-time emergency response, and threat assessments involving nuclear, radiological, chemical, biological or natural emissions. NARAC predictions provide information on affected areas and populations, potential casualties, health effects, and protective action guides to assist decision makers and responders (for more information, see http://narac.llnl.gov). On April 15, 2004, the Homeland Security Council designated NARAC as the interim provider for the new DHS-led Interagency Modeling and Atmospheric Assessment Center (IMAAC), whose role under the National Response Plan is to serve as the single source of federal atmospheric dispersion predictions during Incidents of National Significance.

In NARAC's suite of three-dimensional models, the ADAPT model (Sugiyama and Chan, 1998) assimilates data from observations (e.g., from surface stations, rawinsondes, profilers) and/or weather forecast models, as well as land-surface data, for use in the NARAC dispersion model, LODI. ADAPT constructs meteorological fields (mean winds, pressure, precipitation, temperature, turbulence quantities, etc.) based on a variety of interpolation methods and atmospheric parameterizations (Chan and Sugiyama, 1997; Sugiyama and Chan, 1998). ADAPT produces non-divergent wind fields using an adjustment procedure based on the variational principle and a finite-element discretization. A finite-element representation is used for spatial discretization because of its effectiveness in treating complex terrain and its flexibility in dealing with variable resolution grids. The solution is obtained via a choice of conjugate gradient solvers, using a stabilization matrix to improve computational efficiency. The turbulent diffusivities, K_x, K_y, and K_z, are calculated as a function of height and horizontal location using scaling parameters and similarity-theory relationships described by Nasstrom *et al.* (2000). LODI is a Lagrangian particle model, but for the purposes of calculating the concentration, an Eulerian grid is used. In the cases that we simulated, the grid spacing near the source was 10 m x 10 m or 100 m^2. Until the plume width approximately exceeds the length of 2 grid cells, LODI does not properly resolve the peak concentration, and therefore may underestimate the concentration near the source. A more detailed discussion of the NARAC modeling system and its validation is available in Nasstrom *et al.* (2006).

High concentrations of material injected into the atmosphere are most likely to occur with low wind speeds and a thermally stable atmosphere (i.e., a temperature inversion). Material disperses in the atmosphere due to the mean wind (transport) and turbulent mixing (diffusion). Obviously, transport will be small with slow wind speeds. Turbulence is primarily generated by wind shear and buoyancy forces. Wind shear is the changing of the wind vector (speed and direction) in the atmosphere. When the wind speeds are low, wind shear is small. The effects of buoyancy forces are suppressed in a stable atmosphere, resulting in less generation of turbulence. Therefore with low wind speeds and a stable atmosphere, dispersion is minimal and high concentrations of air-borne material are most likely to occur.

The predicted consequences from a maximal release of 225 kg/sec on a quiet day (November 25), a wind day (May 10), and an average day (March 1) are shown in Figures 1, 2, and 3. The concentrations shown are 15 minute averages representing the greatest levels of toxicity during the simulations. As expected for such large releases, there is a hazard in the immediate vicinity of the release when there is little or no wind. Regardless of the wind direction, toxic levels of CO_2 would occur only in the near vicinity of the source. All three cases were selected as representative. The wind direction may vary over the entire compass for high, average or low winds, but is better defined for the average and high wind cases. In none of the three cases do concentrations associated with hazardous TEEL levels 2 or 3 exist far from the source, always occurring within the first few hundreds of meters. The maximum extent for TEEL level 2 predicted on the quiet day is 274 meters from the well head.

The calculations for figures 1, 2 and 3 are conservative because they require that all the released carbon dioxide stay near the ground. In actual well blowouts, much of the carbon dioxide vents high in the air where it mixes with the atmosphere and presents no hazard. This was the case for the Sheep Mt. CO_2 failure event. It is important to note that releases of this size are not clandestine (Skinner 2003). The gas is leaving the well at the speed of sound and often snow condenses from the air – it is unlikely to go unnoticed. This was true of the Sheep Mt. events, equivalent events in the Otway Basin, Australia, and much smaller events such as those at Crystal Geyser (Bogen *et al.* 2006). Skinner describes some of the recent oil industry experience in controlling blowouts of this kind – no special safety measures are taken. This is in accord with our calculations, which indicate that it requires special considerations to generate hazardous conditions except right at the wellhead.

It is of interest to evaluate if weather conditions other than our hand picked minimum, average, and maximum days might theoretically result in larger hazard areas. In order to evaluate this we used a simple Gaussian model with assumed winds of 1, 3, and 7 m s^{-1}, approximating the LODI simulations with low and moderate wind speeds (Figure 4). These models are conservative because they ignore turbulence and inhomogeneity in the wind field, often over-predicting the concentration. Gaussian Plume Models are frequently used in air pollution studies and for regulatory purposes. A simple GPM (Arya, 1999) was formulated and run for the six Pasquill-Gifford (PG) classes, where class A is the most unstable and class F is most stable. With source strength of 225 kg s^{-1}, the source is assumed to have momentum such that the effective source height is 10 meters. The thin black lines represent the center-line concentrations for the PG classes as predicted by the GPM. The thick red line represents TEEL-3 (40000 ppm) and the thick orange line TEEL-2 (30000 ppm). The high wind speed case (7 m s^{-1}) is not reproduced here as toxic levels of CO_2 are never reached, even very near the source. Results from the low wind case (1 m s^{-1}) indicate that TEEL-3 levels are exceeded for all stability classes. The interesting point to note is that for the more unstable cases (A through C) the distances at which the levels are first toxic are near the source, whereas for the more stable cases that distance is farther downwind. The distances at which the levels recede to be again below toxic levels are also farther downwind for the more stable cases. For example, TEEL-3 levels are exceeded up to about 750 m downwind for PG stability class F (most stable). For the moderate wind case, Figure 2, the wind speeds are assumed to be 3 m s^{-1}. The TEEL-3 level is exceeded only very near the source for the most unstable case while TEEL-2 levels are exceeded up through PG stability class D. The more stable cases, E and F never exceed toxic levels.

According to the Gaussian Plume Model, a narrow plume with toxic levels of CO_2 may exist several hundred meters downwind from the source, due to slow growth of the cross-wind spread of the plume. As stated above, this is a conservative estimate. Inhomogeneous wind or turbulence fields are ignored in the GPM. Near the source, the LODI estimates are most likely too low and the area where toxic levels occur may be several tens of meters greater than that model estimates. However, farther from the source, LODI, using the ADAPT generated winds provides a better estimate of the dispersion.

The results of both types of analysis indicate that, as has been observed in the oil industry, releases of this size represent a significant local hazard but do not affect a large area. Operational wells or abandoned wells in the immediate vicinity of populated areas may warrant additional monitoring or controls, but there is minimal or no risk presented at significant distances from wells.

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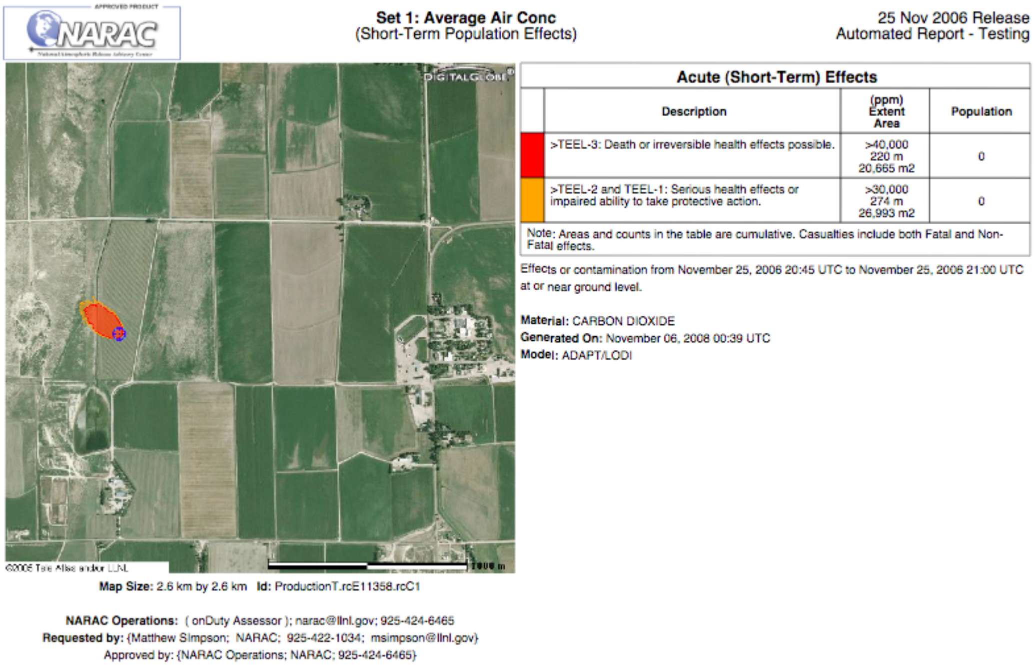
5. Disclaimer

Figure 1. Health effects of a hypothetical release of carbon dioxide on November 25, a day with low wind.



Set 1: Average Air Conc
(Short-Term Population Effects)

25 Nov 2006 Release
Automated Report - Testing

Acute (Short-Term) Effects

	Description	**(ppm) Extent Area**	**Population**
🟥	>TEEL-3: Death or irreversible health effects possible.	>40,000 220 m 20,665 m2	0
🟧	>TEEL-2 and TEEL-1: Serious health effects or impaired ability to take protective action.	>30,000 274 m 26,993 m2	0

Note: Areas and counts in the table are cumulative. Casualties include both Fatal and Non-Fatal effects.

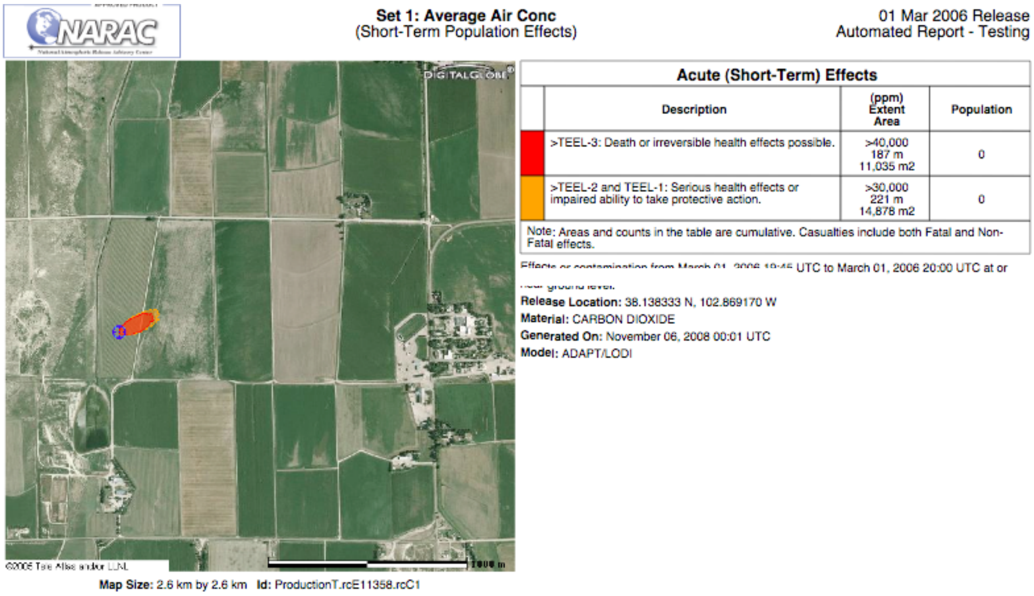
Effects or contamination from November 25, 2006 20:45 UTC to November 25, 2006 21:00 UTC at or near ground level.

Material: CARBON DIOXIDE
Generated On: November 06, 2008 00:39 UTC
Model: ADAPT/LODI

Map Size: 2.6 km by 2.6 km **Id:** ProductionT.rcE11358.rcC1

NARAC Operations: (onDuty Assessor); narac@llnl.gov; 925-424-6465
Requested by: {Matthew Simpson; NARAC; 925-422-1034; msimpson@llnl.gov}
Approved by: {NARAC Operations; NARAC; 925-424-6465}

Figure 2. Health effects of a hypothetical release of carbon dioxide on a day with average winds.



Set 1: Average Air Conc
(Short-Term Population Effects)

01 Mar 2006 Release
Automated Report - Testing

Acute (Short-Term) Effects

	Description	(ppm) Extent Area	Population
🟥	>TEEL-3: Death or irreversible health effects possible.	>40,000 187 m 11,035 m2	0
🟧	>TEEL-2 and TEEL-1: Serious health effects or impaired ability to take protective action.	>30,000 221 m 14,878 m2	0

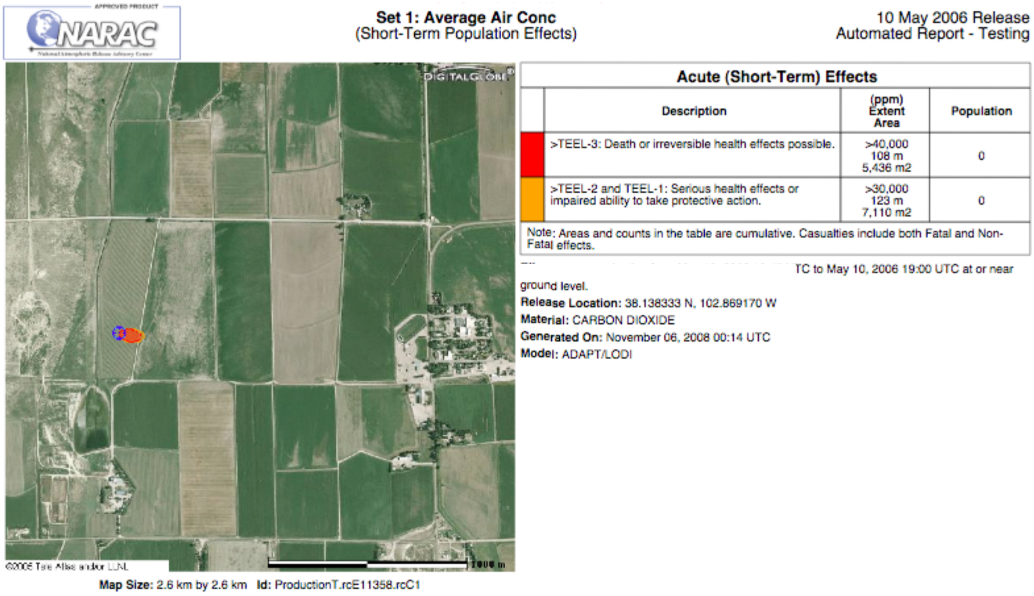
Note: Areas and counts in the table are cumulative. Casualties include both Fatal and Non-Fatal effects.

Effects or contamination from March 01, 2006 19:45 UTC to March 01, 2006 20:00 UTC at or near ground level.

Release Location: 38.138333 N, 102.869170 W
Material: CARBON DIOXIDE
Generated On: November 06, 2008 00:01 UTC
Model: ADAPT/LODI

Map Size: 2.6 km by 2.6 km **Id:** ProductionT.rcE11358.rcC1

Figure 3 Health effects of a hypothetical release of carbon dioxide near on May 10, 2007, a windy day.



Set 1: Average Air Conc
(Short-Term Population Effects)

10 May 2006 Release
Automated Report - Testing

Acute (Short-Term) Effects

	Description	(ppm) Extent Area	Population
🟥	>TEEL-3: Death or irreversible health effects possible.	>40,000 108 m 5,436 m2	0
🟧	>TEEL-2 and TEEL-1: Serious health effects or impaired ability to take protective action.	>30,000 123 m 7,110 m2	0

Note: Areas and counts in the table are cumulative. Casualties include both Fatal and Non-Fatal effects.

TC to May 10, 2006 19:00 UTC at or near ground level.

Release Location: 38.138333 N, 102.869170 W
Material: CARBON DIOXIDE
Generated On: November 06, 2008 00:14 UTC
Model: ADAPT/LODI

Map Size: 2.6 km by 2.6 km **Id:** ProductionT.rcE11358.rcC1

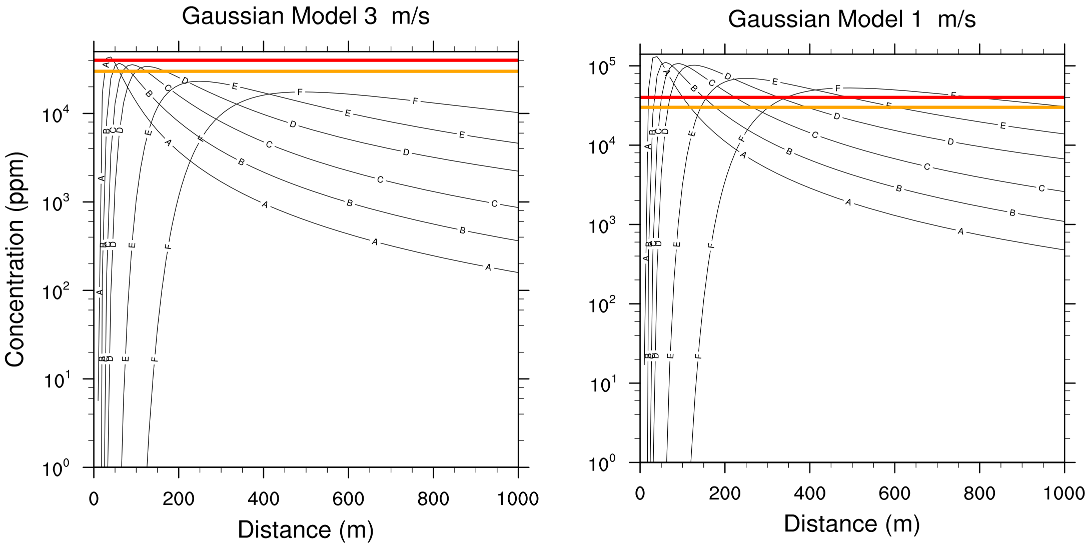


Figure 4. Centerline concentration values for the six Pasquill-Gifford stability classes, labeled A through F, with a wind speed of 3 m/s (left) and 1 m/s (right). Above the red line, TEEL-3 conditions exist, above the orange line TEEL-2 conditions exist.