Final Risk Assessment Report
for the
FutureGen Project Environmental Impact Statement

Contract No. DE-AT26-06NT42921

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(Revision 1 April 2007)

(Revision 2 October 2007)

April 2007 Summary of Major Revisions: This document has been revised in response to comments received during the Department of Energy's review. Substantive changes were made in the following areas: (1) the analyses of pipeline accidents were extended and automated via computer programs to estimate the expected number of individuals within predicted air dispersion plume areas (for seven meteorological conditions and 16 wind directions) should an accident occur at points located every 984 feet (300 meters) along the length of the proposed pipelines; (2) the number of individuals potentially affected was estimated based on the areas of each predicted plume. Previously this document presented estimates of the number of individuals within a circular region of concern (i.e., the area of a circle, whose radius equals the maximum possible downwind distance of dispersion where each threshold air concentration is reached) and labeled this group as "potentially affected" in the event of a release; and (3) the locations of the injection wells at Jewett and Tuscola were modified to be consistent with the revised plans. While the plume radii are the same as the Final EIS, there are small differences in the acreage computed between the EIS and the Risk Assessment due to unit conversion and round-off. The subsurface modeling of slow releases from the sequestration reservoir is primarily dependent on the estimated leakage rates (tonnes/year), which did not change. The EIS provides the estimated CO_2 plume acreage after 50 years, but these values are not used in the subsurface modeling of leakage from the sequestration reservoirs.

September 2007 Summary of Major Revisions: This document has been revised in response to comments received during the Department of Energy's review, from the public hearings on the Draft Environmental Impact Statement, and from other comments received on the Final Risk Assessment dated April 2007. Small changes were made to the Risk Assessment in response to suggestions made in the comments. Additional analyses were conducted and presented to evaluate the effect of a pipeline rupture or puncture during the co-sequestration test using 2% H_2S. The same pipeline-walk method was used as was done for the base case at each site. A summary of the risk results for the co-sequestration experiment is found in Section 4.5.5. Details on the modeling for the experiment are found in Appendix C, Section C.5 and C.6.

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ACRONYMS

3-D	Three dimensional
ACE	Army Corps of Engineers
ACGIH	American Conference of Governmental Industrial Hygienists
AEGLs	Acute Exposure Guideline Levels
AIHA	American Industrial Hygiene Association
ALTER	Acceptable Long-term Exposure Range
AMCL	Alternative Maximum Contaminant Level
ASTER	Acceptable Short-term Exposure Range
ATSDR	Agency for Toxic Substances and Disease Registry
AWQC	Ambient water quality criteria
AZ	Arizona
BEI	Biological Exposure Indices
bgs	Below ground surface
BTU	British Thermal Unit
C	Ceiling
°C	Degrees Celsius
CA	California
CalEPA	State of California, Environmental Protection Agency
CCC	Criterion Continuous Concentration
CCS	Carbon capture and sequestration
CH_4	Methane
CMC	The Criteria Maximum Concentration
CN	Cyanide
CNS	Central nervous system
CO	Carbon monoxide

CO_2	Carbon dioxide
COPC	Chemicals of potential concern
C-PEL	Ceiling permissible exposure levels
C-REL	Ceiling reference exposure levels
CSM	Conceptual site model
CVS	Cardiovascular system
DOE	Department of Energy
DWEL	Drinking Water Equivalent Level
EIS	Environmental Impact Statement
EIV	Environmental Information Volume
EOR	Enhanced oil recovery
ERPG	Emergency Response Planning Guidelines
ESP	Electrostatic Precipitators
ESRI	Environmental Systems Research Institute
F	Degrees Farenheit
FEP	Features, Events and Processes
FeS	Iron sulfide
FGD	Flue gas desulfurization
ft	Foot
FWS	U.S. Fish and Wildlife Service
GHG	Greenhouse gas
GIS	Geographical Information System
gpd	Gallon(s) per day
gpm	Gallon(s) per minute
HA	Health Advisory
Hg	Mercury

H_2S	Hydrogen sulfide
HSE	Health, safety, and environmental
HQ	Hazard quotient
ID	Inner diameter (of a pipeline)
IDLH	Immediately Dangerous to Life or Health
IDNR	Illinois Department of Natural Resources
IEA	International Energy Agency
IEPA	Illinois Environmental Protection Agency
IL	Illinois
in	Inch(es)
IPCC	Intergovernmental Panel on Climate Change
ISWS	Illinois State Water Survey
kg	Kilogram(s)
kg/m^2-s	Kilogram(s) per meter squared - second
kg/sec	Kilogram(s)/second
km	Kilometer(s)
lbs	Pound(s)
LBNL	Lawrence-Berkeley National Laboratory
m	Meter(s)
m^3	Cubic meter(s)
MBI	Macroinvertebrate Biotic Index
MCL	Maximum contaminant level
MCLG	Maximum contaminant level goal
mD	Millidarcy
MDEA	Methyl diethanol amine
mg/l	Milligrams per liter

mi	Mile(s)
min	Minute(s)
MMT	Million metric tonnes
MMT/yr	Million metric tonnes per year
MMV	Monitoring, mitigation, and verification
mph	Miles per hour
MRL	Minimal Risk Levels
MSL	Mean sea level
MW	Megawatt(s)
μmol/m^2-s	Micromoles per meter squared - second
NA	Not appropriate/Not applicable
NAAQS	National Ambient Air Quality Standards
NCDC	National Climatic Data Center
NIOSH	National Institute for Occupational Safety and Health
NIOSH RELs	National Institute for Occupational Safety and Health, Reference Exposure
NM	New Mexico
NNSA	National Nuclear Security Administration
NO_x	Nitrogen oxides
NR	Not recommended due to insufficient data
NRCS	Natural Resources Conservation Service
NWI	National Wetlands Inventory
OEHHA	State of California, Office of Environmental Health Hazard Assessment
OSHA	Occupational Safety and Health Administration
OSHA PELs	Occupational Safety and Health Administration, Permissible Exposure Limit
pCi/L	pico Curies per Liter
PELs	Permissible Exposure Limits

ppm	Parts per million
ppmv	Parts per million by volume
psi	Pounds per square inch
RCT	Railroad Commission of Texas
R&D	Research and Development
REL	Reference Exposure Level
RfC	Reference Concentration
RfD	Reference Dose
ROI	Region of influence
RRA	Resource Rich Area
SCAPA	Subcommittee on Consequence Assessment and Protective Actions
sec	Second(s)
S_{HMax}	Maximum horizontal stress
S_{hmin}	Intermediate horizontal stress
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
SO_x	Sulfur oxides
ST	Short term
STEL	Short-term exposure limit
SRF	Screening and ranking framework
TCEQ	Texas Commission on Environmental Quality
TDCJ	Texas Department of Criminal Justice
TDS	Total dissolved solids
T/E	Threatened or Endangered
TEEL	Temporary Emergency Exposure Limits
TPWD	Texas Parks and Wildlife Department

TRV	Toxicity Reference Value(s)
TLV	Threshold Limit Value
TWA	Time-weighted daily average
TWA-PEL	Time-weighted average, permissible exposure limit
TWA-REL	Time-weighted average, reference exposure limit
TWDB	Texas Water Development Board
TX	Texas
U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency
U.S. FWA	United States Fish and Wildlife Service
USGS	United States Geological Society
UT	Utah
VHM	Volcanic, hydrothermal, and metamorphic
WIPP	Waste Isolation Pilot Project
WWTP	Wastewater Treatment Plant(s)
yr	Year(s)

1.0 INTRODUCTION

FutureGen represents a technological advancement that integrates advanced coal gasification technology, the production of hydrogen from coal, electric power generation, and carbon dioxide (CO_2) capture and geologic storage. Carbon capture and sequestration (CCS) technology is an innovative method for reducing greenhouse gas (GHG) emissions, but the new technology comes with added design and operational complexities and potential health, safety and environmental (HSE) risks. This document reports the results of the human health and environmental risk assessment conducted to support the preparation of an Environmental Impact Statement (EIS) for the FutureGen Project. The Risk Assessment addresses the potential releases of captured gases at the power plant, during transportation via pipeline to the geologic storage site, and during subsurface storage.

The approach to risk analysis for CO_2 sequestration in geologic formations is still evolving. However, a substantial amount of information exists on the assessment and management of risks associated with the geologic storage of CO_2 from natural-gas storage, deep injection of hazardous wastes, and the injection of either gaseous or supercritical CO_2 in hydrocarbon reservoirs for enhanced oil recovery (EOR). There are also numerous projects underway at active CO_2 injection sites to determine the long-term fate of CO_2 injected into deep geological formations. The FutureGen Risk Assessment relies heavily on the technical approach and findings from these previous and ongoing projects. However, there are a number of special considerations for the FutureGen Project that translate into guiding principles that influenced the risk assessment approach:

- **The Risk Assessment Approach is Generic and Applied to Multiple Sites and Plant Configurations**. Four candidate sites selected by the FutureGen Alliance are evaluated using a common set of performance characteristics and hazard scenarios. The results of the analysis provide a basis for comparing the candidate sites.

- **Readily Available Analytical Tools were Utilized in the Risk Assessment**. The development of the risk assessment work plan and the risk assessment analyses were completed over a three-month period. The methodology was developed and tested using generic data, and the final analyses were conducted as the site-specific data were made available. Emphasis was placed on the use of quantitative methods when practicable, but some aspects of the risk assessment were conducted using qualitative methods. Conservative assumptions regarding the probability of releases and the magnitude of releases were adopted to minimize the possibility that risks are underestimated.

- The focus of the analysis is on risk aspects that are specific to carbon sequestration and likely to be encountered in the FutureGen Project. Emissions that occur in commonly designed coal-fueled power plants are not addressed.

The results of the human health and ecological risk assessment are presented in five parts:

- **Conceptual Site Models** (CSMs) are presented in Section 2. A central task in the risk assessment is the development of the CSMs for the proposed site locations. Potential pathways of gas release during capture, transport and storage are identified. The risk assessment approach is described for the potential exposure pathways associated with pre- and post-injection of sequestered gases. Site-specific elements of the four candidate FutureGen Project sites are described in detail. Information from the Environmental Information Volumes (EIVs) provided by the FutureGen Alliance (2006) is summarized. These data provide the basis for the parameterization and analysis of likely human health and ecological exposure routes.

- **Toxicity Data, and Benchmark Concentration Effect Levels** were determined for all of the potentially complete exposure pathways and are presented in Section 3. The toxicity assessment provides information on the potential for the chemicals of potential concern (COPCs) to cause adverse human-health and environmental effects. These data provide the basis for the comparison of estimated exposures and the assessment of potential risks.

- **The Pre-Injection Risk Assessment** in Section 4 provides the evaluation of the plant and facilities for separating, compressing and transporting CO_2 to the injection site. The risk assessment approach for the pre-injection components is based on qualitative and quantitative estimates of gas releases under different failure scenarios. Failures of the engineered system include catastrophic events, leakage, and fugitive releases of captured gases. The transport of the released gas in the air is estimated through modeling. The predicted concentrations in air of CO_2 and hydrogen sulfide (H_2S) are used to estimate the potential for exposure and any resulting impacts on human and ecological receptors.

- **The Post-Injection Risk Assessment** in Section 5 presents the analysis of potential impacts from the release of CO_2, and H_2S, after the injection of CO_2 into subsurface reservoirs. A key aspect of this analysis is the compilation of an analog database that includes the site characteristics and results from studies performed at other CO_2 storage locations and from sites with natural CO_2 accumulations and releases. The analog database is used to evaluate the feasibility of geologic containment over the long-term and for characterizing the nature of potential risks associated with surface leakage through cap-rock seal failures, faults, fractures or wells. CO_2 leakage from the FutureGen reservoirs is estimated using a combination of relevant industry experience, natural analog studies, modeling, and expert judgment. Qualitative risk screening of the four candidate sites is based upon a systems analysis of the site features and scenarios portrayed in the CSM. Risks are qualitatively weighted and prioritized using procedures identified in a HSE risk screening and ranking framework recently developed by Lawrence Berkeley National Laboratory (LBNL) for geologic CO_2 storage site selection (Oldenburg, 2005). The atmospheric transport of potential gas releases is estimated through modeling. The predicted concentrations in air are used to estimate the potential for exposure and any resulting impacts on human and ecological receptors.

- **The Risk Screening and Performance Assessment** is presented in Section 6. Site comparisons are presented using the results of both qualitative and quantitative analyses. Uncertainties are presented and discussed, and recommendations are made to address issues of concern and data gaps.

The FutureGen Risk Assessment closely adheres to the work plans that were prepared for the analysis of risks associated with pre- and post injection of captured gases (Tetra Tech, 2006 a, b). These work plans describe the overall approach and steps in the evaluation of potential human health and environmental risks. The work plans were reviewed by a panel of CCS and risk assessment experts.

2.0 CONCEPTUAL SITE MODELS

2.1 Generic Conceptual Model Applicable to All Sites

Figure 2-1 conceptually shows the FutureGen Power Plant, sequestered gas storage approaches, release pathways, and potential receptors that are being considered in this risk assessment. Potential gas releases can occur at the plant, during transportation via pipeline, or from subsurface storage. Above ground, the engineered systems that produce and transport CO_2 can be sources of released gas, either during normal operations or when systems fail due to external disruptions. Once injected below ground, sequestered gas can escape through failure of the injection borehole seal, through known or previously unrecognized abandoned wells, and through fractures or faults that may transect the reservoir cap rock. The sequestered gas may also have environmental impacts even without leakage to the atmosphere, either by transport into aquatic ecosystems or underground sources of drinking water, or by enhancement of radon migration into indoor air. Receptors of concern from atmospheric emissions include workers in the plant, nearby human populations, and areas of natural resource value. Besides these groups of individuals, receptors of concern from surface leaks include aquatic ecosystems, consumers of affected drinking water supplies, and residents affected by enhanced radon intrusion into indoor air.

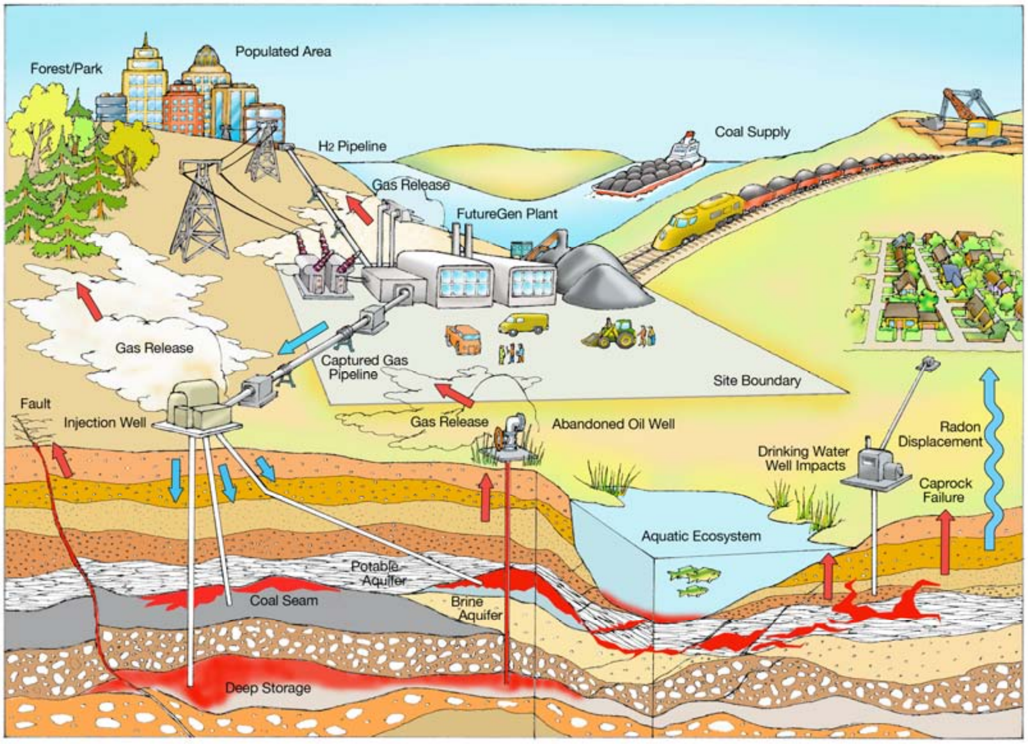


Figure 2-1. Conceptualization of FutureGen Project to Capture and Store CO_2 in Geological Formations

(Potential pathways of stored gas release and receptors of concern are shown.)

The steps involved in conducting the above-ground (pre-injection) portion of the risk assessment are shown schematically in Figure 2-2. The primary release mechanisms can either produce direct exposures to humans or ecological receptors by inhaling atmospherically released gases, or be responsible for secondary releases, such as discharge to surface water or soil. These secondary releases can then possibly produce exposures to aquatic receptors in nearby surface waters or plants via uptake from soil. The potential for possible adverse ecological or human health effects are also examined, should there be direct releases of gases to surface waters, such as pipeline discharge into a stream or lake. The effects of the exposures for both human and ecological receptors are then evaluated and risk estimates provided. The time frame of the risk assessment includes the entire pilot and operational periods of CO_2 capture at the plant to plant closure (estimated to be 50 years).

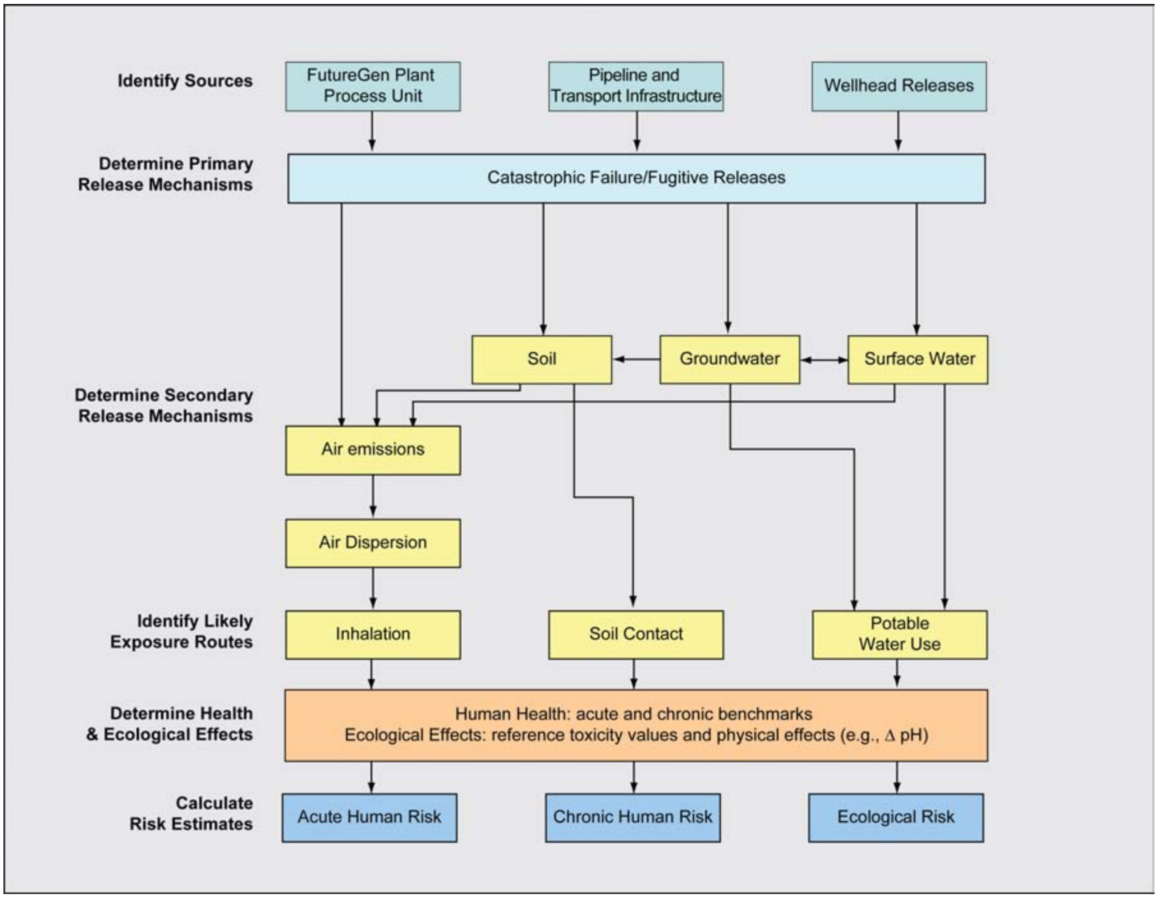


Figure 2-2. Generic Risk Assessment Approach Prior to Injection of Sequestered Gases

Figure 2-3 identifies the steps in the post-injection component of the risk assessment process. The primary release mechanisms can be either short-term (catastrophic) or long-term. Within this report, the term “catastrophic” is defined as a large volume release that most likely is event triggered (well failure, earthquake, etc.) and is of a limited time duration. It is important to note that the term catastrophic refers to the release magnitude, and does not necessarily refer to the consequences of the release, which may not be significant to either human health or the environment. These primary release mechanisms can either produce direct exposures, be responsible for secondary releases such as discharge to surface waters, or lead to pressure impacts and land deformation. These secondary releases can then lead to exposures. The effects of the exposures for both human and ecological receptors are evaluated and risk estimates are provided.

The time frame of the risk assessment includes the entire pilot and operational periods of CO_2 capture at the plant to plant closure (estimated to be 50 years), and a much longer time period for the post-injection part of the risk assessment [i.e., on the order of 5,000 years, was previously selected as the time horizon at the Weyburn EOR project] in order to address potential issues associated with slow leakage of the injected CO_2.

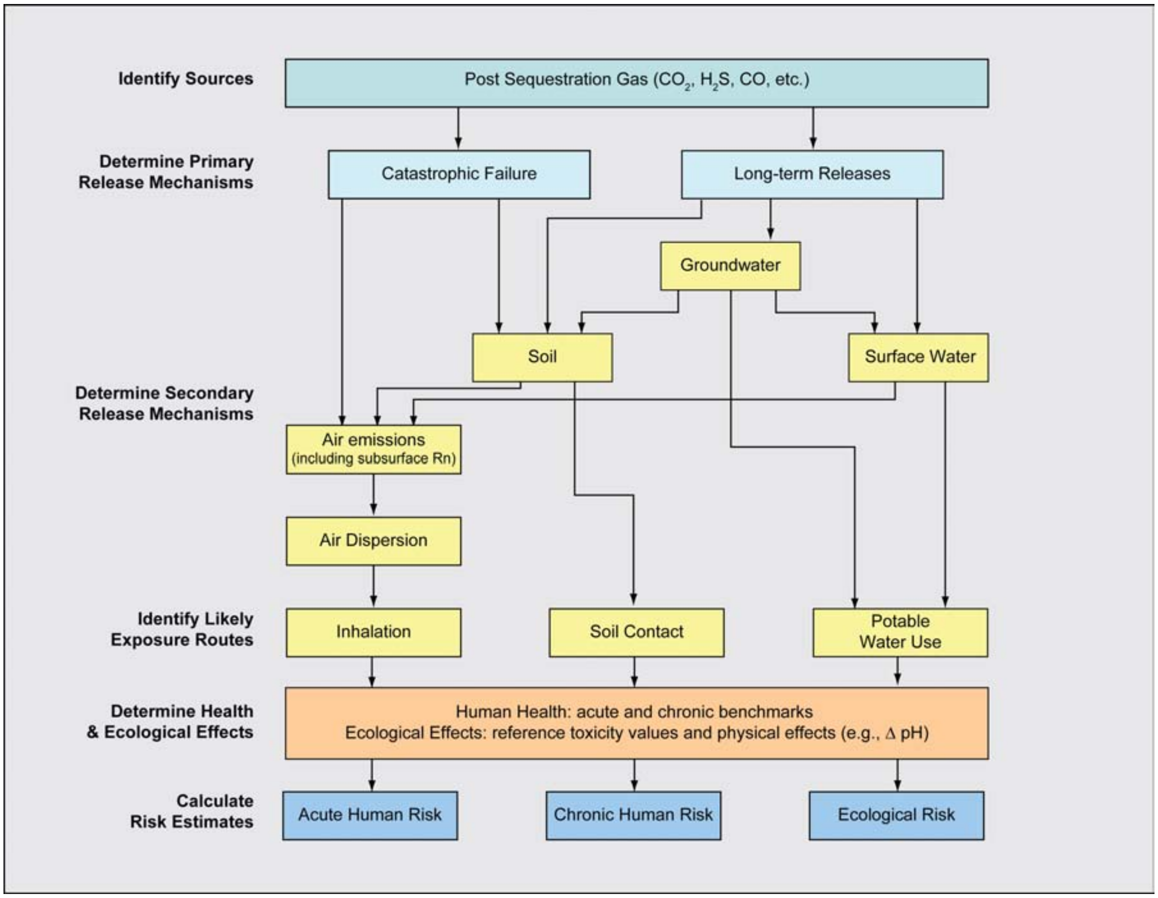


Figure 2-3. Steps in Risk Assessment for Post Injection of Sequestered Gases

2.2 Power Plant and Capture of Carbon Dioxide and Other Gases

The FutureGen Power Plant is planned to operate as a nominal 275 megawatt (MW) facility that produces hydrogen from coal which is used as fuel for the generation of electricity while removing more than 90 percent of the coal's carbon and 99 percent of its sulfur. The carbon would be sequestered deep below ground at 1.1 -2.8 million tons/year (1-2.5 million metric tons per year [MMT/year]) of CO_2 and the sulfur converted to a salable byproduct. The total operational period could be at least 30 years. The plant is expected to be online by the year 2012.

A conceptual schematic of the plant highlighting the aboveground facilities for separating, compressing and transporting CO_2 to the injection site has been developed from existing information (shown in Figure 2-4). At the core of the FutureGen Project will be an advanced coal gasifier. Although the specific type of gasifier has not yet been selected, there are several choices that are commercially proven and available and others that are in the late stages of development may offer additional operating efficiencies. FutureGen may offer opportunities to assist in that development. Rather than burning coal directly, gasification breaks down the coal and converts its constituents into a raw synthesis gas by means of partial oxidation and other chemical reactions. The raw gas from the gasifier is composed predominantly of carbon monoxide (CO), hydrogen (H_2), CO_2, methane (CH_4), H_2S, water vapor and smaller amounts of other compounds.

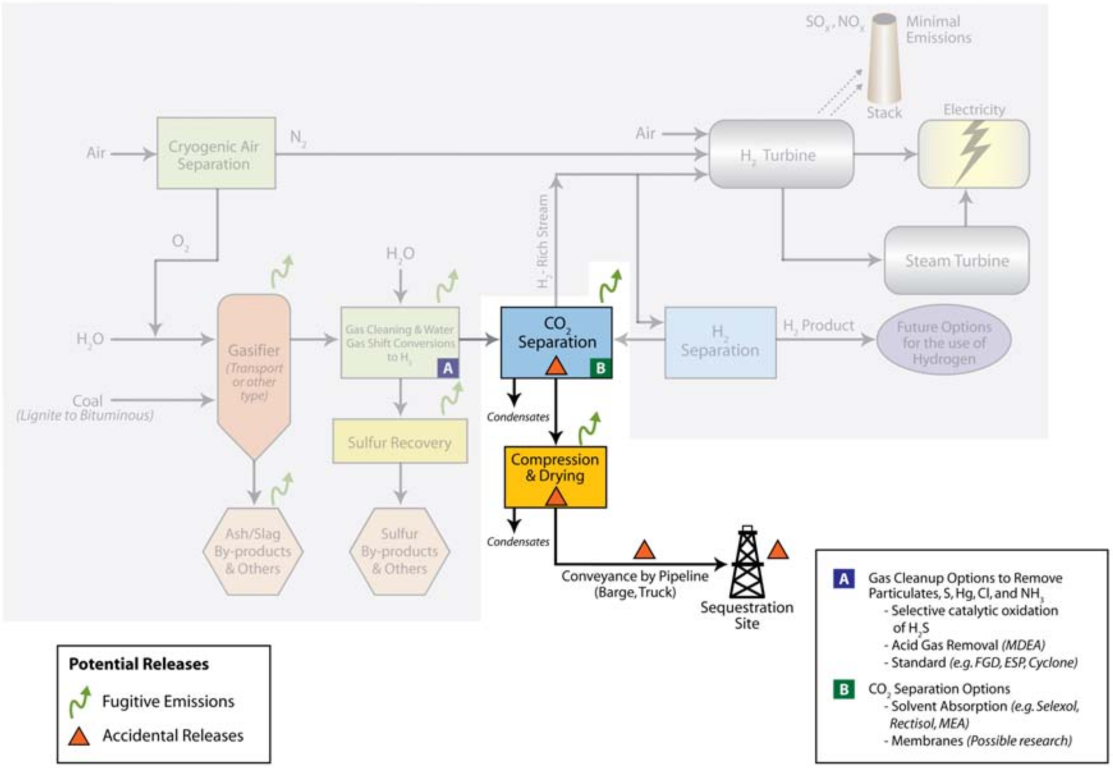


Figure 2-4. Schematic of FutureGen Project Coal-fueled IGCC Plant with Products and Potential Releases

The plant will be designed to convert this raw gas to a clean hydrogen-rich turbine fuel by: 1) removing particulates, 2) increasing hydrogen content by catalytically reacting CO with water vapor to form additional H_2 and CO_2, 3) removing the H_2S and CO_2 and 4) removing the ammonia, chlorides and mercury. Although all the specific processes have not yet been selected for these steps, multiple well proven options exist for each step. Numerous applications exist of coal particulate removal with wet and dry scrubbers and filters. Physical or chemical solvent processes (such as Selexol, Rectisol and MDEA (methyl diethanol amine)) have been successfully used for decades to remove H_2S and CO_2. However, they come with an efficiency penalty due to the energy required for solvent regeneration and a cost penalty for separate absorber systems for H_2S and CO_2. New technologies (such as novel sorbents, membranes and selective catalytic oxidation of H_2S) when fully proven, could increase efficiencies up to 5 percent. Long term, steady state, co-sequestration of CO_2 and H_2S could negate the need for separate absorbers and a sulfur recovery unit (such as a Claus unit) reducing CO_2 capture cost by as much as 25 percent. Short term co-sequestration would not reduce capture cost but would improve availability by allowing the rest of the plant to stay online during a Claus unit outage.

The hydrogen-rich gas will fuel a gas turbine to produce electricity. The energy in the hot turbine exhaust gas will be recovered to generate steam in a heat recovery boiler. This steam will power a steam turbine generator to produce additional electricity. The separated CO_2 gas stream, which will contain small amounts of H_2S and the other gases mentioned above, will be processed for sequestration.

The final step is compression and drying of the CO_2 gas prior to transport by pipeline to wellhead(s) at an injection site. This process may involve several compression units and a multi-stage drying process using glycol and potassium oxide.

Transport of the captured gas stream to a location for injection underground is assumed to occur via pipeline, as shown conceptually in Figure 2-4. The distance of transport from the plant site to the injection point varies from 1 to 60 miles (1.6 to 97 kilometers) for the four candidate sites. The number of compressor facilities may vary among the sites. Based on past experience with CO_2 pipelines, pipelines away from the plant would probably be buried to a typical depth of 3.3 feet (1 meter) (IPCC, 2005), with releases primarily occurring to the atmosphere.

At the injection site, CO_2 will be delivered to the injection wells at a pressure and temperature to achieve target injection rates (e.g., 1,500 pounds per square inch absolute [psia] through 2,200 psia; 95°F [35°C]). At these pressure and temperature combinations, the gas is supercritical (i.e., CO_2 is in a high density state where gas and liquid are indistinguishable) to facilitate injection into the target reservoir.

2.3 Generic Sequestration Site Description

In general, CO_2 sequestration in sub-surface formations will most likely occur in one of the following five scenarios: depleting/depleted oil reservoirs, depleting/depleted gas reservoirs, organically-rich shales, saline formations, and unmineable coal beds. Once injected into the storage formation, the fraction of CO_2 and low levels of other gases retained depends on a combination of physical and geochemical trapping mechanisms that have different time scales and levels of security (IPCC, 2005). Physical trapping to block upward leakage of CO_2 can be provided by an impermeable caprock or capillary forces that retain CO_2 in the pore spaces of the formation. In some cases, however, one or more sides of the formation may remain open and allow for lateral migration of CO_2 beneath the caprock. Additional mechanisms (such as geochemical trapping) are especially important in these cases for the long-term entrapment of the injected CO_2. Geochemical trapping occurs as: (1) CO_2 dissolves in water and (over time scales of hundreds to thousands of years) the CO_2-laden water becomes dense and sinks rather than rises (IPCC, 2005); and (2) dissolved CO_2 then reacts with certain rocks (e.g., feldspars) so that a fraction of the injected CO_2 will be converted to solid carbonate minerals over millions of years (IPCC, 2005).

Under the right conditions, CO_2 may remain trapped for long time periods due to a combination of these physical and geochemical trapping mechanisms. However, these gases may also be accidentally released through one of the following key mechanisms (IPCC, 2005):

- Upward leakage through the caprock due to either catastrophic failure and quick release or gradual failure and slow release;
- Release through existing faults or induced faults due to the effects of increased pressure;
- Lateral or vertical leakage into non-target aquifers due to an unknown structural or stratigraphic connection with the target zone, or due to a lack of geochemical trapping and inadequate retention time in the target zone; and
- Upward leakage through inadequately constructed wells, abandoned wells, or undocumented wells.

For example, CO_2 injection into a partially depleted hydrocarbon reservoir can increase pressure until there is leakage through the caprock due to exceeding either the capillary entry pressure, the hydraulic fracture limit, and/or the dynamic fault-slip limit (Zoback, 2004). This can occur on a large scale if the site is operated too close to these pressure limits or on a small scale if injection wells are inadvertently overpressured due to a decline in reservoir injectivity. Yet, experience with engineered systems (IPCC, 2005) suggest a small fraction of operational storage sites may release CO_2 to the atmosphere or shallow subsurface, even though storage sites will presumably be designed to confine all injected CO_2 for geological time scales.

2.4 Sequestered Chemicals and Processes of Potential Concern

Because FutureGen is designed to be a near-zero emissions power plant, not only is CO_2 captured and sequestered, but so are other chemicals. These estimates of capture requirements were given in an early U.S. Department of Energy (DOE) description of FutureGen (DOE, 2004):

- Sequester at least 90 percent of CO_2 by weight
- Sequester > 99 percent of sulfur by weight
- Emit <0.05-pounds (22.7-grams) NO_x per million BTUs
- Emit less than 0.005 pounds (2.3 grams) of particulates per million BTUs
- Sequester >90 percent mercury by weight

More recently, these estimates of sequestered chemical concentrations in the pipeline have been generated:

- CO_2: 95 percent mol per mol (FutureGen Alliance, 2006)
- H_2S: 0.01 percent-2.0 percent mol per mol (personal communication, Battelle)
- CH_4: 0.34 percent-0.7 percent mol per mol (IPCC, 2005)
- CO: 0.1 percent mol per mol (IPCC, 2005)

In addition to these chemicals, other secondary processes may be of concern in terms of generating risks to human health or the environment:

- Radon: Natural radon release might be enhanced if an inadvertent release of CO_2 diffuses at high enough rates through the soil and shallow subsurface. The risk pathway would be into a dwelling space, and by subsequent inhalation of radon and its progeny.
- Decreased pH in small stagnant ponds or lakes should a CO_2 plume settle over the water, or if CO_2 seeps into the pond at high rates from the subsurface.
- Mobilization of metals in ground water should a CO_2 plume mix with groundwater, lower the pH, and mobilize metals that would otherwise be insoluble.

2.5 Site Specific Elements for the Four Candidate FutureGen Project Sites

Figure 2-5 shows the general locations within the United States of the four candidate sites. Two of the sites are located within 30 miles (48 kilometers) of each other in the State of Illinois, while the other two sites, Odessa and Jewett, are located in west and east Texas, respectively. In this section, a description of the four sites is provided. The information has been excerpted and summarized from EIVs provided by the FutureGen Alliance (2006). Evaluations of the site conditions by the risk assessment team are provided in Sections 4 and 5 of this report.

Table 2-1 summarizes information provided in the EIVs for each of the four sites and provides a cross-reference of features for the four sites. The first part of the table focuses on surface features and the second focuses on subsurface features. The sites vary in size from the smallest (Tuscola) at 345 acres (140 hectares) to the largest (Odessa) at 600 acres (243 hectares). All the sites are generally flat.

Both of the Texas sites propose to use more than one injection well, while both Illinois sites propose to use exactly one injection well each. A backup well will likely be proposed for reliability should the primary well be taken out of service for maintenance or non-performance. The distance from the power plant to the injection sites is as far as 60 miles (97 kilometers) for the Odessa site to several thousand feet (injection is close to the power plant) for Mattoon. Depths of injection of the fluids is between 3,000 feet (914 meters) (Odessa) and nearly 10,000 feet (3048 meters) (Jewett). All target reservoirs have cap rock seals hundreds of feet in thickness.

Figure 2-5. Locations of Four Candidate FutureGen Sites

Table 2-1. Summary of Surface and Subsurface Features of Four Candidate Sites

Site Characteristic	**Site Name**			
	Jewett, TX	**Odessa, TX**	**Mattoon, IL**	**Tuscola, IL**
Location of Proposed FutureGen Project	Between College Station and Waco, TX	15 miles (24 kilometers) west of Odessa, TX	One mile (1.6 kilometers) northwest of Mattoon, IL	Two miles (3.2 kilometers) west of Tuscola, IL
Area of site (acres [hectares])	400 (162)	600 (243)	444 (180)	345 (140)
Site elevation (feet [meters] above msl)	426-492 (130-150)	2920-2969 (890-950)	679-718 (207-219)	680-686 (207-209)
Sensitive receptors	Health care facilities, prisons, schools, pre-schools, colleges	Schools, retirement center, prisons, day care	Schools, hospitals, nursing homes	Schools, nursing homes
Wetlands in areas investigated	Numerous small wetlands exist on both power plant and sequestration sites	Wetlands exist within the pipeline corridor and above sequestration site; no areas on power plant site	18 small wetland areas delineated	19 small wetland areas delineated (6-8 acres total)
Soil types	Variety of loams and sands	Variety of loams with underlying discontinuous caliche	Organic topsoil, brownish gray silty clay subsoil,glacial outwash and till	Variety of loams
Climate	***Average*** seasonal daily temperatures: 52-***80***℉ (11.1-***26.6***℃)	***Average*** seasonal daily temperatures: ***47.2-79.9***℉ (***8***.4-***26.6***℃)	***Average seasonal daily*** temperature: ***36.5-76***℉ (***2.5-24.4***℃)	***Average seasonal daily*** temperature: ***36.5-77***℉ (***2.5-25***℃)
	Average seasonal precipitation: ***8.4-12.6*** inches (***21.3-32.0*** centimeters)	***Average*** seasonal precipitation: ***1.6-4.3*** inches (***4.1-10.9*** centimeters)	***Average seasonal precipitation: 7.0-11.5 inches (17.8-29.2 centimeters)***	***Average seasonal precipitation: 10.0-17.8 inches (17.8-29.2 centimeters)***
	Annual precipitation: 42.6 in (108.2 cm)	***Annual precipitation: 14.9 in (37.8 cm)***	***Annual precipitation: 39.2 inches (99.6 centimeters)***	***Annual precipitation: 40.7 inches (103.4 centimeters)***
Shallow groundwater resources	One major aquifer beneath site: Carrizo-Wilcox, extends from near surface to 500 feet (152.4 meters); suitable for potable water supply	Several aquifers lie beneath or near the site, including Pecos Valley Aquifer and the Dockum aquifer	Groundwater exists in shallow sand and gravel deposits 20 (6.1 meters) to 125 feet (38.1 meters) below surface; very sporatic; several private wells	Sand and gravel aquifers 70 feet (21.3 meters) to 100 feet (30.5 meters) below surface; sufficient for 10 gallons per minute (gpm) (37.9 liters/minute) discharge

Table 2-1 (continued). Summary of Surface and Subsurface Features of Four Candidate Sites

Site Characteristic	Site Name			
	Jewett, TX	**Odessa, TX**	**Mattoon, IL**	**Tuscola, IL**
Shallow groundwater total dissolved solids (TDS)	300 mg/l typical	Fresh to slightly saline waters (approximately 1900 mg/l)	700 mg/l (few data available)	100-400 mg/l
Surface water resources	Small intermittent creeks; Lake ***Limestone*** (3 miles (4.8 kilometers) west of site); Trinity River	Ephemeral streams and pools exist following heavy rainfall events; Pecos River	Small streams near watershed boundaries; several small lakes and small rivers	Small streams near watershed boundaries; several rivers
Aquatic ecology	No protected aquatic species known	Ephemeral streams and pools are present, and may provide aquatic habitat; no federal or state-listed species occur	Several Natural Areas; threatened Eastern Sand Darter	No listed or endangered species
Terrestrial ecology	Numerous federally protected species frequent the site environs, such as the bald eagle	Bald eagle, whooping crane, and peregrine falcon migrate through the area, and their presence is only transient	Landscape dominated by agriculture; Endangered Indiana Bat resides in caves in Coles County	Landscape dominated by agriculture; Endangered Indiana Bat resides in caves in Douglas County
Floodplain	Outside of 500-year floodplain	Outside of 500-year floodplain	Outside of 500-year floodplain	Outside of 500-year floodplain
Present primary use of site lands	Operating lignite mine; woodlands and savannah	Rangeland	Agriculture	Industry and agriculture
Fuel sources	Six alternative sources including coal, lignite, and coke	Six alternative sources including coal, lignite, and coke	Illinois and Powder River Basin Coal	Illinois and Powder River Basin Coal
Source of cooling water	Groundwater from Carrizo-Wilcox aquifer (3,000 gpm) [11,356 liters/minute])	Groundwater from Ogallala, Pecos Valley, Edwards-Trinity Plateau, Dockum, or Capitan Reef Aquifers	Waste water from Mattoon and Charleston wastewater treatment plants (WWTPs)	Existing water works plant at the Lyondell-Equistar chemical facility
Distance to source of cooling water	2000 feet (610 meters)	Alternate sources: between 28 miles (45 kilometers) to 54 miles (87 kilometers)	6.2 miles (10 kilometers) (to Mattoon WWTP); 8.1miles (13 kilometers) (to Charleston WWTP)	1.5 miles (2.4 kilometers)
Target injection reservoir	Woodbine and Travis Peak sandstones	Brine-bearing Guadalupian sandstones	Mt. Simon deep saline formation	Mt. Simon deep saline formation
Number of injection wells	Woodbine Site: 2 Travis Peak Site: 1	10 (probable) to 18 (possible)	1, plus 1 backup	1, plus 1 backup
Distance to injection site(s)	Woodbine Site: 52-59 miles (84-95 kilometers) ; Travis Peak Site: 52 miles (84 kilometers)	58 miles (93 kilometers) to site, have multiple wells	Injection is directly below FutureGen Project Site	11 miles (18 kilometers)

Table 2-1 (continued). Summary of Surface and Subsurface Features of Four Candidate Sites

Site Characteristic	Site Name			
	Jewett, TX	Odessa, TX	Mattoon, IL	Tuscola, IL
Depth below surface to top of primary injection target	4,700 feet (1433 meters) and 9,600 feet (2926 meters) (two targets)	2,950 feet (899 meters) and 3,600 feet (1097 meters) (two targets)	7,000 feet (2134 meters)	6,100 feet (1859 meters)
Thickness of primary injection target (feet [meters])	500 (152) and 1,500 (457)	300 (91) and 2,000 (610)	Over 1,000 (305)	Over 1,000 (305)
Seal thickness (feet [meters])	380-420 (116-128) (Eagle Ford shale)	700 (213) and 400 (122)	300-500 (91-152)	300-500 (91-152)
Approximate plume radius, 5 years; 2.8 million tons/year (2.5 MMT/year)	0.8 miles (1.3 kilometers)	0.3 miles (0.5 kilometers) (each well; 10 wells)	0.5 miles (0.8 kilometers)	0.5 miles (0.8 kilometers)
Approximate plume radius 30 years; 2.8 million tons of CO_2 per year (2.5MMT-CO_2/year)	1.6 miles (2.6 kilometers)	0.6 miles (1.0 kilometers) (each well; 10 wells)	.0.8 miles (1.3 kilometers)	0.8 miles (1.3 kilometers)
Approximate plume radius 50 years; 1 million ton per year (1MMT/year)	1.7 miles (2.7 kilometers) per well*	1.0 mile (1.6 kilometers) per well	1.2 miles (1.9 kilometers) per well	1.1 miles (1.8 kilometers) per well
Area of plume per well after 50 years, (acres [hectares])	5,800 (2,347)	2,024 (819)	2,800 (1,133)	2,430 (983)
Length of post injection modeling period and footprint	Not available	970 years; footprint not available	Not available	Not available
Number of deep oil and gas wells within 30 year plume footprint	57 (within 55 million tons (50 MMT) plume footprint)	0	0	0
Number of undocumented deep wells	13	2	2	3
Number of production wells	4	0	0	0
New monitoring wells proposed?	Yes	Yes	Yes	Yes
Major faults that extend into injection zone	Faults SE & NW of site, plus small faults in Woodbine formation	No known faults	No known faults	No known faults

*Plume radii shown for Jewett are for a Woodbine formation well. For this well, the maximum plume radius was for the 2.8 million tons of CO_2 per year (2.5 MMT-CO_2/year) injection rate for 20 years followed by 30 years of spreading. The plume radius for the 1.1 million tons (1 MMT) for 50 years of injection was 1.5 miles. Results are from modeling in EIVs.

2.5.1 JEWETT, TX

2.5.1.1 Surface Features

Figure 2-6 shows the location of the proposed Jewett FutureGen Power Plant site, sequestration site, CO_2 pipeline, human receptors, major surface water bodies, and topographic variations.

General Description and Climatology

The proposed power plant site is located just north of the town of Jewett. The site sits at the juncture of Leon, Limestone, and Freestone counties, with centroid coordinates at 31° 25' North by 96° 13' West. The proposed power plant site is a contiguous 400-acre (81-hectare) parcel of land. The proposed power plant site is a relatively flat area with a maximum ground slope of 0.5 percent. Its elevation ranges between approximately 426 and 492 feet (130 and 150 meters) above mean sea level (MSL), averaging approximately 450 feet (137 meters) above MSL (USGS, 1982).

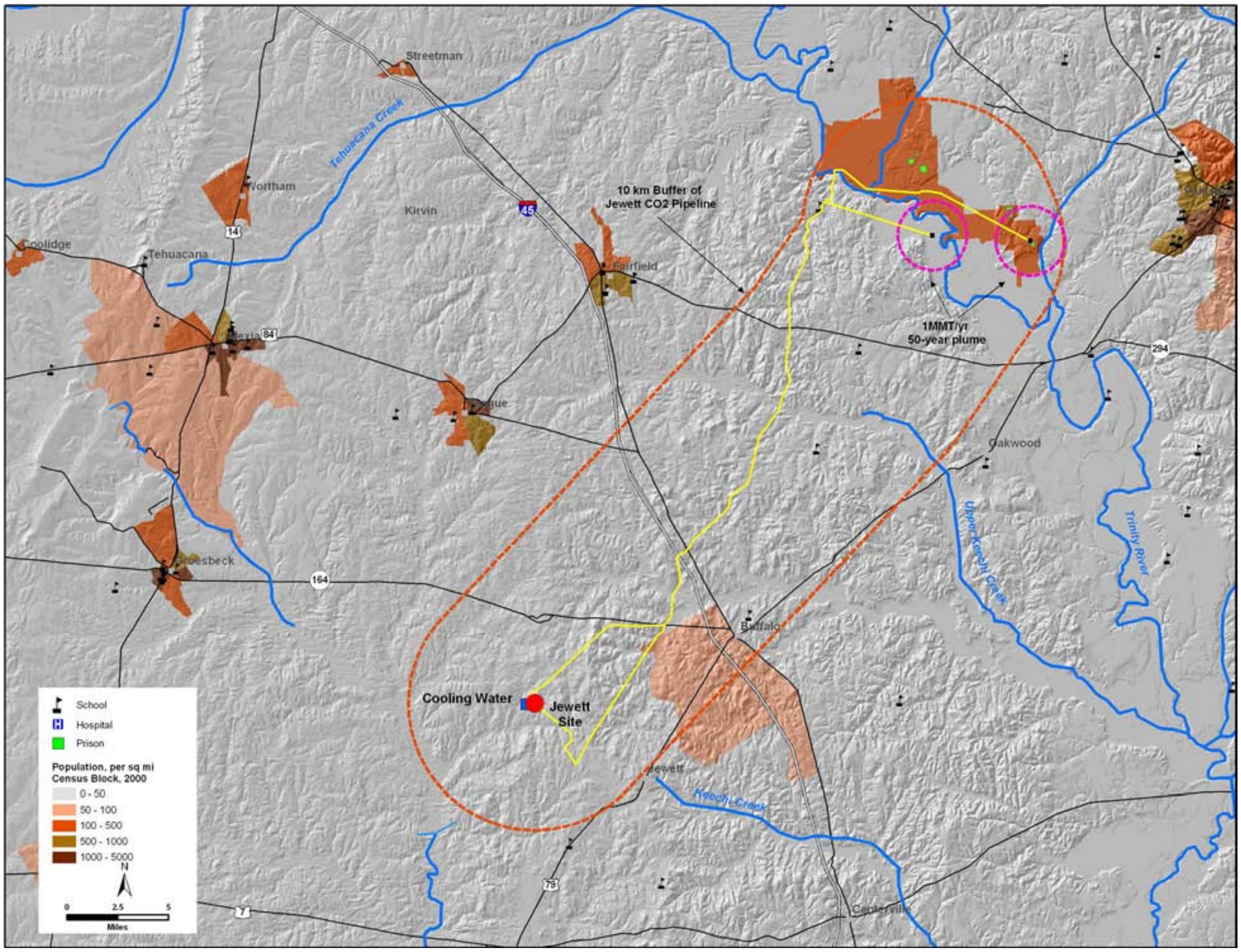


Figure 2-6. Proposed Jewett FutureGen Site, Injection Site, CO_2 Pipeline, and Surroundings

Sufficient groundwater resources are available onsite from the Simsboro formation of the Carrizo-Wilcox aquifer to meet all facility water demands. Thus, it is unlikely that there would be a cooling water pipeline corridor longer than 2,000 feet (610 meters) to the north of the plant site boundary. However, several other aquifers also exist nearby the proposed site that could supply additional water, if necessary.

The proposed power plant site would be interconnected to the proposed sequestration reservoir by a CO_2 pipeline 25 to 45 miles (40 to 72 kilometers) in length. A network of potential corridor options has been proposed that provides flexibility and extension of the pipeline, as needed. Additionally, several smaller diameter pipelines would be used to link the wells within the proposed sequestration reservoir to the CO_2 spur, if necessary.

The surface extent of the land area above the proposed sequestration reservoir is located within Freestone and Anderson Counties, TX, with centroid coordinates at 31° 41' North by 95° 55' West. The area covers a total land area of approximately 134,000 acres (54,200 hectares) and is minimally developed both for surface or subsurface uses. The area is characterized by open woodlands and savannah ecological habitats and is transected by the Trinity River. One small community is located on the land area above the proposed sequestration reservoir (Figure 2-6). Soils range from a variety of loam, sands, and clays.

No meteorological data are directly available for the proposed power plant site or nearby communities; however, average weather information for Jewett, TX is available. The information includes average temperature, precipitation, humidity, wind speed, snow fall, sunshine, and cloudy days by month. Table 2-2 provides observations derived from that data.

Table 2-2. Weather Information for Jewett, TX

Weather Parameter	Spring	Summer	Fall	Winter
Average Daily Temperature, °F (°C)	71 (21.6)	80 (26.6)	59 (15.0)	52 (11.1)
Average Monthly Precipitation, inches (centimeters)	4.0 (10.1)	2.9 (7.3)	4.0 (10.1)	3.3 (8.3)
Average Wind Speed, miles per hour (kilometers per hour)	11.6 (18.6)	9.8 (15.7)	10.2 (116.4)	11.7 (18.8)

Average wind direction is not available for each season, but the wind rose suggests that wind direction in the area is predominantly south to south-southeast throughout the year.

Water Resources and Wetlands

The State of Texas designates the aquifers in the state as major and minor aquifers. There is one major aquifer, the Carrizo-Wilcox, beneath and within 1 mile (1.6 kilometers) of the proposed power plant site. Although the Carrizo-Wilcox is designated as a single aquifer, it is more properly an aquifer system consisting of many hydraulically distinct and diverse units. Four aquifer units are formally recognized in the Carrizo-Wilcox aquifer in this portion of Texas. They are: Hooper, Simsboro, and Calvert Bluff formations of the Eocene Wilcox Group, and Carrizo, the lowermost formation of the Eocene Claiborne Group. The proposed power plant site is located on the down dip edge of the Calvert Bluff outcrop. The Carrizo crops out within 1 mile (1.6 kilometers) of the site but exists as caps on hill tops and is unlikely to yield suitable quantities of groundwater.

Water quality data are available for three Simsboro and one Calvert Bluff well within 1 mile (1.6 kilometers) of the proposed power plant site and indicate that the groundwater is fresh, with all samples having TDS concentrations of less than 350 milligrams per liter (mg/l). Based on a reporting of Texas Commission on Environmental Quality (TCEQ) information, there is no documented evidence of contaminated groundwater within 1 mile (1.6 kilometers) of the proposed power plant site.

The proposed power plant site lies within the eastern portion of the Brazos River Basin near Lake Limestone. No major surface water bodies are located on the proposed power plant site or within its region of influence (ROI). The closest significant water body is Lake Limestone, approximately 3 miles (5 kilometers) west of the site. Four small, intermittent creeks, Lynn Creek, Red Hollow, Lambs Creek, and Cottonwood Springs Branch Creek, are within the ROI. Several small surface impoundments are also located within the ROI of the proposed power plant site but do not appear to be hydrologically connected to the creeks, reservoir, or other surface water bodies.

No existing contamination has been identified in water bodies within the ROI of the proposed power plant site or in any nearby water bodies. Lake Limestone is the only assessed water body nearby and it has been determined to fully support or to have no concerns related to all of its designated uses, including contact recreation, high aquatic life use, and water supply.

The proposed CO_2 pipeline corridor segments extend from the Brazos River Basin into the Trinity River Basin. Surface water features are characterized by numerous small creeks and small ponds and reservoirs. Creeks are typically intermittent within the southern proposed corridor segments and become more perennial as the northern segments approach and cross the Trinity River. Approximately 37 water bodies are known to exist along the CO_2 corridor. The Trinity River above Lake Livingston (TCEQ water quality Segment ID 0804) is the only major water body in the area potentially affected by any of the proposed corridor segments. This portion of the Trinity River fully supports all of its assessed designated uses, including high aquatic life, recreation, fish consumption, and general use.

An investigation of the proposed power plant site revealed that several areas potentially subject to Section 404 of the Clean Water Act jurisdiction exist on the site. Maps produced by the U.S. Department of the Interior's Fish and Wildlife Service (FWS), referred to as National Wetlands Inventory (NWI) maps, indicate one named creek channel (Red Hollow) coursing along the eastern boundary of the site, several small herbaceous and forested wetlands associated with the creek, and several stock ponds in the northern and southern portions of the site. A review of NWI maps for the proposed CO_2 pipeline corridor revealed that several areas potentially subject to Section 404 jurisdiction exist within the corridor. An investigation of NWI maps of the land area above the proposed sequestration reservoir revealed that several areas potentially subject to Section 404 jurisdiction exist in this area. Several small herbaceous and forested wetlands associated with the creeks and tributaries, and several on-channel stock ponds exist within the land area.

Aquatic and Terrestrial Ecology

The proposed power plant site and its ROI lie where Freestone, Leon and Limestone Counties converge. Hydrologically, the region is divided between two major watersheds. Streams in the eastern portion of the region are part of the Trinity River Basin, while those in the western portion belong to the Brazos River Basin. This has ecological implications as some species are geographically restricted and may occur in a single watershed.

A number of aquatic surveys have been conducted within the three-county area comprising the proposed power plant site and its ROI. Sampling events occurred in the spring and fall of 1992 and 1996, and in August of 1999. The only known report or survey regarding aquatic habitat/species that has been conducted within the past five years on the proposed power plant site is a field reconnaissance performed in April 2006 to confirm the absence of habitat for threatened or endangered (T/E) species. Aerial photographs and U.S. Geological Society (USGS) topographic maps indicate that the only surface waters on the proposed power plant site are three small, intermittent creeks and a few man-made holding ponds. No major creeks, rivers, or large impoundments are located in the immediate area of the power plant.

Aquatic invertebrates expected to be found in the streams and ponds of the proposed power plant site and its ROI include a variety of insects, crustaceans, mollusks, and segmented worms. Aquatic crustaceans common to streams in the Trinity and Brazos River drainage basins include crayfish, freshwater prawns, and planktonic forms such as water fleas (Cladocera). A total of 70 fish species representing 18 families are estimated to have geographic ranges that include the ROI. From the field studies, 49 species have been collected from the site area. Based upon a review of the previous studies, the fish population appears reasonably diverse and seasonally abundant. Overall, the habitats on the site are relatively small but diverse.

The potential occurrence of any aquatic federally or state-protected species on the proposed power plant site and its ROI is negligible. Based on review of T/E species databases generated by the Texas Parks and Wildlife Department (TPWD) and FWS, there are no protected aquatic species in Freestone, Leon, or Limestone counties.

The northern portion of the proposed sequestration area has perennial streams and ponds of a larger size than the southern portion, and contains the Trinity River and its floodplain system throughout its central portion. Many ephemeral streams occur in this region and fast-growing, opportunistic macrophytes should be expected when flow is present. Permanent creeks and riverine habitat are also found in the area. Because there are no federally listed species known to occur in the land area above the proposed sequestration reservoir, no critical habitat has been designated by the FWS.

The dominant vegetation types on the proposed power plant site include Post Oak Woods/Forest and Post Oak Woods/Forest and Grassland Mosaic.

Much of the ROI includes portions of the Westmoreland Coal Company's Jewett Surface Lignite Mine (Jewett Mine). Within the mine boundary, recurring vegetation surveys have been conducted in support of the mine's permit application to the Railroad Commission of Texas (RCT). The proposed power plant site and sequestration sites and their ROIs lie within the Texan Biotic Province described by Blair (1950). The Texan Biotic Province corresponds to open woodland and savannah vegetational types as the landscape transitions from the wetter forests in the east toward the slightly drier grassland provinces in the west.

Sensitive Receptors

There are 64 sensitive receptors located within the general vicinity of the proposed power plant, pipeline, and injection points. School properties include 12 elementary schools, four middle and junior high schools, six high schools, four alternative or special education schools, two private schools, two preschools, two universities, and three administration offices. Ten child care centers are also located in the area. Hospital and nursing home facilities include three hospitals, six health care facilities, two hospices, and two assisted living centers.

The Leon Independent School District campus at 12168 Highway 79 West is located just less than 10 miles (16 kilometers) from the proposed power plant site boundaries. The elementary, middle, and high schools are all located on this campus. No other sensitive receptors (e.g., nursing homes, hospitals, prisons) are reported within 10 miles (16 kilometers) of the proposed power plant site. Near the pipeline, several schools are located not far from the proposed injection sites.

The ROI for sensitive receptors also includes the land area above the proposed sequestration reservoir plus a 10-mile (16-kilometer) radius. Eleven schools (7 elementary schools, one junior high, 2 high schools, and one special education school), 4 preschools, one university, one school administration office, and four health care facilities are located within the ROI for the land area above the proposed sequestration reservoir (DOE, 2007). Five prison units with approximately 4,115 prisoners are also located in the ROI.

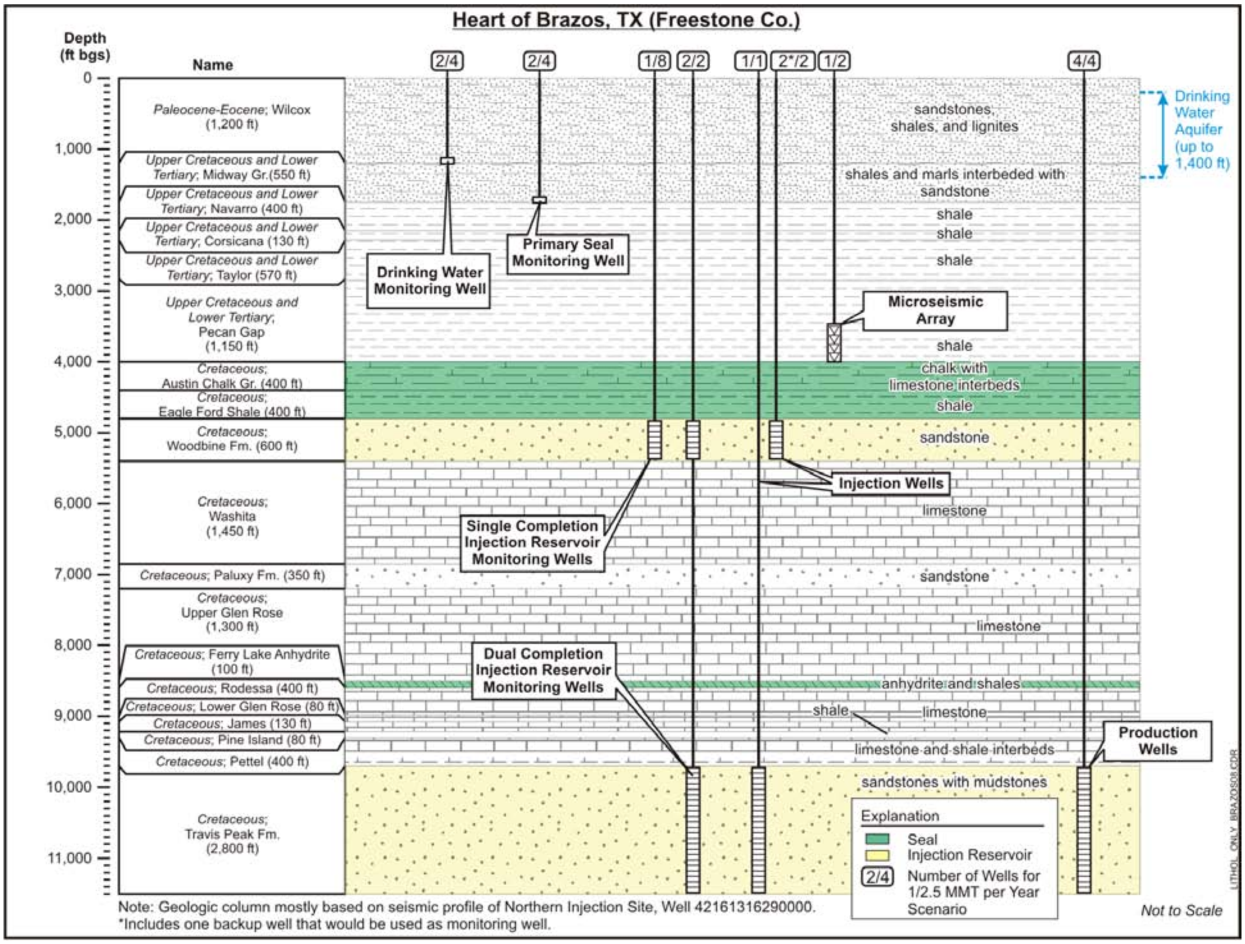
2.5.1.2 Subsurface Features

Saline Formation and Seals

Proposed gas injection is divided between the 500 feet (152 meters) Woodbine sandstone and the heterogeneous 1800 feet (549 meters) Travis Peak sandstones. Figure 2-7 shows the site lithology, injection zones, seals, and the proposed well types. There are also two thinner (200-450 feet [60-137 meters]) optional injection carbonate targets: the Rodessa and Pettit grainstones. All lie beneath an ultimate top seal, the Eagle Ford Shale, which has a thickness of 400 feet (122 meters). The primary injection zone, the Woodbine sandstone, is directly beneath the Eagle Ford. The Travis Peak, the Rodessa, and the Pettit are individually sealed by shales and or fine grained limestone. In the case of the Travis Peak, both low permeability shale-rich intervals at the top of the Formation, and low permeability carbonates at the base of the Pettit are expected to provide effective barriers to vertical migration of fluids. Over 2,296 feet (700 meters) of low permeability carbonates and shales above the Eagle Ford provide additional protection for the shallow drinking water aquifers.

The top of the Woodbine is 4,800 feet (1,463 m) below ground surface. It is a hydrocarbon reservoir in other parts of east Texas. The top of the Lower Cretaceous Travis Peak is approximately 9,000 feet (2,743 meters) below ground surface. The Travis Peak Formation consists of as much as 2,000 feet (609 meters) of stacked fluvial sandstones separated by low-permeability floodplain mudstones at depths down to 11,000 feet (3,353 meters). The Travis Peak at the injection site contains about 350 - 400 feet (107 - 122 meters) of sandstone, with porosity values typically ranging from 5 to 12 percent.

Salinities in both Jewett injection targets are approximately 100,000 mg/l. Temperatures in the Woodbine at 5,575 feet (1,699 meters) are expected to be 162°F (72°C), and 242°F (117°C) at the base of the Travis Peak sandstone. Bottom hole hydrostatic pressure is estimated to be 4,763 pounds per square inch (psi), at a depth of approximately 11,000 feet (3,353 meters).



Note: Geologic column mostly based on seismic profile of Northern Injection Site, Well 42161316290000.
*Includes one backup well that would be used as monitoring well.

Figure 2-7. Schematic Illustration of Well Types for Jewett, TX

There are numerous shallow petroleum exploration wells within five miles of the injection wells, and the projected plumes for the FutureGen injection wells could encounter approximately 16 plugged and unplugged wells. None of these wells are actively producing hydrocarbons.

Regional Controls on Capacity and Injectivity

The injection rate of the single Travis Peak (Figure 2-8) well is limited by the maximum pressure that can be safely maintained without causing reservoir fracturing. The most dominant regional controls on capacity and injectivity in both the Travis Peak and Woodbine are reservoir heterogeneity due to depositional environment. The two proposed Woodbine wells are well separated to avoid plume interference. Neither injection rate nor capacity is expected to be restricted in the Woodbine. The current well layout plan has two Woodbine injection wells. The second well helps to reduce plume size and provides backup capacity during well maintenance and monitoring activities.

Tectonic Setting

The Jewett site is located in a seismically stable area within the East Texas Salt Basin, one of the basins that formed marginal to the Gulf of Mexico during the early Mesozoic. Structural dip on the Travis Peak is less than one degree. The principal tectonic features of the region include down-to-the coast normal faults southeast and northwest of the injection sites, and various salt tectonic features. In addition there are small normal faults that cut the Woodbine within the sequestration site, but that do not off-set the Eagle Ford caprock seal. Surface faults within 10 miles (16 kilometers) of the proposed injection wells are local features clustered around salt domes located south and east of the injection wells. Three dimensional seismic data reveal the presence of a normal fault at the southern margin of the northern injection zone.

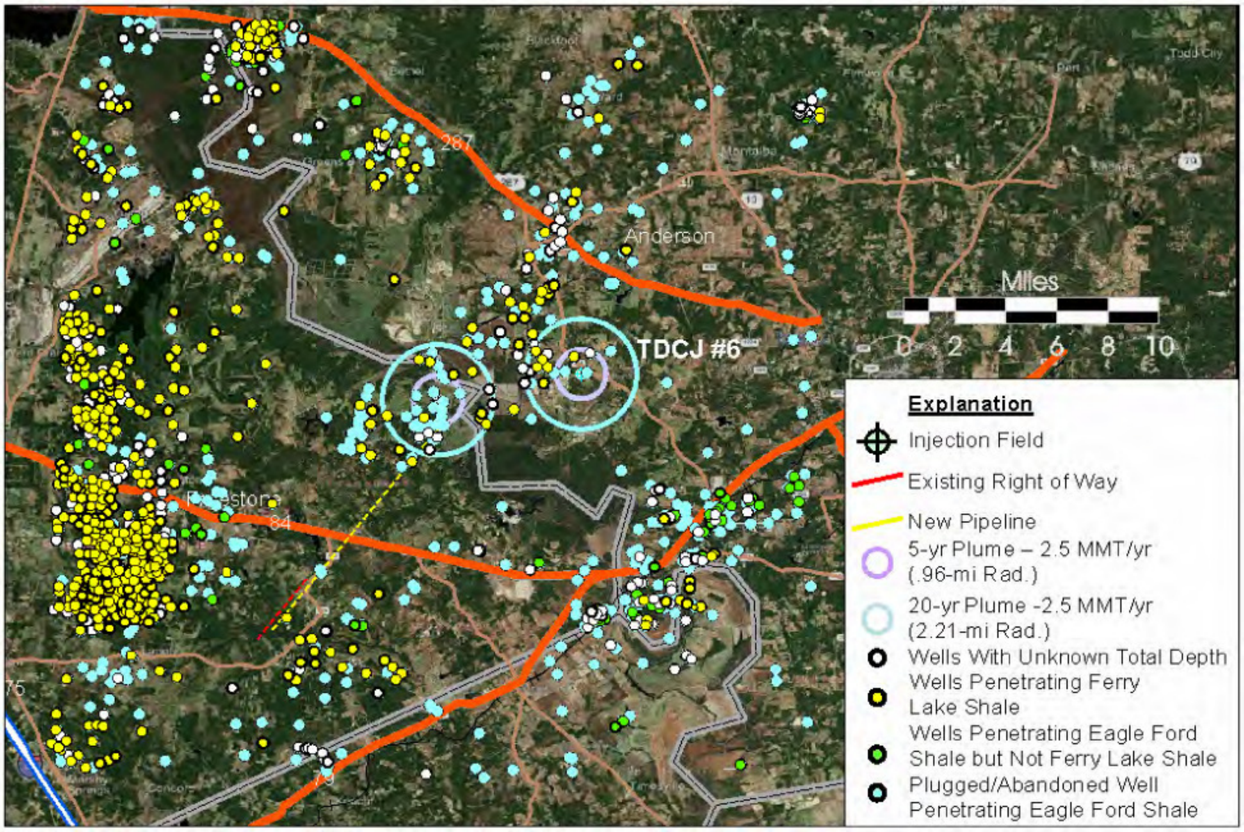


Figure 2-8. Map of Existing Wells that Penetrate the Eagle Ford Shale at the Jewett Injection Site, and Plume Footprints (FutureGen Alliance, 2006)

The closest earthquake to the proposed sequestration site occurred on April 9, 1932, between Mexia in Limestone County and Wortham in Freestone County, had a Richter magnitude of 4.0, and was likely induced by oil production.

Geologic Features of the Seal and Reservoir that Impact Leakage Scenarios

The major sources of leakage of geologically sequestered CO_2 according to Oldenburg and Unger (2003) are: 1) slow or sudden failure of the caprock seal, and 2) leakage along well bores.

Mineralogy and permeability of the seal are main controls on slow permeation that can result in seal failure. Mineralogy and permeabilities of the seals at the Jewett site indicate strong containment. The two most important seals at the Jewett site are the primary seal, the Eagle Ford, and a second seal, the Ferry Lake, located immediately above the Rodessa carbonate and approximately 2,600 feet (792 meters) below the Woodbine. The ultimate or primary caprock seal for the deep saline formations is the Eagle Ford Shale. The Eagle Ford is the main seal for some of the largest oilfields in East Texas and is 380- 420 feet (116-128 meters) thick in the CO_2 injection area. An excess of 2,296 feet (700 meters) of low permeability carbonates and shales above the Eagle Ford provide additional protection for the shallow drinking water aquifers.

The Eagle Ford seal appears to have fairly high capillary entry pressure, as does the Ferry Lake seal and marine shale lithologies within the top of the Travis Peak and the Woodbine. The Ferry Lake, which will act as a minor seal for Travis Peak and Pettet (if injected) consists of interbedded anhydrite, and low permeability carbonates and cemented quartz sandstone. Evidence of the efficacy of these multiple seals is suggested by the fact that oil and gas reservoirs within the Travis Peak, the Rodessa, and the Pettet within Freestone and surrounding Counties are contained within the individual units rather than occurring at the base of the Ferry Lake Anhydrite. Similarly the upper Woodbine sand is overlain by regionally continuous shale over 20 feet (6 meters) thick that appears to form an effective seal elsewhere for large oil reservoirs in the Gulf Coast.

The mineralogy and heterogeneity of the sandstones of the Travis Peak are particularly amenable to slowing upward migration of CO_2. The fluvial sandstones are separated by extensive shale layers with good lateral continuity and with measured permeabilities of 0.0001 millidarcy (mD) or less. In addition, reactive clays and minerals are expected to enhance mineral trapping of the CO_2. The plagioclase feldspar, carbonates, some of the clays, and the bitumen will be reactive in the presence of CO_2.

Sudden, brittle failure of caprock seals, either through reservoir over-pressuring and induced seismicity or through natural seismicity is considered as a potential leakage hazard of geologically sequestered CO_2. Because of low permeability, injection pressure in the Travis Peak has a higher intrinsic likelihood of exceeding safe pressures. Two factors are designed to prevent reservoir over-pressuring and brittle failure of reservoir or seal in the Travis Peak well. The first is the best practices operation of maintaining injection pressures below 80 percent of the fracture opening pressure. The second reservoir management tool is the proposed well layout of four water production wells, drilled around the Travis Peak injection well in the form of a “five spot”, designed to control the long term buildup of reservoir pressures. A third factor is the 5,000 feet (1.5 kilometers) stratigraphic distance from the top of the Travis Peak to the base of the Eagle Ford.

For the “five spot” approach to be successful several factors need to be considered in the design. They include:

- The location of the production wells and injection wells in the same formations needs to be addressed (see Figure 2-7). Since these four wells provide conduits for sequestered gas entrainment, and transport out of the storage reservoir the probability of this increasing as injection continues over 50 years should be considered.

- The volume and disposal of the produced water needs to be addressed. If the water quality of the produced water is poor, some treatment of the water prior to disposal may be required.

Brittle failure of the Eagle Ford seal due to over-pressuring of the Woodbine is considered highly unlikely, both because of the much higher permeabilities and injectivity of the Woodbine, and also because of the best practices field management of keeping pressures well below fracture opening pressures.

In contrast to opening new fractures, reopening existing faults and fracture zones requires much less energy and can be a leakage hazard. In addition to initiating fractures through over- pressuring the reservoir, changes in pore pressure associated with the injection of CO_2 can decrease friction on pre-existing faults, and may cause them to become transmissive in part, or to slip. Induced seismic activity due to oil production activities may have caused a 4.0 magnitude earthquake between Mexia in Limestone County and Wortham in Freestone County, in 1932. Decrease of friction on fault surfaces due to CO_2 injection is a concern at the Jewett site where the regional stress regime is extensional. While fault initiation, or fault reactivation through natural seismicity is a scenario for leakage, the Jewett site is in an area of low natural seismic hazard.

Leakage of CO_2 along wellbores is considered a hazard for sequestered CO_2. Fifty-seven wells are located within the maximum plume footprint of the two Woodbine wells, as currently outlined, and at least eight of them penetrate the primary seal. Mitigation techniques at this site may require appropriate plugging to seal the formation, reworking of deep wells, and using state-of-the-art drilling and completion techniques on new injection wells.

2.5.2 ODESSA, TX

2.5.2.1 Surface Features

Figure 2-9 shows the location of the proposed Odessa FutureGen Power Plant site, sequestration site, CO_2 pipeline, human receptors, major surface water features and topographic variations.

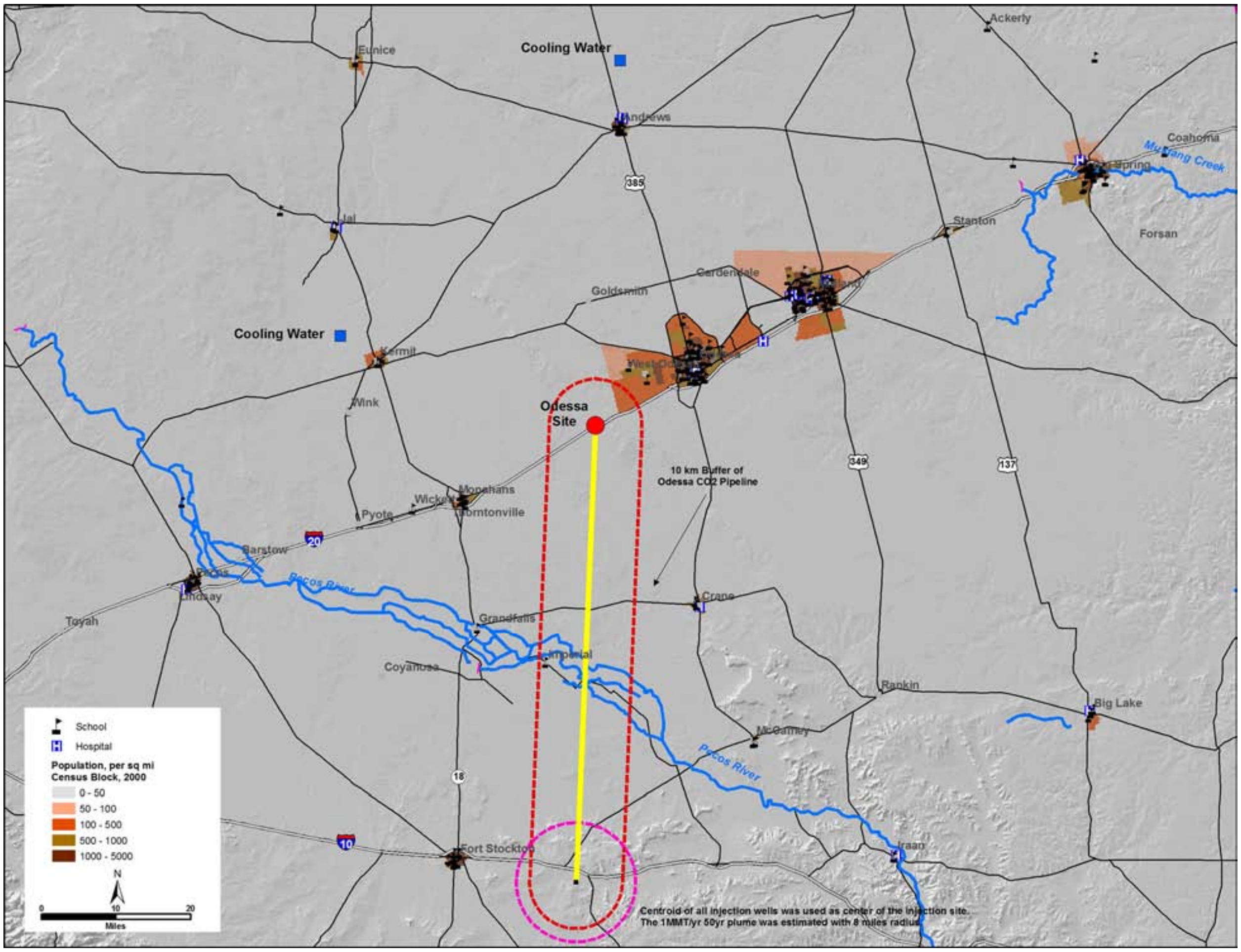


Figure 2-9. Proposed Odessa FutureGen Site, Sequestration Site, CO_2 Pipeline, and Surroundings

General Description and Climatology

The plant site is located 24 kilometers (15 miles) west of Odessa in Ector County, TX, with centroid coordinates at 31° 44’ North by 102° 35’ West. The plant site is a nearly rectangular, 600-acre (243-

hectare) parcel of land. The proposed power plant site is flat and requires minimal grading for facility construction. Elevation ranges across the site from 2,920 feet (890 meters) to 2,969 feet (905 meters) above MSL, with a ground slope of less than 0.5 percent.

More than sufficient groundwater is available within comparatively short distances from the proposed power plant site for use as a water supply source for the facility. These include the Ogallala (High Plains aquifer system), Pecos Valley, Edwards-Trinity Plateau, Dockum and Capitan aquifers. Each of these aquifers or some combination of them can furnish all of the required water supply for the facility. Water for the power plant could be developed from new well fields in these aquifers or acquired from several existing or proposed well fields in the area.

The proposed power plant site would be interconnected to the proposed sequestration reservoir by a network of existing CO_2 pipelines used for secondary oil recovery in the region. These existing pipelines have sufficient excess capacity to accommodate the volume of CO_2 expected from the proposed power plant. The plant site is approximately 58 miles (92.8 kilometers) from the proposed sequestration reservoir.

The surface extent of the land area above the proposed sequestration reservoir is located within Pecos County, TX, with centroid coordinates at 30° 51’ North by 102° 37’ West. The area falls within the Trans-Pecos Mountains and Basins ecological area of Texas characterized by diverse habitats and vegetation, varying from desert valleys and plateaus to wooded mountain slopes.

Average weather information for Odessa, TX includes average temperature, precipitation, humidity, wind speed, snow fall, sunshine, and cloudy days by month. Table 2-3 provides observations derived from that data:

Table 2-3. Weather Information for Odessa, TX

Weather Parameter	Spring	Summer	Fall	Winter
Average Daily Temperature, °F (°C)	72 (22.2)	79 (26.1)	56 (13.3)	49 (9.4)
Average Monthly Precipitation, inches (centimeters)	1.3 (3.3)	2.0 (5.0)	1.1 (2.7)	0.5 (1.2)
Average Wind Speed, miles per hour (kilometers per hour)	12.2 (19.6)	9.9 (15.9)	10.3 (16.5)	11.7 (18.8)

Average wind direction is not available for each season, but the wind direction in the area is predominantly south to south-southeast throughout the year.

Water Resources and Wetlands

The State of Texas designates the aquifers in the state as major and minor aquifers. One major aquifer, the Pecos Valley (formerly referred to as the Cenozoic Pecos Alluvium), lies beneath and in the near vicinity of the proposed power plant site, but is estimated to be largely unsaturated (TWDB, 1995), as noted in the EIV for Odessa. The Dockum and Rustler aquifers, designated minor aquifers in the state, also lie beneath the site (TWDB, 1995).

The depth to water in the Dockum was measured at 205.6 feet (62.7 meters) below ground level in 1947 in a well located immediately to the south of the proposed power plant site. However, due to groundwater development in the Dockum, water levels have fallen over the years. Current estimation of the depth to water in the Dockum beneath the proposed power plant site is on the order of 320 feet (98 meters) below ground level.

Groundwater quality in the Dockum aquifer in Texas is typically brackish to saline, with TDS generally less than 5,000 mg/l. Water quality in the Dockum typically decreases in quality (higher mineralization) with depth.

No surface water bodies are located on the proposed power plant site or within its ROI. The closest significant water body is the Upper Pecos River, more than 30 miles (50 kilometers) south of the site. The plant site and surrounding area is arid. Some dry, intermittent creek beds appear nearby. No existing contamination has been identified in water bodies within the ROI of the proposed power plant site or in any nearby water bodies.

Maps produced by the FWS, referred to as NWI maps, indicate no areas potentially subject to Section 404 jurisdiction existing on the proposed power plant site (FWS, 1994). An on-site investigation of the proposed power plant site confirmed that.

NWI maps indicate no areas potentially subject to Section 404 jurisdiction of the Clean Water Act within the proposed CO_2 pipeline corridor east or west of the proposed power plant site (FWS, 1994). NWI maps indicate a tributary of Tunas Creek and a palustrine, unconsolidated bottom, artificial, temporary, diked/impoundment as areas potentially subject to Section 404 jurisdiction within the proposed corridor east of the proposed sequestration reservoirs. NWI maps indicate Sixshooter Draw, Monument Draw, Tunas Creek, and several on-channel impoundments as areas potentially subject to Section 404 jurisdiction within the land area above the proposed sequestration reservoir (FWS, 1994).

Aquatic and Terrestrial Ecology

Aerial photographs and USGS topographic maps indicate that there are no permanent surface waters within the proposed power plant site boundaries. This was confirmed through a field reconnaissance performed in April 2006. While man-made stock tanks exist within the surrounding ROI, the ecology of such artificial tanks is generally determined by landowner management practices and is not indicative of natural ponds. An aerial photograph of the proposed power plant site and its ROI shows visible drainage patterns suggesting seasonal run-off associated with heavy rainfall. Ephemeral streams and pools related to such events may provide habitat to a number of aquatic species.

The NRCS PLANTS Database was searched for common aquatic plants found in Texas (NRCS, 2006), as reported in the EIV for Odessa. No records were found for aquatic plants in Ector County. Because of the lack of surface waters on the proposed power plant site, habitat for aquatic macrophytes is not available.

The two transmission line corridors and one CO_2 pipeline corridor associated with the proposed power plant site are all located in Ector County and contain no aquatic habitat. The CO_2 pipeline corridor is crossed by one unnamed ephemeral draw. The remaining CO_2 pipeline corridors are associated with the proposed sequestration reservoir in Pecos County. The corridor proposed to the west of the sequestration area contains three ephemeral draws, of which two are direct tributaries to Six Shooter Draw. All three constitute the upstream end of these draws and are approximately 1 to 1.5 miles (1.6 to 2.4 kilometers) long. The CO_2 pipeline corridor proposed to the east of the sequestration area contains four crossings by tributaries of Six Shooter Draw.

Pecos County, which contains the CO_2 pipeline corridors proposed to the west and east of the proposed sequestration reservoir, has three fish species of potential occurrence listed by the FWS and TPWD as endangered, and two species listed by the TPWD as threatened. Both FWS and TPWD list the Comanche Springs pupfish (*Cyprinodon elegans*), the Leon Springs pupfish (*Cyprinodon bovinus*), and the Pecos

Gambusia (*Gambusia nobilis*) as endangered species. These three species are located well to the north and west of the proposed CO_2 pipeline corridors in Pecos County. All require permanent, generally spring-fed habitat, which does not occur within the vicinity of the proposed corridors. The two state-listed threatened species, the Pecos pupfish and the proserpine shiner (*Cyprinella proserpina*) would both be restricted to the Pecos River and its permanent tributaries, well to the north and west of the proposed corridors. The CO_2 pipeline corridors proposed to the east and west of the proposed sequestration reservoir would not be inhabited by any federally or state-listed fish species.

The proposed power plant site is situated within the High Plains and the Trans-Pecos Mountains and Basins vegetational areas of Texas (Gould, 1975). The High Plains Vegetational Area occurs on a relatively level high plateau and receives an average of 15 to 21 inches (38.1 to 53.3 centimeters) per year of rain. The vegetation is variously classified as mixed-prairie, shortgrass prairie, and in some locations as tall-grass prairie. The High Plains region characteristically is free from brush, but mesquite and yucca have invaded some of the area. Sand sage and shinnery oak are common on the sandylands and junipers have spread out of some of the breaks onto the Plains proper.

The Trans-Pecos Mountains and Basins Vegetational Area is a region of diverse habitats and vegetation, varying from desert valleys and plateaus to wooded mountain slopes. Because of the wide range of ecological sites, many vegetation types exist. The most important of these are creosote-tarbush desert shrub, grama grass land, yucca and juniper savannahs, pinion pine and oak forest, and a limited amount of ponderosa pine forest.

No federally protected terrestrial species of plants or animals are listed for Ector County by the FWS. No federally designated critical habitat for any species is present in Ector County (FWS, 2006). No sensitive areas for any federally or state-protected terrestrial vegetation or wildlife species are noted for Ector County.

Sensitive Receptors

Gary Bittick, GIS Coordinator for the city of Odessa, reported in the EIV that two elementary schools, Murry Fly Elementary and Cavazos Elementary, are each located a little more than 8 miles (13 kilometers) from the proposed power plant site boundary. In addition, Chris's Country Retirement Center is also located approximately 7 miles (12 kilometers) from the site. No other sensitive receptors (e.g. nursing homes, hospitals, schools, prisons) are reported to be within 10 miles of the proposed plant site.

The ROI for sensitive receptors includes the land area above the proposed sequestration reservoir plus a 10-mile (16-kilometer) radius. There are 10 sensitive receptor groups located within the ROI. All of the sensitive receptors are in the city of Fort Stockton and are located approximately 9 to 10 miles (14 to 15 kilometers) from the land area above the reservoir.

2.5.2.2 Subsurface Features

Saline Formation and Seals

The targeted injection horizons consist of a lower interval of Delaware Mountain Group sandstones and an upper interval of Queen Formation sandstones (Figure 2-10). Figure 2-10 also shows the proposed well types for the injection site. These porous sandstone intervals are separated by an intermediate seal that consists of predominantly non-porous and impermeable carbonates of the Goat Seep Limestone. The upper injection horizon is overlain by a 700 feet (213 meters) thick primary seal, the Seven Rivers Formation. The Seven Rivers consists of anhydrite along with minor carbonate and halite. The top, or secondary, seal is formed by the 500 feet (152 meters) Salado Formation. The Salado is a regionally extensive evaporite-dominated succession of anhydrite and halite along with minor low permeability carbonate, mudstone and siltstone. 328 feet (100 meters) of low permeability sandstones and siltstones further protect the deepest underground sources of drinking water. Groundwater is not produced in the sequestration area although local aquifers exist in the Cretaceous interval. The water table is approximately 200 feet (61 meters) below surface. There is no oil or gas production from the sequestration interval in this area, but regionally both the Delaware Mountain and the lower Queen sandstones are prolific producers, with well demonstrated seals above each reservoir.

Multiple injection wells are required for this site.

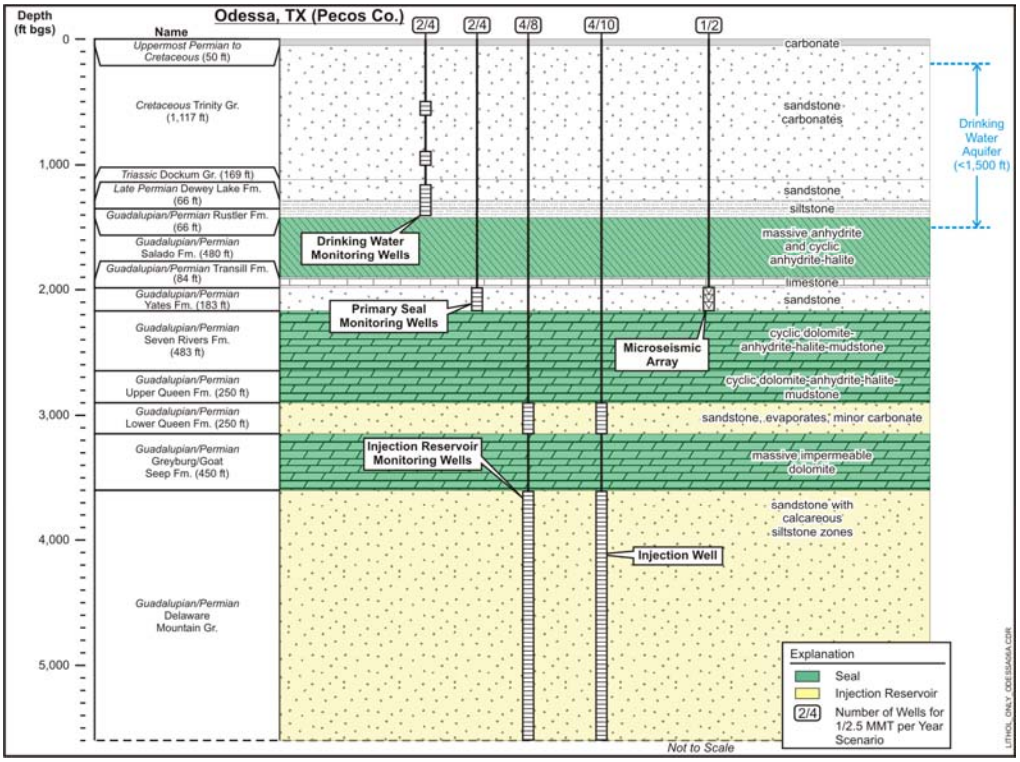


Figure 2-10. Schematic Illustration of Well Types for Odessa, TX

The proposed primary injection target consists of two intervals of fine-grained sandstones and siltstones with low to moderate porosity and permeability. The Delaware sandstones are at a depth of about 3,600 feet (1,097 meters), and form a thick (1300-800 feet [396-549 meters]) succession of deep-water sandstones that increase in thickness from northeast to southwest across the injection field area. This southwestward increase in thickness parallels the gentle structural dip of the unit, and reflects the depositional environment of submarine slope deposits adjacent to the Central Basin Platform. These sandstones are separated from the Queen shallow water sandstones by a thick (450 feet [137 meters]) inter-reservoir seal of low permeability carbonates. The top of the Queen injection interval is about 3,000 feet (914 meters).

Salinities in the Odessa saline formations are around 100,000 parts per million (ppm) TDS. Temperature at the bottom of the Delaware sandstone interval is expected to be about 107°F (42°C), and bottom hole hydrostatic pressure is estimated to be 2338 psi at a depth of approximately 5,600 feet (1,707 meters).

The Odessa site is characterized by large storage capacity, but low permeability as is typical of many saline reservoirs across the United States. Sixteen wells penetrate the Delaware Mountain sandstone interval, and the maximum plume size of two of the originally proposed wells would intersect petroleum exploration dry holes. The results of additional numerical modeling indicate that 10 wells rather than 18 wells (as originally proposed) should meet the maximum injectivity and capacity requirements and that repositioning of the wells will likely avoid having non-program well penetrations intersect any plume.

Regional controls on Capacity and Injectivity

Because of low reservoir permeabilities, the injection rate of each well is limited by the maximum pressure that can be safely used without causing reservoir fracturing. Numerical modeling results indicate ten wells will meet the maximum injection rates and capacity required by the FutureGen Project. The most dominant regional controls on capacity and injectivity are reservoir heterogeneity due to depositional environment, and associated abundance of calcite cement. Figure 2-11 illustrates the approximate sizes of the plume footprint for 10 injection wells.

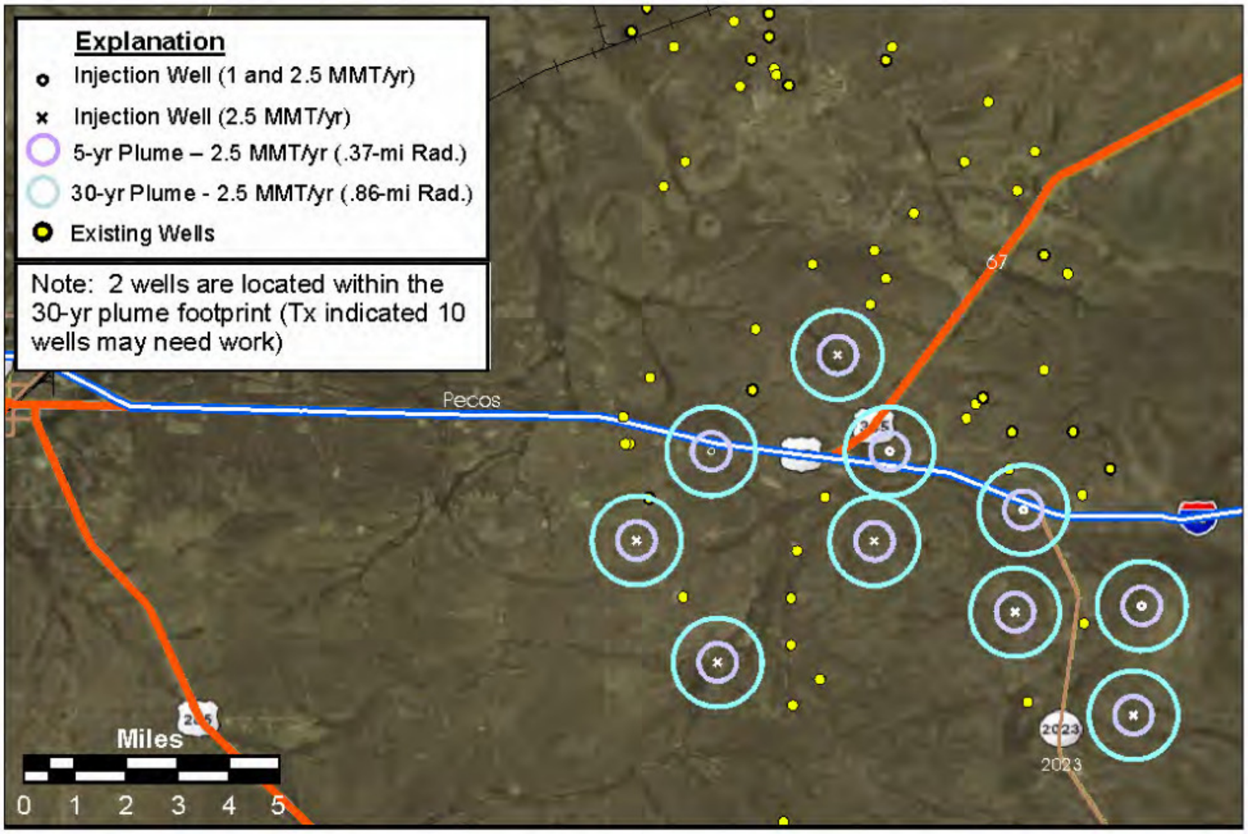


Figure 2-11. Map of Existing Wells in the Vicinity of the Odessa Site, and Plume Footprints (EIV FutureGen Alliance, 2006)

The shallow-water Queen sandstones are interbedded with thin, low permeability carbonates and anhydrite cemented siltstones. Porous sandstones are likely to increase in abundance in a basinward, down-dip direction to the southwest. Carbonate cements are more common toward the top of the Delaware Mountain sandstones, and are common in the Queen sandstones. Carbonate cement increases up dip, toward the platform margin, providing a regional lateral seal in the Queen, well beyond the edge of the modeled maximum extent of the CO_2 plume.

Tectonic Setting

The Odessa site is located in a seismically stable area at the margin of the Central Basin Platform in the Permian Basin of West Texas-New Mexico. The principal tectonic features of the Odessa site are the deep Delaware Basin and the uplifted Central Basin Platform. These geologic features originated during the

Pennsylvanian, when northeastward directed tectonic compression folded and faulted the older rock layers and formed the southern edge of the Central Basin Platform. The area has since undergone minor east-west extension associated with Tertiary age Basin and Range faulting in New Mexico.

There are no mapped faults or fracture zones within the sequestration area. Deep-seated faults are common throughout the region, associated with the formation of the Permian Basin and carbonate platform. Recent three dimensional (3-D) seismic data indicate that none of these faults have penetrated the Delaware Mountain Group, the Queen, or overlying stratigraphic units.

Geologic Features of the Seal and Reservoir that Impact Leakage Scenarios

The major sources of leakage of geologically sequestered CO_2 are thought to be: 1) slow or sudden failure of the caprock seal, and 2) leakage along well bores (Oldenburg and Unger, 2003).

Three 300+ feet (100+ meters) seals (one intra- reservoir, one primary and one secondary) provide low risk of CO_2 escape through permeation. The dominance of thin, permeable reservoir sandstones separated by low permeability lithologies in both the Delaware Mountain interval and in the lower Queen reservoir provide effective baffles that slow the vertical migration of CO_2 within the reservoir, and reduce buildup of pressure on the seal. The intra-reservoir seal, the Goat Seep limestones, are expected to have very low porosities (2-3 percent) and permeabilities.

Dominant facies in the Delaware Mountain Group are feldspar bearing sandstones and siltstones. Sediment texture ranges mainly between coarse silt and very fine-grained sand in the upper beds, with slightly more coarse fine-grained sand in the lower beds. Intergranular pores contain variable quantities of cements composed of calcite and authigenic clay minerals. Clays are dominantly illite and chlorite and are not abundant. Calcite cement is most abundant in the very fine grained levee and overbank deposits, and is less common in the lower part of the Delaware Mountain Group. Cemented intervals locally form baffles. Both calcite and chlorite are expected to be reactive in the presence of CO_2.

Porosity and reservoir potential are best developed in fine-grained Queen sandstones where feldspar has been dissolved. Kaolinite, a product of feldspar weathering, is common. To the north, toward the carbonate platform, anhydrite cements become more common and are expected to provide an updip seal that will prevent lateral migration of injected CO_2.

The lack of hydrocarbon accumulation in the Delaware Mountain Group in the region of the Odessa site is noteworthy. This may be due to lack of sufficient organic material or sufficient burial of the strata. Alternatively, hydrocarbons may have been generated within the Delaware Mountain Group and may have migrated updip to reservoirs on the Central Basin Platform. Thus, the lack of hydrocarbons may suggest the possibility of lack of a lateral seal between the basin slope sandstones and the carbonate platform deposits. Porosity in the Delaware Mountain Group presently appears to be occluded updip by calcite, and high permeability thief zones do not seem likely.

Mineralogy and permeability of the seal are main controls on slow permeation that can result in seal failure. The primary seal lithologies of the upper Queen and Seven Rivers units are dolomites, limestones and anhydrites with low permeabilities and high capillary entry pressures. The upper Queen and Seven Rivers are seals to hydrocarbon accumulations across several counties. These rocks display very little porosity (typically less than 1 percent) and extremely low permeabilities (below measurement limits of less than 0.01 md).

The ultimate seal for the Odessa saline formations consists of Salado anhydrites and halite. This Formation has been extensively studied at the Waste Isolation Pilot Project (WIPP) site in the Delaware Basin of New Mexico, where it forms the seal for long-term storage of radioactive waste.

Brittle failure of the seals is due to natural or induced seismicity and is considered a hazard for geologic storage of CO_2. Regional stresses indicate the Odessa site is in a somewhat extensional, slightly strike slip regime. The extensional regime suggests the possibility of fault slip and transmissive fractures. However, the low differential stress, together with multiple thick seals and a lack of seismically observable faults in the Delaware Mountain Group or higher units decreases the likelihood of undetected, transmissive fractures breaching multiple seals. Seismic data from a few miles northwest of the site show no disruptions in the bedded evaporites of the Salado seal. The preservation of salt layers within the sealing zones indicates that the seal has not been compromised by fracturing and associated flow of brines.

Existing faults and fracture zones that open during sequestration operations are a leakage hazard. Compromise of the seal can be caused by changes in pore pressure associated with the injection of CO_2 that can decrease friction on pre-existing ruptures, and may cause them to become transmissive in part, or to slip. To mitigate this leak hazard, injection pressures can be held to 85 percent of fracture gradient.

Leakage of CO_2 along wellbores is considered a hazard for sequestered CO_2. There are 16 wells that penetrate the Delaware Mountain Group in the area. Through strategic placement of the injection wells at the Odessa site, the CO_2 plumes should not intersect these existing wells. The presence of any unidentified wells within the projected CO_2 plumes will present a potential leakage hazard, but site characterization could include surveys to locate any previously undetected wellbores for remediation. Anticipated mitigation techniques at this site could include cementing up to 10 wells in the vicinity of the injection field. Also many different monitoring techniques such as remote sensing, atmospheric monitoring, and near-surface and subsurface CO_2 monitoring could be employed.

2.5.3 MATTOON, IL

2.5.3.1 Surface Features

Figure 2-12 shows the location of the proposed Mattoon FutureGen Power Plant site, sequestration site, CO_2 pipeline, human receptors, small streams and rivers, and topographic variations.

General Description and Climatology

The Mattoon Site (including both the plant and injection sites) consists of 444 acres (180 hectares) making up most of the eastern three quarters of Section 8 of Mattoon Township, Coles County, in the State of Illinois. The property is located at latitude 39° 29’ 49” N and longitude 88° 26’ 33” W. Most of the site is currently used for agricultural purposes. The site is essentially flat with a slope averaging between 0.5 and 1 percent. A drainage swale crosses the northwest corner of the site. The elevation of the site varies from 718 feet (219 meters) to 679 feet (207 meters). The CO_2 injection well sits near the center of the Mattoon Dole Site. The injection well will be located at approximately latitude 39° 29’ 50” N and longitude 88° 26’ 30” W.

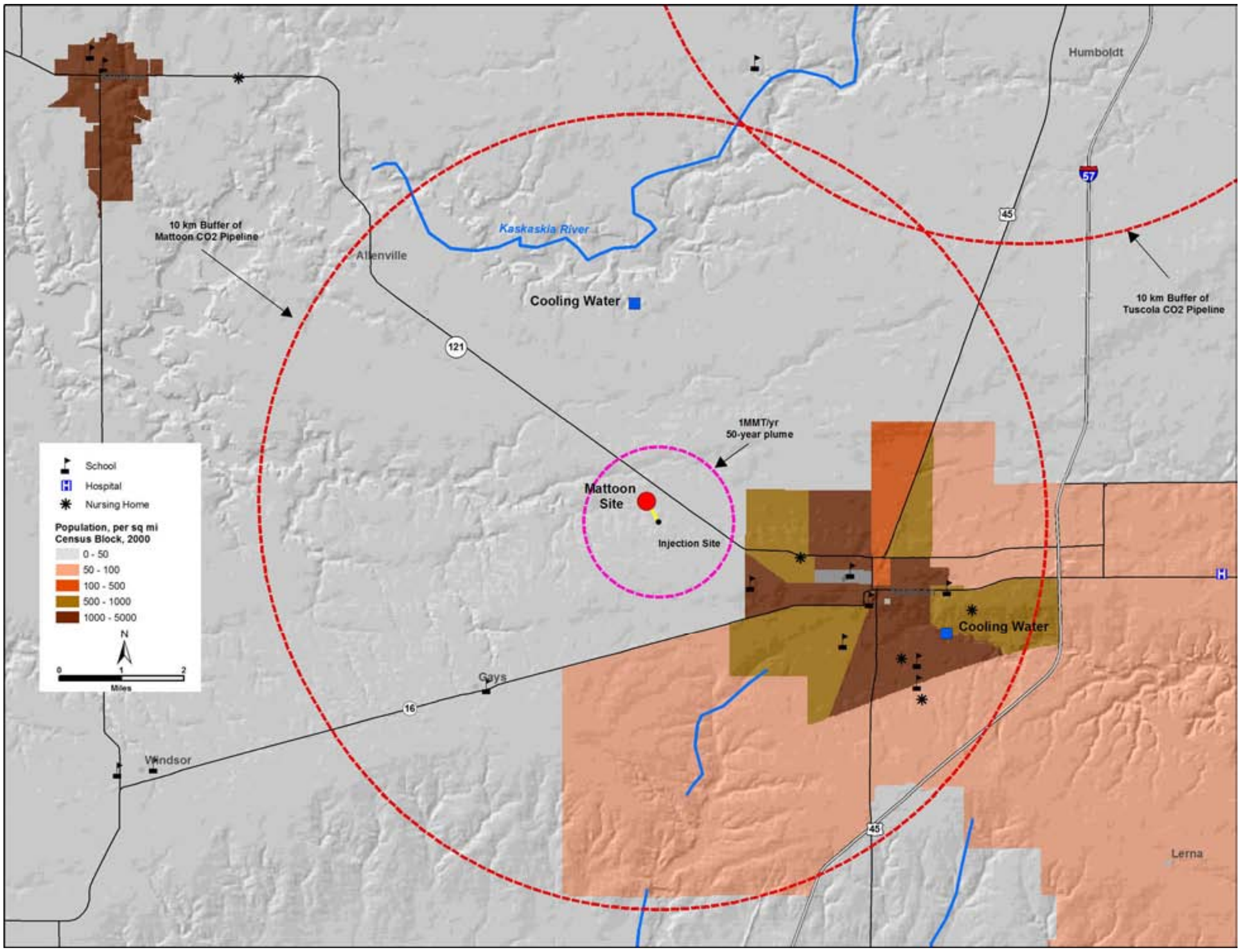


Figure 2-12. Proposed Mattoon FutureGen Site

As the source of cooling water for the Mattoon Site, the City of Mattoon intends to use the combined effluent from the municipal WWTPs in Mattoon, IL and Charleston, IL. The Mattoon WWTP is 6.2 piping miles (10 kilometers) from the plant and has a daily average flow of 4.4 million gallons per day (16.7 million liters per day). The Charleston WWTP is 8.1 piping-miles (13 kilometers) from the proposed Mattoon piping system and has a daily average flow of 2.6 million gallons per day (9.8 million liters per day).

The climatological data is derived from local National Climatic Data Center (NCDC) data for Mattoon and are based on historical norms derived from the past 30 years of weather data (1971-2000). The area has a humid continental climate, with rainfall heaviest in the summer and at a minimum in winter, totaling around 40 inches (100 centimeters) for the year. Winters are cold, with average highs just over freezing in January, while morning lows average in the upper teens. Seven or eight days a year will experience zero degrees or colder on average during a winter. Average winter snowfall totals only around 20 inches (50 centimeters), and only one snowfall per season on average amounts to 5 inches (13 centimeters) or more. Transition seasons are more variable in temperature, while in general, precipitation increases through spring and decreases through the fall. By July, average high temperatures are in the upper 80s (upper 20s in °C), with lows in the mid 60s (upper 10s in °C). High temperatures frequently reach 90 degrees (upper 30s in °C) or more during the summer months. June and July are the heaviest precipitation months in this area.

In the winter, the most frequent wind direction is south through southwest, with a milder spike of occurrences from the northwest. The most frequent wind speeds are 8 to 19.6 mph (13 to 32 kilometers per hour); with an average of 11.2 mph (18 kilometers per hour). Winds from the northeast quadrant are rare. In the spring, the wind directions of south and south-southwest are even more dominant than in winter, with no apparent secondary maximum from any other direction. Winds from the northeast quadrant are a little more frequent than during the winter. The most frequent wind speeds are 12.7 to 19.6 mph (20 to 32 kilometers per hour), while the average wind speed in the summer increases to nearly 11.6 mph (19 kilometers per hour).

Water Resources and Wetlands

Groundwater resources for the proposed power plant site are available in limited quantities based on information obtained from the Illinois State Water Survey's (ISWS) Private Well Database and presented in the EIV for Mattoon. According to documents from the ISWS, groundwater in this vicinity is normally obtained from sand and gravel deposits that are contained in unconsolidated material above bedrock. The sand and gravel deposits for the vicinity of the proposed power plant site range in depth from about 20 to 125 feet (6 to 38 meters) below ground surface. The sand and gravel deposits are sufficient groundwater sources when small or large diameter drilled wells are constructed for domestic and farm uses. Groundwater quality data were not available for the proposed power plant site, but data were available from the ISWS on samples taken from private wells located in the vicinity of the proposed power plant site, as reported in the EIV for Mattoon. No data have been discovered that showed existing contamination present at the proposed power plant site. According to documents obtained from the ISWS, water obtained from bedrock wells at depths below approximately 175 feet (53 meters) may be highly mineralized and too salty for most uses.

There were no other groundwater uses discovered for the proposed power plant and injection site besides the private wells that were present in the vicinity of the proposed site. There was also no specific data available on the annual amount withdrawn from the sand and gravel deposits in the vicinity of the proposed power plant and injection site.

The proposed site lies within the Kaskaskia River Watershed west of the Kaskaskia/Wabash/Embarras River watershed divides. Surface runoff from the site drains to the Kaskaskia River via overland flow, an existing unnamed tributary running through the site to Whitley Creek, and Whitley Creek itself. Within 1 mile (1.6 kilometers) of the proposed site boundary, the majority of the surface runoff ultimately drains to the Kaskaskia River. Water quality data are not routinely recorded for surface streams within the vicinity of the site.

Eighteen jurisdictional wetland areas were identified by means of on-line databases, field investigations, and consulting standard wetland reference texts and manuals. These eighteen wetlands range in size from 108 square feet to 25 acres (10 square meters to 10 hectares).

Aquatic and Terrestrial Ecology

The Illinois Environmental Protection Agency (IEPA) conducted a fisheries survey of the Kaskaskia River in summer 2002 approximately 8 miles (13 kilometers) northeast of the proposed plant site. These data have not been officially published, but were provided by IEPA in the EIV for Mattoon. The survey resulted in a calculated Index of Biotic Integrity of 50, indicating a low "B" rated stream segment (moderate aquatic resource). No listed species were found during the survey. In addition, the IEPA also conducted a macroinvertebrate survey. The calculated Macroinvertebrate Biotic Index (MBI) for this reach was 5.468, indicating an overall healthy aquatic macroinvertebrate community.

The terrestrial landscape within the study areas consists predominantly of agricultural land dedicated to the production of corn and soybean crops. The croplands are typically managed and controlled to maintain and support a single plant species, and the management of the monoculture precludes the establishment of non-agricultural native vegetation. Natural terrestrial habitat within the ROI is limited predominantly to the riparian corridors along Riley Creek, Little Wabash River, and their tributaries. No biological reports or surveys for terrestrial habitat within the ROI were identified.

The FWS has indicated the potential presence of the endangered Indiana bat (*Myotis sodalis*) in Coles County. This species occupies caves and abandoned mines during the winter. During the remainder of the year, Indiana bats utilize trees with rough or exfoliating bark and/or cavities for roosting. Although Indiana bats will forage over open areas, they prefer to forage within the canopy of forests. Because the majority of the study area consists of agricultural cropland, the only potential habitat would be located within the wooded riparian habitat along the rivers or tributaries. Because there are no proposed impacts to the riparian areas, the power plant, or the sequestration site, no impacts to the Indiana bat or its breeding habitat are anticipated during operational activities.

Sensitive Receptors

The IEPA performed a series of queries to determine the proximity of sensitive receptors within a 10-mile (16-kilometer) radius from potential site boundaries, as reported in the EIV for Mattoon. This analysis addressed only schools and hospitals. Ten schools and one hospital are located within the 10-mile (16-kilometer) buffer zone. Data for these receptors were acquired from 2005 ESRI GIS data layers. Due to data limitations, the IEPA was unable to provide sensitive receptor information for correctional institutions and nursing homes. A search of an online database of long-term care facilities at www.carepathways.com identified five nursing homes within a 10-mile (16-kilometer) radius. There are no known correctional institutions within the area.

2.5.3.2 Subsurface Features

Saline Formation and Seals

The Mattoon Site has one primary saline formation, the Mt. Simon, and one optional saline formation, the St. Peter. There is a thick regional seal above the primary target and two secondary seals above the regional seal (see Figure 2-13). Figure 2-13 also shows proposed wells at the injection site, except for the back-up injection well. Pennsylvanian cyclic shales, limestones, and sandstones provide almost 3,000 feet (914 meters) of protective barriers between the uppermost secondary seal and the deepest underground sources of drinking water. There is no oil or gas production from the Mt. Simon in Illinois; but statewide, there are 38 natural gas storage reservoirs in this formation.

The sequestration target is the Cambrian-age Mt. Simon Sandstone, which is the thickest and most widespread saline reservoir in the Illinois Basin. The Mt. Simon consists of stacked, thin porous sandstone units, separated by thin beds of less permeable siltstone and shale. The Mt. Simon is overlain by a thick (500-700 feet [152-213 meters]) regional seal of low permeability siltstones and shales of the Eau Claire Formation, and is underlain by Precambrian granitic basement. The St. Peter Sandstone is proposed as an optional target reservoir, but would require a separate well. It occurs at a depth of 4,700 feet (1,432 meters), which is about 2,200 feet (670 m) above the Mt. Simon.

The Mt. Simon Formation at the Mattoon Site is estimated to be at a depth of 6,500-6,950 feet (1,981-2,545 meters), with thicknesses of 1300-1400 feet (396-427 meters), and with approximately 585 feet (178 meters) of effective porosity. Porosity in the Mt. Simon generally ranges from five to 15 percent, with effective porosity generally restricted to sandstones with greater than 12.6 percent porosity. Effective porosity occurs in numerous 1-2 feet (0.3-0.6 meters) sandstones, separated by lower permeability rock.

In situ conditions of the Mt. Simon are expected to be as follows: salinities 130,000 ppm; temperature at base of the formation (8,350 feet [2,545 meters]), 145°F (62.8°C); and hydrostatic bottom hole pressure, 3,590 psi at 8,400 feet (2,560 meter).

The optional reservoir, the St. Peter Sandstone, is estimated to be over 200 feet (61 meters) thick with state-wide lateral continuity, average porosity of about 16 percent, and average permeabilities of about 20 md. Both Mt. Simon and St. Peter reservoirs have been successfully used for natural gas storage in other parts of Illinois. The closest analog well with geophysical porosity logs through the Mt. Simon is 36 miles (57 kilometers) south of the proposed injection well. This introduces some uncertainty into the thickness and reservoir properties of the Mt. Simon at Mattoon. However, approximately 25 wells have penetrated the Mt. Simon in southern Illinois, so there are sufficient regional data to suggest low probability of the Mt. Simon not being present at the Mattoon Site. The regional depositional environment of the Mt. Simon sandstones is fairly uniform across Illinois, so the rock character is not expected to be greatly different from the areas that have equivalent depth well data.

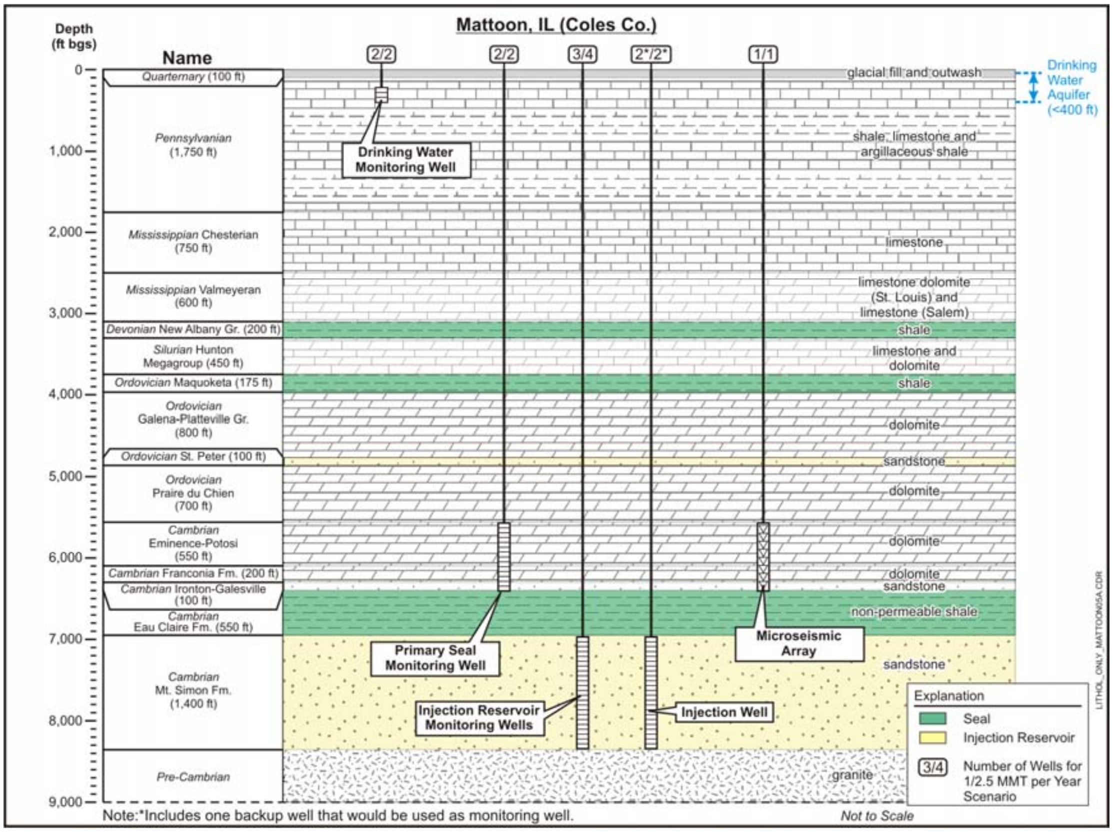


Figure 2-13. Schematic Illustration of Well Types for Mattoon, IL

Regional Controls on Capacity and Injectivity

Capacity and injectivity at the Mattoon Site appear adequate to meet the FutureGen sequestration capacity and injectivity goals. Reservoir modeling indicates that a single well will provide sufficient capacity to meet maximum FutureGen injection rate requirement (Figure 2-14). A backup well will likely be proposed for reliability. Sensitivity modeling shows that the injectivity target at Mattoon can be met even if the number of meters of effective porosity is reduced by 2/3. However, this analysis also is predicated on an assumption that regional scale outflow boundaries exist that would allow movement of the water displaced by the injected CO_2. Should those boundaries not exist or be more restrictive in allowing water to exit the system, additional wells may be required to distribute the CO_2 over a wider area; alternatively pressure relief wells (water extraction wells) may be required to control reservoir pressure.

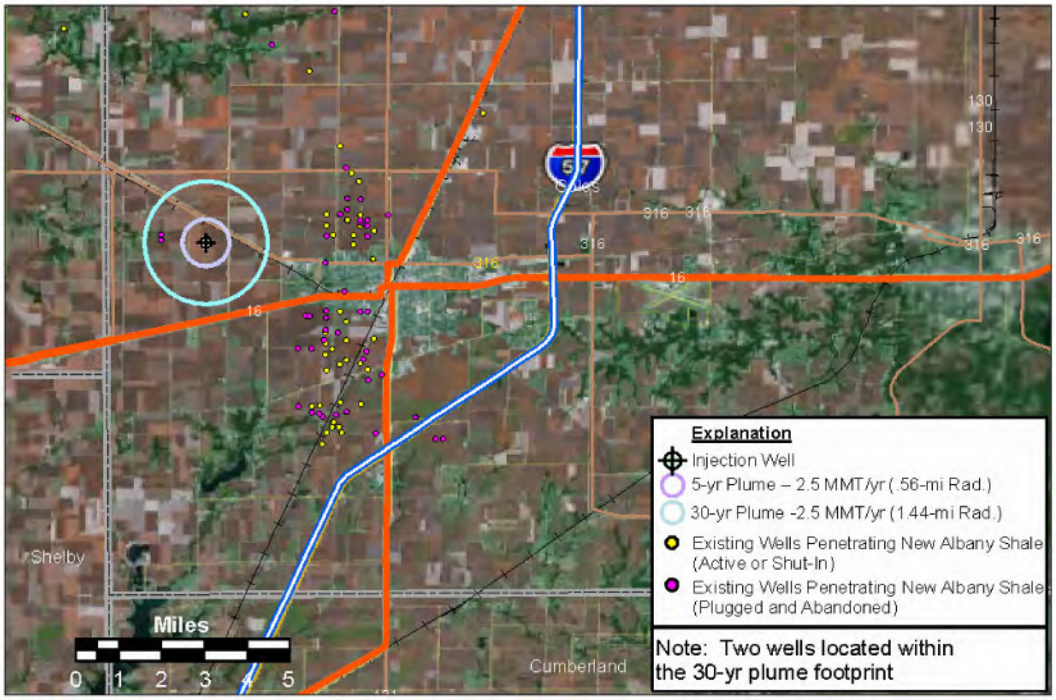


Figure 2-14. Map of Existing Wells that Penetrate the New Albany Shale at the Mattoon Injection Site, and Plume Footprints

Tectonic Setting

The Mattoon Site is located in a seismically stable area in the northern Illinois Basin. The near-surface rocks are of Late Pennsylvanian age and lie close to horizontal. There are no mapped faults in the sequestration area, and there have been no earthquake epicenters located within 10 miles (16 kilometers) of this site as detected by seismic networks to indicate any recent active faults. The closest network-located earthquake was 12 miles (19 kilometers) east of the Mattoon in 1990, and the second closest event was 23 miles (37 kilometers) to the northeast; neither was over magnitude 3.0.

The site lies in a very gentle syncline, immediately east of a series of north-south anticlinal folds that serves as traps for oil reservoirs above the Mt. Simon. Structural dip across the site is expected to be less than one degree.

The principal tectonic feature of the Mattoon area is the Charleston Monocline. This step-like fold marks the western edge of a series of anticlinal folds known as the La Salle Anticlinorium. The Charleston fold strikes north-northwest and its steep limb dips southwest. Structural relief is as great as 2,500 feet (763 meters) at the level of the Ordovician Galena Dolomite, making this the largest fold in the Illinois. The Mattoon Site is about 6 miles (9.5 kilometers) west of the lower limb of the Charleston Monocline, as mapped on the Devonian New Albany Shale seal. The axis of a smaller fold, the Mattoon Anticline, passes about 2 mile (3 kilometers) east of the Mattoon Site. This anticline trends north-south and provides structural trapping for the Mattoon oil and gas field (Figure 4.2). It is likely that basement faults controlled formation of the anticline, but large through-cutting transmissive faults within the Paleozoic rocks seem unlikely because of the existence of vertically separated oil accumulations within the anticline.

The thick primary seal is a mix of relatively low permeability lithologies that serves as a competent caprock in 38 natural gas storage reservoirs elsewhere in Illinois. Two secondary shale seals at 3,000 feet (914 meters) and 3,700 feet (1,228 meters), respectively) above the Eau Claire provide backup to the main seal. The thin, interbedded permeable and low permeability lithologies of the reservoir interval provide numerous reservoir baffles that slow the vertical migration of CO_2 within the reservoir. In addition, the stable tectonic setting and compressive regional stress regime, coupled with apparent high fracture opening pressures, indicate that any fracture zones or faults that penetrate the seal are most likely to be sealing, and not transmissive. Finally, no wellbores penetrate the primary seal.

Geologic Features of the Seal and Reservoir that Impact Leakage Scenarios

The major sources of leakage of geologically sequestered CO_2 are, according to Oldenburg and Unger (2003): 1) slow or sudden failure of the caprock seal, and 2) leakage along well bores.

Mineralogy and permeability of the seal are the main controls on slow permeation that can result in seal failure. Both mineralogy and permeabilities of the seals at the Mattoon Site indicate strong potential for containment from permeation. The primary seal was studied in detail by Peoples Gas Light and Coke before they installed the Manlove Gas Storage Field, 58 miles (93.3 kilometers) north of the Mattoon Site. These companies reported that the Eau Claire is a heterogeneous unit that contains K-feldspar, quartz, dolomite, and detrital clay with lesser amounts of glauconite, plagioclase, calcite, pyrite, and hornblende. The detrital clays have been largely converted to relatively stable illite, and the siltstones and scattered thin sandstones are well-cemented by silica. Feldspars have been largely altered to clays, leaving behind the more stable K-spar.

Lateral changes in mineralogy of the Eau Claire could result in increased permeability of the caprock and make it susceptible to slow permeation. Regionally there are changes in lithology, but not great changes in permeability. There are only 25 penetrations of the Eau Claire in southern Illinois, so there are few data on changes in lithology at the sequestration site.

Both secondary seals, the Maqouketa and New Albany, are predominantly marine shales with vertical permeabilities to water of 0.001 or less. The New Albany shale, in particular, is characterized by vertical permeabilities of less than 0.0001, and is a regional seal to hydrocarbon accumulations.

The mineralogy and heterogeneity of the sandstones of the Mt. Simon are favorable for slowing buoyancy driven, upward migration of CO_2. The Mt. Simon consists primarily of medium to coarse quartz sandstone with local granule-rich sandstone beds. Thin beds of red, green, or gray micaceous shale are sparsely interbedded with the sandstone, especially toward the top of the Mt. Simon. Also interbedded are thin beds of fine to medium feldspar bearing sandstone. The Mt. Simon is present throughout most of Illinois, ranging in thickness from less than 500 feet (150 meters) in southwestern Illinois to over 2,600 feet (780 meters) in the east-central part of the state. In some areas of west-central Illinois, the Mt. Simon is very thin or absent. Porosity generally decreases with depth as the rock is subjected to compaction and cementation. The thin, interbedded permeable and low permeability lithologies provide numerous reservoir baffles to vertical migration, and the presence of feldspar is expected to enhance mineral trapping of the CO_2.

Sudden, brittle failure of caprock seals, either through reservoir over-pressuring and induced seismicity or through natural seismicity is considered as a major potential leakage hazard of geologically sequestered CO_2. Because of high permeabilities of the Mt. Simon in gas storage fields north of the proposed sequestration site, and because Illinois regulatory field practices operation requires injection pressures below 80 percent of the regional fracture opening pressure, reservoir over-pressuring is not considered to be a major leakage hazard at Mattoon. The compressive nature of the regional stress regime suggests that faults should not easily rupture or become transmissive in the event of natural or induced seismicity.

Existing faults and fracture zones that open during sequestration operations are a leakage hazard. Compromise of the seal can be caused by changes in pore pressure associated with the injection of CO_2 that can decrease friction on pre-existing ruptures, and may cause them to become transmissive in part, or to slip. Again, the compressive nature of the regional stress suggests that fractures and faults will not tend to open due to normal field operations.

Leakage of CO_2 along wellbores is considered a hazard for sequestered CO_2. There are five oil fields with anticlinal closure within a 10-mile radius surrounding the Mattoon Site. The Mattoon field to the east of the injection site produces from Devonian and Mississippian strata at depths of 1,700-3,200 feet (518 – 975 meters). Three petroleum exploration wells are located above the maximum plume footprint projected for the Mattoon injection well; one well was drilled to the Mississippian, one to the Devonian and one to the Silurian. None penetrates the primary seal of the Eau Claire.

2.5.4 TUSCOLA, IL

2.5.4.1 Surface Features

Figure 2-15 shows the location of the proposed Tuscola FutureGen Power Plant site, sequestration site, pipeline, human receptors, wetlands, major surface water features, and topographic variation.

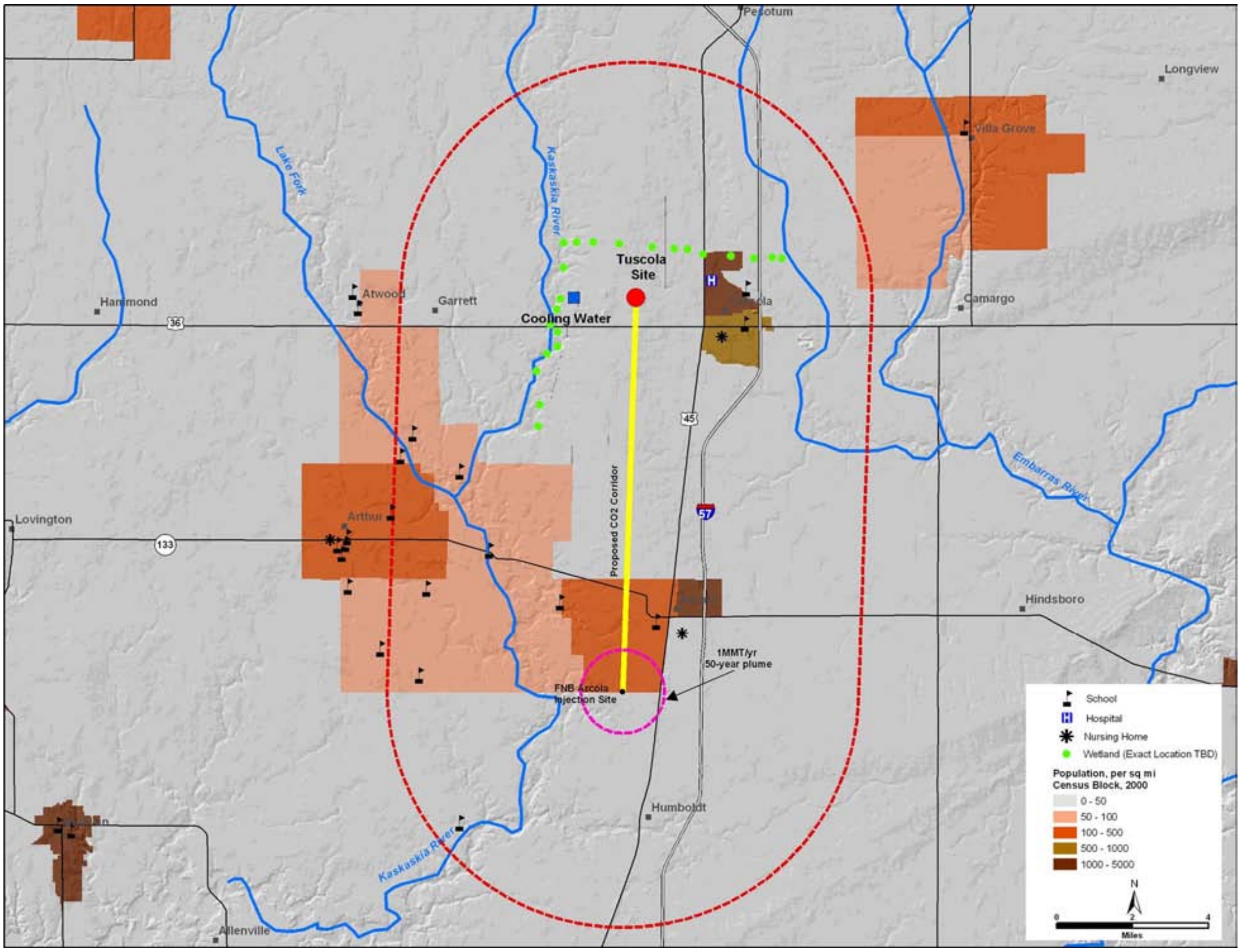


Figure 2-15. Proposed Tuscola FutureGen Site

General Description and Climatology

The proposed site consists of 345.4 acres (140 hectares) located in Tuscola Township, Douglas County, in the State of Illinois. The precise geographic location is latitude 39° 48’ 9.46” N, longitude 88° 19’ 8.57” W. The general topography of the site is flat. There are slight natural drainage swales that exist along the southwestern section of the site. The elevation of the site varies from 686 to 679 feet (209 to 207 meters). The area of the proposed power plant site consists entirely of agriculture land (soybean and corn).

Cooling water for plant operation would be provided by Equistar Chemicals LP (Lyondell). A water line would be installed from the pump station at Lyondell’s 150 MG reservoir to the plant site. This arrangement would provide water to the plant site at a flow rate of 2,500 gpm (9,464 million liters per minute) or 3.6 million gallons per day (mgd) (14 million liters per day).

The proposed CO_2 pipeline is approximately 11 miles (18 kilometers) long. It will be constructed across State of Illinois, Douglas County, and Township rights-of-way and will occupy new rights-of-way where needed. The proposed sequestration site is located on a land trust known as Land Trust number L-745. The site is a 10-acre (4-hectare) portion of a larger parcel of 80 acres (32.4 hectares). The proposed sequestration site is located in Arcola Township, Douglas County, in the state of Illinois. The precise geographic location is Latitude 39° 39’ 7.16” N, longitude 88° 19’ 57.05” W.

The proposed area has a humid continental climate, with rainfall heaviest in the summer and at a minimum in winter, totaling around 40 inches (100 centimeters) for the year. Winters are cold, with average highs just over freezing in January, while morning lows average in the upper teens. Seven or eight days a year temperatures will drop to zero degrees or colder. Average winter snowfall totals only around 20 inches (50 centimeters), and only one snowfall per season on average amounts to 5 inches (13 centimeters) or more. Transition seasons are more variable in temperature, while in general, precipitation increases through spring and decreases through the fall. By July, average high temperatures are in the upper 80s (upper 20s in °C), with lows in the mid 60s (upper 10s in °C). High temperatures frequently reach 90 degrees (upper 30s in °C) or more during the summer months. June and July are the heaviest precipitation months in this area.

In the winter, the most frequent wind direction is south through southwest, with a milder spike of occurrences from the northwest. The most frequent wind speeds are 8 to 19.6 mph (13 to 31.5 kilometers per hour) with an average of 11.2 mph (18 kilometers per hour). Winds from the northeast quadrant are rare. In the spring, the wind directions of south and south-southwest are even more dominant than in winter, with no apparent secondary maximum from any other direction. Winds from the northeast quadrant are a little more frequent than during the winter. The most frequent wind speeds are 12.7 to 19.6 mph (20.4 to 31.5 kilometers per hour), while the average wind speed in the spring increases to nearly 11.6 mph (18.7 kilometers per hour). In the summer, wind directions from south through southwest are still dominant, but the resulting wind directions are evenly distributed through the other sectors. Summer wind speeds drop off dramatically, with calms on more than 6 percent of the hours, and an average wind speed of only around 8 mph (13 kilometers per hour). The fall season is characterized most frequently by winds from the south or south-southwest, with a minor peak from the west-northwest. Winds blowing from the northeast quadrant are very unusual during this season. With an average speed of 10.3 mph (16.6 kilometers per hour), fall winds increase some in intensity from summer, but do not reach the speeds that occur during winter and spring, on average.

Water Resources and Wetlands

Groundwater resources for the proposed power plant site are available in limited quantities from the sand and gravel deposits that are contained in the unconsolidated glacial material above the bedrock surface and from some shallow bedrock aquifers. According to the private well logs obtained, the sand and gravel deposits in the vicinity of the proposed power plant site range in depth from approximately 70 to 100 feet (20 to 30 meters) below ground surface. These sand and gravel deposits are sufficient groundwater resources for domestic and farm uses with an average withdrawal rate of 10 gpm (38 liters per minute) or less. Several private and commercial/industrial wells utilize the shallow Pennsylvanian and Mississippian bedrock as a source of groundwater. These units consist primarily of thin, interbedded sandstones and limestones, which provide a limited source of groundwater (approximately 10 gpm).

No other groundwater uses were discovered near the proposed power plant site except the private wells that were present in the vicinity of the site. There were also no specific data available on the annual amount withdrawn from either the sand and gravel or the bedrock aquifers in the vicinity of the proposed power plant site. The off-site groundwater wells within 1 mile (1.6 kilometers) of the proposed power plant site boundaries are all private wells. These wells are all classified as domestic and farm use wells. There is one well used as a commercial well at the Tuscola Airport and one private-use well.

Surface runoff from the site drains to the Embarras River via overland flow, roadside ditches, and the Scattering Fork Creek, which is located less than 1 mile (1.6 kilometers) east of the proposed site. Within 1 mile of the proposed site boundary, the majority of the surface runoff ultimately drains to the Embarras River, with the exception of a small portion. Water quality data is not routinely recorded for surface streams mentioned above.

The study area was investigated for wetlands on August 23, 2006, through August 25, 2006, generally using procedures outlined in the 1987 Corps of Engineers' (Corps) Wetland Delineation Manual (ACE, 1987). The study area included the land for the proposed power plant, a 350-foot (107-meter) wide corridor along the proposed 345-kV line, a 300-foot (90-meter) wide corridor along the proposed water line, a 300-foot wide corridor along the proposed CO_2 line, and a 1.1-mile (1.7-kilometer radius above the proposed sequestration reservoir.

All areas were inspected, with areas of mapped wetlands or hydric soils prioritized for investigation. If inspection revealed that wetland plant species comprised more than 50 percent of the plant cover, the suspected wetland was further examined for field indicators of hydric soil and hydrology. The Corps approved field indicators of hydrology include visual observation or photographic evidence of soil inundation or saturation during the growing season, oxidized channels associated with living roots and rhizomes, water marks, drift lines, waterborne sediment deposits, waterstained leaves, surface scoured areas, and drainage patterns. Hydrologic criteria were met in all areas delineated as wetland or Waters of the United States. Dominant vegetation and habitat features were documented. A total of 19 areas were identified in the project area.

Aquatic and Terrestrial Ecology

Discussions with Illinois Department of Natural Resources (IDNR), as reported in the EIV for Tuscola, revealed one potential listed species issue with respect to the Tuscola site; that issue concerned mussel beds in the Chicken Bristle segment of the Kaskaskia River, approximately two miles upstream from the proposed water intake point. Interest in this segment of the river stems from the fact that the Kaskaskia River will provide the water source for Tuscola FutureGen via the Lyondell water reservoir west of Tuscola. The IEPA conducted a fisheries survey of the Kaskaskia River in summer 2002, as described in the EIV for Tuscola. No contamination of aquatic plant or animal species was observed.

The only aquatic macarophytes that were observed were in the industrial ponds and segment of the Kaskaskia River. These species included coontail (*Ceratophyllum demersum)* and milfoil (*Myriophyllum sp.)*. The relatively turbid conditions of the river limit the number of aquatic plants that can be supported in the project area. For the Embarras River, land cover is characterized by pasture, large estate residential, wooded area, and row crops. No aquatic plants were observed within the project area. No contamination of aquatic plant or animal species was observed or is known for the project area. Despite seasonal low flows and the fact that overall land use in the watershed is dominated by agriculture, the entire length of the Embarras River was identified as a Resource Rich Area (RRA). The river has rich species diversity and a high species count and offers a variety of habitats in its better sections, including gravel bars, gravel and sand raceways, sandbars, riffles and deep pools.

Above the sequestration site, no federal or state-listed species are known. Also, no areas of sensitive or critical habitat for any listed species are known for this area. Aquatic habitat above the sequestration reservoir is limited to a small section of the Kaskaskia River, the adjacent floodplain, and several intermittent drainage ways.

The terrestrial landscape within the study areas consists predominantly of agricultural land dedicated to the production of corn and soybean crops. The croplands are typically managed and controlled to maintain and support a single plant species, and the management of the monoculture precludes the establishment of non-agricultural native vegetation. Natural terrestrial habitat within the ROI is limited predominantly to the riparian corridors along the Kaskaskia River, the Embarras River, and the tributaries that were addressed in the previous section. No biological reports or surveys for terrestrial habitat within the ROI were identified as part of this study.

The FWS indicated the potential presence of the endangered Indiana bat *(Myotis sodalis)* in Douglas County. This species occupies caves and abandoned mines during the winter. During the remainder of the year, Indiana bats utilize trees with rough or exfoliating bark and/or cavities for roosting. Although Indiana bats will forage over open areas, they prefer to forage within the canopy of forests. Since the majority of the study area consists of agricultural cropland, the only potential habitat would be located within the wooded riparian habitat along the rivers or tributaries.

Sensitive Receptors

The IEPA performed a series of queries, as reported in the EIV for Tuscola to determine the proximity of sensitive receptors within a 10-mile (16-kilometer) radius from potential power plant, pipeline, and sequestration boundaries. These sensitive receptors represent only schools and hospitals. Due to data limitations, the IEPA was unable to provide additional sensitive receptor information (correctional institutions and nursing homes). Twenty-six schools and one hospital are located within the 10-mile radius of the proposed power plant, pipeline, and sequestration site. A total of 16 schools were located within the 10-mile radius of the proposed power plant and 12 schools were located within the 10-mile radius of the sequestration site. Searching the online database of long term care facilities at www.carepathways.com identified three nursing homes within the 10-mile radius of the power plant and three nursing homes with the 10-mile radius of the sequestration site.

2.5.4.2 Subsurface Features

Saline Formation and Seals

The Tuscola site has one primary target deep saline formation, the Mt. Simon, and one optional saline formation, the St. Peter (Figure 2-16) for CO_2 injection. There is a thick regional seal above the primary target and two secondary seals above the regional seal. Pennsylvanian cyclic shales, limestones, and sandstones provide almost 3,000 feet (900 meters) of protective barriers between the uppermost secondary seal and the deepest underground sources of drinking water. Figure 2-16 also shows the proposed wells at the injection site. However, the shallow back-up injection well is not shown. There is no oil or gas production from the Mt Simon in Illinois; but statewide, there are 38 natural gas storage reservoirs in this formation. The top of the Mt Simon at the Tuscola Site is estimated to be between 5,500 – 6,250 feet (1,676- 1,905 meters) below ground surface; thickness is estimated to be between 1,500 - 1,700 feet (457- 518 meters), and net effective porosity was estimated by the offeror to be between 600-675 feet (183-205 meters). The base of the Mt. Simon at Tuscola is estimated to be at a depth of about 7,750 feet (2,362 meters). The Tuscola site references the Weaber-Horn #1 as the closest analog, although that well is about 56 miles (90 kilometers) south of the Tuscola site.

The Tuscola sequestration target is the Cambrian-age Mt. Simon Sandstone, which is the thickest and most widespread saline reservoir in the Illinois Basin. The Mt. Simon consists of stacked, thin porous sandstone units, separated by thin beds of less permeable siltstone and shale. The Mt. Simon is overlain by a thick (500-700 feet [152-213 meters]) regional seal of low permeability siltstones and shales of the Eau Claire Formation, and is underlain by Precambrian granitic basement. The St. Peter Sandstone is proposed as an optional target reservoir, but would require a separate well. It occurs at a depth of 4,700 feet (1,432 meters), which is about 2,200 feet (670 meters) above the Mt. Simon.

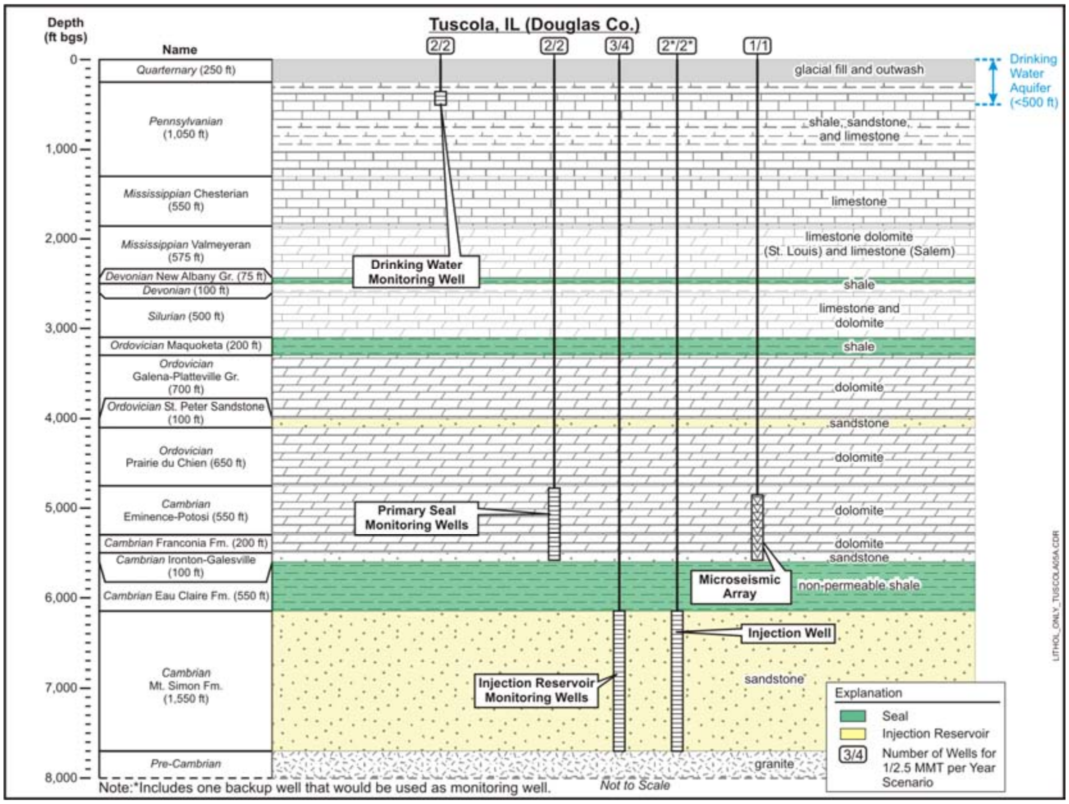


Figure 2-16. Schematic Illustration of Well Types for Tuscola, IL

Porosity in the Mt. Simon generally ranges from five to 15 percent, with effective porosity generally restricted to sandstones with greater than 12.6 percent porosity. Effective porosity occurs in numerous 1-2 feet (0.3-0.6 meters) sandstones, separated by lower permeability rock. The lower part of the Mt. Simon is arkosic, and in to the north where it occurs at more shallow depths, the basal part of the Formation has increased porosity and permeability.

The optional reservoir, the St. Peter Sandstone, is estimated to be over 200 feet (61 meters) thick with state-wide lateral continuity, average porosity of about 16 percent, and average permeabilities of about 20 millidarcies. Both Mt. Simon and St. Peter reservoirs have been successfully used for natural gas storage in other parts of Illinois. In particular, the Mt. Simon supports 38 natural gas storage reservoirs in Illinois.

Salinities in the Mt. Simon and the St. Peter are expected to exceed 125,000 mg/L TDS. Bottom hole temperature at the base of the Mt Simon (8,350 feet [2,545 meters]) is estimated to be 145°F (62.8°C). Bottom hole pressure is estimated to be 3,590 psi at the same depth.

The closest analog well with geophysical porosity logs through the Mt. Simon is 56 miles (90 kilometers) south of the proposed injection well. This introduces considerable uncertainty into the thickness and reservoir properties of the Mt. Simon at Tuscola especially because the Mt. Simon is transgressive onto a high relief Pre-Cambrian surface and thins to zero thickness in some areas. However, approximately 25 wells have penetrated the Mt. Simon in southern Illinois, so there are sufficient regional data to suggest low probability of the Mt. Simon not being present at the Tuscola site. The regional depositional environment of the Mt. Simon sandstones is fairly uniform across Illinois, so the rock character is not expected to be greatly different from the areas that have equivalent depth well data.

Regional Controls on Capacity and Injectivity

Injectivity and reservoir capacity are a function of the formation depth, thickness, effective porosity, temperature, and salinity of the formation water. At Tuscola, there is some uncertainty associated with reservoir depth, and even greater uncertainty with thickness and porosity. Reservoir properties of the primary saline formation at the Tuscola site, based on the analogs, appear adequate to meet the FutureGen sequestration capacity and injectivity goals. Depth may exert some control over preservation of porosity and permeability in the Mt. Simon, and that, in turn, could strongly influence capacity and injectivity. There is regional evidence that porosity in the Mt. Simon becomes more occluded with mineral cement at depths below 7,000 feet (2,134 meters). The Mt. Simon reservoir analog parameters are from underground gas storage facilities, which are at depths much shallower than the depth at the Tuscola site, and thus are expected to be less affected by compaction and mineral cements. Reservoir modeling indicates that a single well will provide sufficient capacity to meet the 2.8 million tons per year (2.5 MMT/year) injection rate requirement, even if permeabilities are an order of magnitude less than those of the gas storage reservoirs (Figure 2-17). In addition, sensitivity modeling shows that the injectivity target can be met even if the number of meters of effective porosity is also reduced by 2/3. This analysis is predicated on an assumption that regional scale outflow boundaries exist that will allow movement of the water displaced by the injected CO_2. Should those boundaries not exist or are more restrictive in allowing water to exit the system, additional injection wells might be required to distribute the CO_2 over a wider area at Tuscola, or pressure relief wells (water extraction wells) might be required to control reservoir pressure.

Tectonic Setting

The proposed Tuscola site is in an area of low seismicity. There is no recorded earthquake activity, and no known faults have been mapped at the site. The closest network-located earthquake was 4 miles (6 kilometers) east of the Tuscola site in 1978, and the second closest event was 17 miles (27 kilometers) to the south, neither over magnitude 3.0.

Tuscola is in the central part of the Illinois Basin, where near-surface rocks are of Virgilian-age (Late Pennsylvanian) and locally, are nearly horizontal. For older rocks, the deepest part of the basin is shifted southward, and the New Albany Shale (a regional marker and important secondary seal) dips southeastward in the Tuscola area at an average rate of less than one degree. The site lies immediately east of a series of north-south anticlinal folds that serves as traps for oil reservoirs above the Mt. Simon in the Cooks Mills Consolidated oilfield; dip across the injection site is expected to be less than one degree.

The dominant structural feature of Douglas County is the Tuscola Anticline. This fold, which extends into southern Champaign County, is 25 miles by 10 miles (40 kilometers by 16 kilometers) wide and has more than 700 feet (213 meters) of structural closure. The fold axis trends slightly west of North and the western flank is much steeper than the eastern.

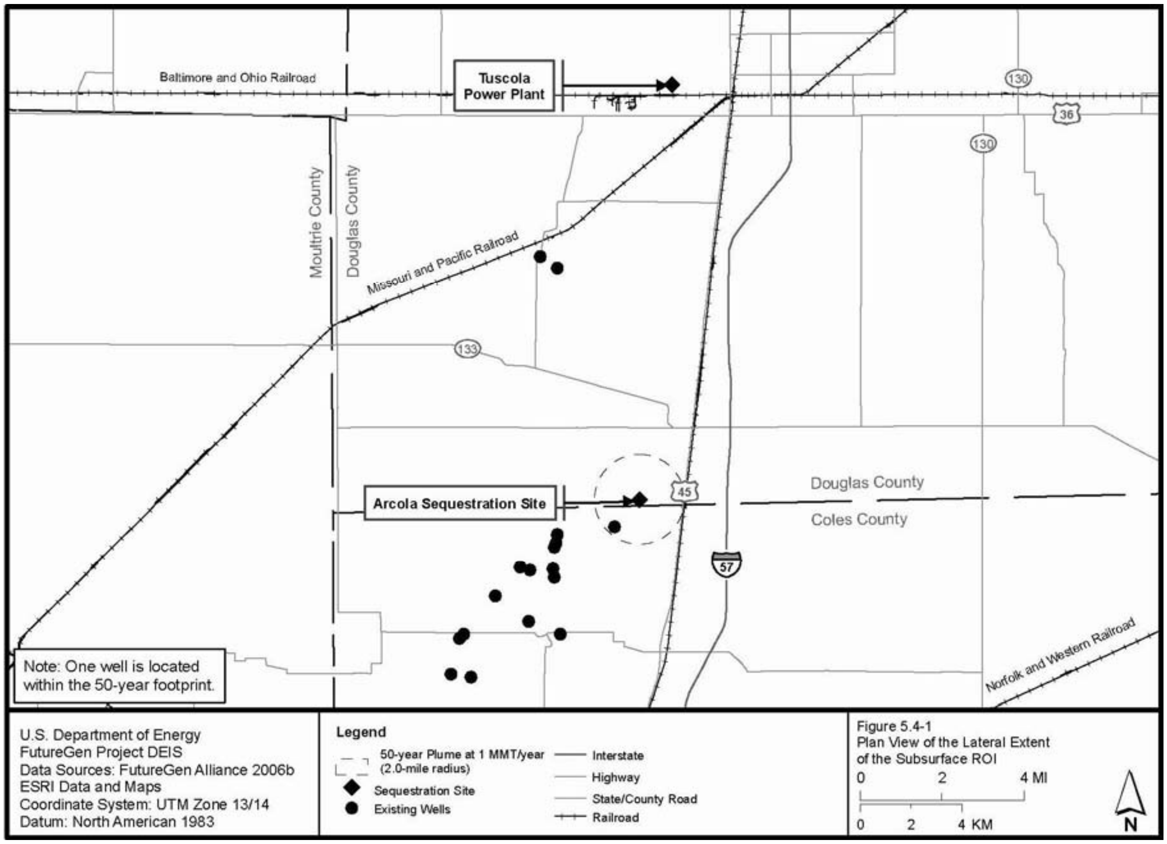


Figure 2-17. Map of Existing Wells that Penetrate the New Albany Shale at the Tuscola Injection Site, and Plume Footprints

Geologic Features of the Seal and Reservoir that Impact Leakage Scenarios

The thick primary seal is a mix of relatively low permeability lithologies that serves as a competent caprock in 38 natural gas storage reservoirs elsewhere in Illinois. Two secondary shale seals at 3,000 feet (914 meters) and 3,700 feet (1,228 meters), respectively) above the Eau Claire provide backup to the main seal. The thin, interbedded permeable and low permeability lithologies of the reservoir interval provide numerous reservoir baffles that slow the vertical migration of CO_2 within the reservoir, and the cyclic Pennsylvanian deposits provide additional protection above the two secondary seals. In addition, the stable tectonic setting and compressive regional stress regime, that any through-going fracture zones or faults that penetrate the seal are most likely to be sealing, and not transmissive. Finally, no wellbores penetrate the primary seal at Tuscola.

The most likely sources of leakage of geologically sequestered CO_2 are considered to be: 1) slow or sudden failure of the caprock seal, and 2) leakage along well bores (Oldenburg and Unger, 2003). Changes in mineralogy and permeability of the seal are the main factors that can result in seal failure. Both mineralogy and permeabilities of the seals at the Tuscola site indicate strong potential for containment from permeation. The Eau Claire was examined in detail by Peoples Gas Light and Coke before installation of the Manlove Gas Storage Field. They reported that the primary seal, the Eau Claire, is a heterogeneous unit that contains K-feldspar, quartz, dolomite, and detrital clay with lesser amounts of glauconite, plagioclase, calcite, pyrite, and hornblende. The detrital clays have been largely converted to relatively stable illite, and the siltstones and scattered thin sandstones are well-cemented by silica. Feldspars have been largely altered to clays, leaving behind the more stable K-spar. The Eau Claire at the Manlove field has porosities that range from less than 1 to as much as 10 percent, with corresponding vertical permeabilities that range from about 0.00004 to 0.0006 md. Capillary entry pressures required to force fluids into the Eau Claire seal are generally high. Statewide, Eau Claire median permeability and porosity are 0.000026 md and 4.7 percent, with corresponding threshold entry pressures of 110 to 1200 psi. At the Manlove field, the Eau Claire separates the Mt. Simon from the overlying porous Galesville Sandstone; a comparison of salinities in the two rocks indicates a lack of fluid communication across the Eau Claire caprock. Lateral changes in mineralogy of the Eau Claire could result in greater permeability of the caprock and make it susceptible to slow permeation. Regionally there are changes in lithology, but no reported large scale changes in permeability. There are only 25 penetrations of the Eau Claire in southern Illinois, and there are no data on changes in lithology in the sequestration area.

Both secondary seals, the Maqouketa and New Albany are dominantly marine shales with vertical permeabilities to water of 0.001 or less. The New Albany shale, in particular, is characterized by vertical permeabilities of less than 0.0001, and is a seal to petroleum accumulations regionally.

The mineralogy and heterogeneity of the sandstones of the Mt. Simon are favorable for slowing buoyancy driven, upward migration of CO_2, although there is some uncertainty associated with the thickness of the Formation at the Tuscola site. The Mt. Simon primarily consists of medium to coarse quartz sandstone, local granule-rich sandstone beds, and thin layers of micaceous shale toward the top of the unit. Feldspar-bearing sandstones are also present. The Mt. Simon is present throughout most of Illinois, ranging in thickness from less than 500 feet (150 meters) in southwestern Illinois to over 2,600 feet (780 meters) in the east-central part of the state. In some areas of west-central Illinois, the Mt. Simon is very thin or absent. Porosity generally decreases with depth as the rock is subjected to compaction and cementation. The thin, interbedded permeable and low permeability lithologies provide numerous reservoir baffles to vertical migration, and the presence of feldspar is expected to enhance mineral trapping of the CO_2.

Sudden, brittle failure of caprock seals, either through reservoir over-pressuring and induced or natural seismicity is considered as a potential leakage hazard of geologically sequestered CO_2. Because of high permeabilities of the Mt. Simon in gas storage fields north of the proposed sequestration site, and because Illinois regulatory injection field operations require injection pressures below 80 percent of the fracture opening pressure, reservoir over-pressuring and caprock rupture through fracture initiation is not considered to be a major leakage hazard at Tuscola, provided reservoir quality is not greatly decreased at the Tuscola site.

In addition to initiating fractures through over-pressuring the reservoir, changes in pore pressure associated with the injection of CO_2 can decrease friction on pre-existing faults, and may cause them to become transmissive in part, or to slip. The general compressive tectonic regime of the Tuscola site suggests that existing faults are not likely to slip as a result of normal field operations. However, the local stresses at Tuscola are likely to be complex and geomechanical characterization of the site is critical.

Improperly plugged wellbores is considered a major hazard for leakage of sequestered CO_2. The Tuscola site is surrounded by mature and abandoned petroleum exploration and production wells; one of which penetrates the New Albany secondary seal above the Tuscola plume footprint. None of the known wells penetrates the Eau Claire. There are a number of wells whose status is not known in the area, and there is a likelihood of improperly plugged oil wells existing near the Tuscola site. However, as extensive monitoring effort is proposed for the site that include remote sensing, atmospheric monitoring, surface and near surface monitoring, and subsurface monitoring, such monitoring could help detect and mitigate leaks.

2.6 Delineation of Exposure Pathways for Human and Ecological Receptors

Figure 2-18 shows the CSM used to guide evaluations of human and biological risks for each of the 4 sites under consideration for the FutureGen Project. This figure shows the potential exposure pathways linking the sources of releases, the release mechanisms, chemical migration pathways, and the environmental media impacted by releases that humans and biological receptors may be exposed to at each site. This general guide is used in characterizing potential pre- and post-sequestration exposures and identifying the appropriate toxicity criteria (Section 3) for characterizing risks associated with each type of exposure. For some of the sites, not all the exposure pathways or receptors may be relevant. The site-specific risk assessments for the pre- and post-sequestration releases are addressed in Sections 4 and 5, respectively.

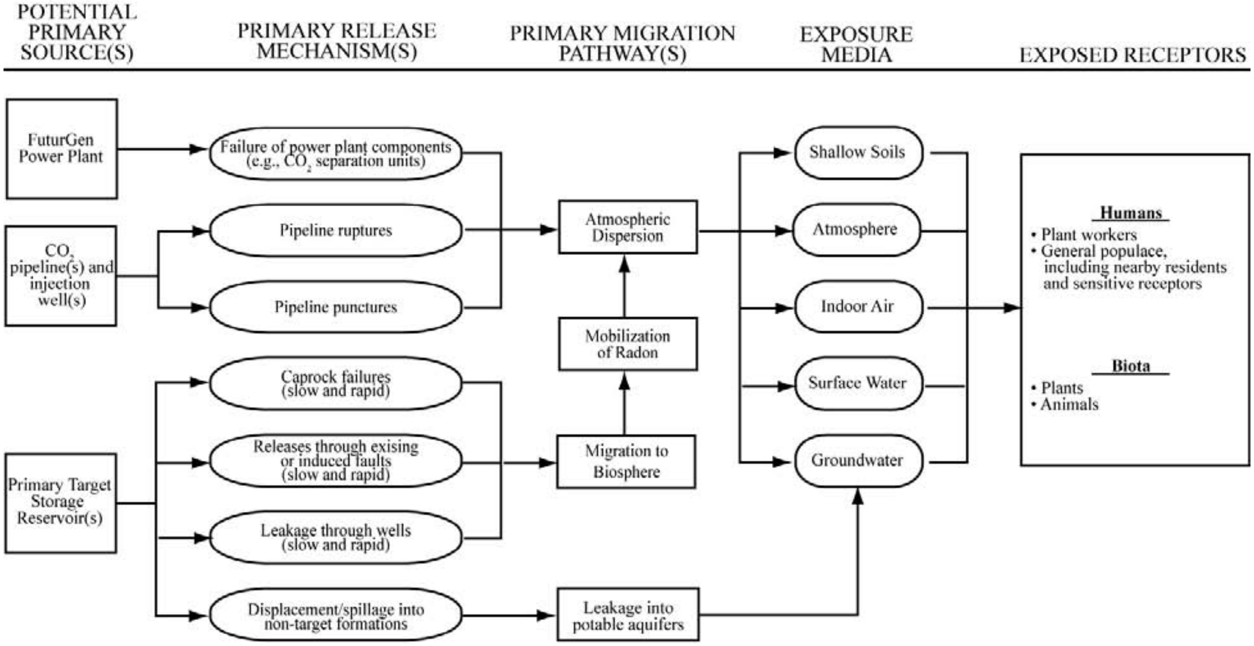


Figure 2-18. CSM for Human and Biological Receptors

3.0 TOXICITY DATA, BENCHMARK CONCENTRATION EFFECT LEVELS

The toxicity assessment provides information on the potential for the COPCs to cause adverse health effects. The main focus of this project is the separation and sequestration of CO_2 produced as a result of the coal gasification process. Understandably, CO_2 is the main COPC for which toxicity data were compiled. As discussed in Section 2, a number of other chemicals may also be present at trace concentrations in the captured gases, including CH_4 and H_2S. The full list of COPCs is provided in Table 3-1. Each of these COPCs may cause adverse health effects to human and biological receptors, depending on the concentration, exposure pathway, and exposure duration.

Table 3-1. Chemicals of Potential Concern (COPCs)

CO_2 Gas after Separation
Other Compounds in Gas
H_2S
SOx
NOx
CO
CH_4
Mercury
Cyanide
Other Potential Concerns
Radon
Change in pH of groundwater and surface water

Benchmark toxicity data (toxicity criteria) were determined for all of the potentially complete exposure pathways, including the catastrophic and fugitive releases of captured gases described in Section 2 and shown in Figure 2-18. Accordingly, toxicity criteria were identified for the following types of exposure:

- Inhalation of airborne gas/vapor
- Dermal contact with vapor
- Inhalation of indoor vapor
- Potable water use, including ingestion (consumption) of water
- Immersion (direct contact) in surface water
- Direct exposure to soil gas (vapor)

3.1 Sources of Toxicity Criteria

The potential for the COPCs to cause adverse health impacts to human and biological receptors was assessed by compiling peer-reviewed chemical concentration effect levels published by the U.S. EPA, Health Canada, and other regulatory agencies. The sources reviewed to identify potentially applicable chemical concentration effect levels are shown in Table 3-2.

Table 3-2. Sources of Human Health and Biota Toxicity Criteria

Inhalation exposures	
Short-term exposures	
•	ATSDR acute MRLs
•	Cal EPA acute RELs
•	U.S. EPA AEGLs
•	AIHA ERPGs
•	U.S. DOE TEELs
•	Saripalli *et al*. (2003) recommended exposure limits for CO_2
•	U.S. EPA (2000) *Carbon Dioxide as a Fire Suppressant: Examining the Risks*
•	Health Canada *Exposure Guidelines for Residential Indoor Air Quality*
•	NIOSH recommended exposure limits
•	OSHA PELs
•	ACGIH *Threshold Limit Values and Biological Exposure Indices*
Long-term exposures	
•	ATSDR intermediate and chronic MRLs
•	Cal EPA chronic RELs
•	U.S. EPA reference concentrations (RfCs)
•	Saripalli *et al*. (2003) recommended exposure limits for CO_2
•	U.S. EPA (2000) *Carbon Dioxide as a Fire Suppressant: Examining the Risks*
•	National Ambient Air Quality Standards (NAAQS)
•	Health Canada *Exposure Guidelines for Residential Indoor Air Quality*
•	NIOSH recommended exposure limits
•	OSHA PELs
•	ACGIH *Threshold Limit Values and Biological Exposure Indices*
•	Heart of Brazos EIV (December 1, 2006)

Note: Acronyms are defined in Table 3-3.

Table 3-2 (continued). Sources of Human Health and Biota Toxicity Criteria

Groundwater/surface water exposures	
Short-term exposures	
•	U.S. EPA drinking water health advisories
•	U.S. EPA ambient water quality criteria
	o *Quality Criteria for Water*, July 1976
	o *Quality Criteria for Water*, May 1986
	o 1995 Updates: Water Quality Criteria Documents for the Protection of Aquatic Life in Ambient Water
•	Saripalli *et al*. (2003) recommended exposure limits for CO_2
Long-term exposures	
•	U.S. EPA ambient water quality criteria
•	U.S. EPA primary and secondary maximum contaminant levels (MCLs)
•	U.S. EPA drinking water health advisories
•	Saripalli *et al*. (2003) recommended exposure limits for CO_2
Soil exposures	
•	Saripalli *et al*. (2003) recommended exposure limits for CO_2
•	Pearce and West (2006). Study of potential impacts of leaks from onshore CO_2 storage projects on terrestrial ecosystems. British Geological Survey.
•	Heart of Brazos EIV (December 1, 2006)

Note: Definitions are provided in Table 3-3.

In addition to developing toxicity criteria for the COPCs, criteria were also identified for assessing physical effects, such as changes in water pH on aquatic receptors and the potential levels of concern for changes in TDS.

All of the identified toxicity criteria were compiled in a database (see Appendices A-1–A-4). This database was then used to identify the toxicity criteria most applicable for the exposure scenarios characterized for this report. The terms used to describe toxicity criteria are listed in Table 3-3.

Table 3-3. Definition of Acronyms Used in the Toxicity Assessment

ACRONYM	DEFINITION
ACGIH	American Conference of Governmental Industrial Hygienists
AEGLs	Acute Exposure Guideline Levels, U.S. EPA
AEGL-1	The maximum concentration in air below which it is believed nearly all individuals could be exposed for up to one hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odor.
AEGL-2	The maximum concentration in air below which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action.
AEGL-3	The maximum concentration in air below which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects.
AIHA	American Industrial Hygiene Association
ALTER	Acceptable Long-term Exposure Range, Health Canada
	A level of exposure below which there are no apparent detrimental effects. This so-called "threshold level" is closely related to the lowest level at which minimal, or reversible, effects can be observed the "lowest-observable-adverse-effect level" (LOAEL). A safety factor may be incorporated into the derivation of a regulatory standard or guideline depending upon the number and quality of studies upon which the LOAEL is based.
AMCL	Alternative Maximum Contaminant Level; a higher alternative maximum contaminant level (AMCL) accompanied by a multimedia mitigation (MMM) program to address radon risks in indoor air. This framework reflects the unique characteristics of radon: in most cases, radon released to indoor air from soil under homes and buildings is the main source of exposure and radon released from tap water is a much smaller source of radon in indoor air. Radon from tap water is a smaller source of radon in indoor air. Only about 1-2 percent of radon in indoor air comes from drinking water. However breathing radon released to air from household water uses increases the risk of lung cancer over the course of your lifetime. Ingestion of drinking water containing radon also presents a risk of internal organ cancers, primarily stomach cancer.
ASTER	Acceptable Short-term Exposure Range, Health Canada
	Because of the wide variation in individual susceptibility to irritants, notably aldehydes, short-term exposure guidelines have been derived by applying a factor of five to the lowest value reported to cause a significant increase in symptoms of irritation.
ATSDR	Agency for Toxic Substances and Disease Registry
AWQC	Ambient water quality criteria
Cal EPA	State of California, Environmental Protection Agency
CCC	Criterion Continuous Concentration; an estimate of the highest concentration of a material in surface water to which an aquatic community can be exposed indefinitely without resulting in an unacceptable effect.
CH_4	Methane
CMC	The Criteria Maximum Concentration; an estimate of the highest concentration of a material in surface water to which an aquatic community can be exposed briefly without resulting in an unacceptable effect.
CO	Carbon monoxide
CO_2	Carbon dioxide

Table 3-3 (continued). Definition of Acronyms Used in the Toxicity Assessment

ACRONYM	DEFINITION	
DWEL	Drinking Water Equivalent Level. A lifetime exposure concentration protective of adverse, non-cancer health effects, that assumes all of the exposure to a contaminant is from drinking water.	
EIV	Environmental Information Volume	
ERPGs	Emergency Response Planning Guidelines, AIHA	
ERPG-1	The maximum concentration in air below which it is believed nearly all individuals could be exposed for up to one hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odor.	
ERPG-2	The maximum concentration in air below which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action.	
ERPG-3	The maximum concentration in air below which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects.	
HA	Health Advisory. A nonregulatory concentration of a contaminant in water that is likely to be without adverse effects on health and aesthetics.	
HA, One-day	The concentration of a chemical in drinking water that is not expected to cause any adverse noncarcinogenic effects for up to one day of exposure. The One-Day HA is normally designed to protect a 10-kilogram child consuming 1 liter of water per day.	
HA, Ten-day	The concentration of a chemical in drinking water that is not expected to cause any adverse noncarcinogenic effects for up to ten days of exposure. The Ten-Day HA is also normally designed to protect a 10-kilogram child consuming 1 liter of water per day.	
HA, Lifetime	The concentration of a chemical in drinking water that is not expected to cause any adverse noncarcinogenic effects for a lifetime of exposure. The Lifetime HA is based on exposure of a 70-kilogram adult consuming 2 liters of water per day. The Lifetime HA for Group C carcinogens includes an adjustment for possible carcinogenicity.	
Hg	Mercury	
H_2S	Hydrogen sulfide	
MCL	Maximum contaminant level. The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to the MCLG as feasible using the best available analytical and treatment technologies and taking cost into consideration. MCLs are enforceable standards.	
MCLG	Maximum contaminant level goal. A non-enforceable health goal which is set at a level at which no known or anticipated adverse effect on the health of persons occurs and which allows an adequate margin of safety.	
MRLs	Minimal Risk Levels	
	Acute MRL	1-14 days
	Intermediate MRL	>14-364 days
	Chronic MRL	365 days and longer
NA	Not appropriate	
NAAQS	National Ambient Air Quality Standards. Primary standards set limits to protect public health, including the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards set limits to protect public welfare, including protection against decreased visibility, damage to animals, crops, vegetation, and buildings.	
NIOSH RELs	National Institute for Occupational Safety and Health, Reference Exposure Levels	

Table 3-3 (continued). Definition of Acronyms Used in the Toxicity Assessment

ACRONYM	DEFINITION
TWA-REL	Time-weighted average concentration for up to a 10-hour workday during a 40-hour workweek.
ST-REL	Short-term exposure limit (STEL), a 15-minute TWA exposure that should not be exceeded at any time during a workday.
C-REL	A ceiling REL, unless noted otherwise, the ceiling value should not be exceeded at any time.
IDLH	Airborne concentration from which a worker could escape without injury or irreversible health effects from an IDLH exposure in the event of the failure of respiratory protection equipment. The IDLH was considered a maximum concentration above which only a highly reliable breathing apparatus providing maximum worker protection should be permitted. In determining IDLH values, NIOSH considered the ability of a worker to escape without loss of life or irreversible health effects along with certain transient effects, such as severe eye or respiratory irritation, disorientation, and incoordination, which could prevent escape. As a safety margin, IDLH values are based on effects that might occur as a consequence of a 30-minute exposure.
NR	Not recommended due to insufficient data
OSHA PELs	Occupational Safety and Health Administration, Permissible Exposure Limit
TWA-PEL	TWA concentration must not be exceeded during any 8-hour workshift of a 40-hour workweek.
ST-PEL	STEL is measured over a 15-minute period unless noted otherwise.
C-PEL	Ceiling concentration must not be exceeded during any part of the workday; if instantaneous monitoring is not feasible, the ceiling must be assessed as a 15-minute TWA exposure.
OEHHA	State of California, Office of Environmental Health Hazard Assessment
REL	Reference Exposure Level
Acute REL	Cal EPA. Exposure averaged over 1 hour, unless otherwise specified.
Chronic REL	Cal EPA; an airborne level that would pose no significant health risk to individuals indefinitely exposed to that level.
RfC	Reference Concentration, Chronic (USEPA IRIS)
RfD	Reference Dose. An estimate (with uncertainty spanning perhaps an order of magnitude) of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime.
Saripalli et al. (2003), criteria:	
Severe	Air - lethal, habitat loss (>10 percent)
	Building: Injury, evacuation (> 5 percent)
Moderate:	Air - Injuries (> 5 percent)
	Building - Irritation, discomfort (> 2 percent)
Low:	Air -Discomfort (> 1 percent)
	Building -Noticeable, no harm (> 1 percent)
SCAPA	Subcommittee on Consequence Assessment and Protective Actions, Office of Emergency Management, Department of Energy/National Nuclear Security Administration (DOE/NNSA)

Table 3-3 (continued). Definition of Acronyms Used in the Toxicity Assessment

ACRONYM	DEFINITION
Secondary MCL	National secondary drinking water regulation, controls contaminants in drinking water that primarily affect the aesthetic qualities relating to the public acceptance of drinking water.
SO_2	sulfur dioxide
SO_3	sulfur trioxide
TDS	total dissolved solids
TEELs	Temporary Emergency Exposure Limits, SCAPA
	The application of TEELs should be a comparison with the concentration at the receptor point of interest, calculated as the peak fifteen-minute time-weighted average concentration.
	TEELs are intended for use until Acute Exposure Guideline Levels (AEGLs), Emergency Response Planning Guidelines (ERPGs) are adopted for chemicals. With the exception of the recommended averaging time, TEELs 1, 2, and 3 have the same definitions as the equivalent ERPG.
TEEL-0	The threshold concentration below which most people will experience no appreciable risk of health effects.
TEEL-1	The maximum concentration in air below which it is believed nearly all individuals could be exposed without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odor.
TEEL-2	The maximum concentration in air below which it is believed nearly all individuals could be exposed without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action.
TEEL-3	The maximum concentration in air below which it is believed nearly all individuals could be exposed without experiencing or developing life-threatening health effects.
TLV	Threshold Limit Value
TWA	Time-weighted average
U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency

3.2 Toxicity Criteria Selection Process

All toxicity criteria were reviewed to develop a single streamlined set for use in assessing potential health effects associated with COPC releases associated with the carbon separation and sequestration processes. The toxicity criteria used in the risk assessment were selected for protection of human and ecological receptors, assuming that there may be either catastrophic, short-term releases or chronic, long-term releases of COPCs to the environmental media identified for each of the evaluated exposure scenarios. Each criterion was selected to be the most health protective criteria available for the evaluated receptors and exposure scenarios. It should be noted that although toxicity criteria were identified for all the COPCs and various exposure scenarios, quantitative risk evaluations were conducted only for exposures to CO_2 and H_2S.

3.3 Human Health Toxicity Criteria

Two main groups of human receptors could potentially be exposed to CO_2 and trace gas releases associated with the carbon separation and sequestration processes. One group consists of the workers at the power plant, during the power generation stage of the project. The other group consists of the general populace, including nearby residents and sensitive receptors, such as school children, surrounding the power plant and the injection site(s), including the sequestration plume area. Separate sets of health protective toxicity criteria were developed for each of these groups of receptors.

3.3.1 PLANT WORKERS

Industrial hygiene criteria have been developed to protect workers potentially exposed to released gases. Based on the potential release scenarios identified with the pre- and post-injection components of this project, two sets of toxicity criteria were identified for evaluating potential CO_2 and trace gas exposures of plant workers. One set of toxicity criteria was identified for short-term release scenarios consisting of the rupture of a carbon separation unit, gas compression unit, a pipeline or possibly wellhead equipment that could result in a rapid release of gases lasting in the range of minutes or hours (see Figure 2-18). The other set of toxicity criteria was identified for release scenarios where long-term releases could occur as a result of fugitive emissions from the carbon separation unit, gas compression unit, valves on plant units, pipeline corrosion, or from wellhead structures. Plant workers were not considered likely to be exposed to releases under post-injection conditions, since the plant is only anticipated to be in operation for 50 years.

Short-term inhalation exposures can be compared to three types of industrial hygiene criteria, including:

- Short-term exposure limits (STELs), a 15-minute time-weighted exposure that should not be exceeded at any time during a workday;
- Ceiling values that should not be exceeded at any time; and
- Immediately Dangerous to Life or Health (IDLH) air concentrations from which a worker could escape without injury or irreversible health effects in the event of the failure of respiratory protection equipment.

The short-term industrial hygiene criteria available for each of the COPCs are provided in Table 3-4. Also shown are the types of health effects that could occur when these criteria are exceeded.

Industrial hygiene criteria for evaluating long-term inhalation exposures are expressed as time-weighted daily average (TWA) concentrations (i.e., an average concentration that should not be exceeded during any 8-hour workshift of a 40-hour workweek). These criteria are variously described as reference exposure levels (RELs), permissible exposure limits (PELs), and threshold limit values (TLVs) as established by the National Institute for Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration (OSHA), and the American Conference of Governmental Industrial Hygienists (ACGIH). The most health protective of these long-term worker-protective criteria that have been established, regardless of source, for each COPC are shown in Table 3-4.

Table 3-4. Plant Worker Acute and Chronic Toxicity Criteria

Agency	Criteria Type	Exposure Time	Chemical	Units (parts per million by volume [ppmv])	Notes
Acute					
NIOSH	IDLH	30 minutes	CO_2	40,000	Immediately dangerous to life or health
NIOSH	NIOSH REL ST	15 minutes	CO_2	30,000	Asphyxiation, frostbite; Short-term exposure level
NIOSH	NIOSH IDLH	Maximum 30 minutes	CO	1,200	Immediately dangerous to life or health; frostbite
NIOSH	NIOSH REL C	Ceiling	CO	200	Ceiling
NIOSH	IDLH	30 minutes	H_2S	100	Immediately dangerous to life or health; based on acute inhalation toxicity data on lethal concentrations for humans [Henderson and Haggard 1943; Poda 1966; Yant 1930] and animals [Back et al. 1972; MacEwen and Vernot 1972; Tansey et al. 1981]
NIOSH	NIOSH REL C	10 minutes	H_2S	10	Ceiling
ACGIH	STEL		H_2S	15	Short-term exposure level
NIOSH	NIOSH IDLH	30 minutes maximum	SO_2	100	Immediately dangerous to life and health
NIOSH	NIOSH REL ST	15 minutes	SO_2	5	Irritation; Short-term exposure level
NIOSH	IDLH	30 minutes	Cyanide, hydrogen	50	Immediately dangerous to life or health, inhalation. Central nervous system (CNS), cardiovascular system (CVS), thyroid [asphyxia, lassitude, headache, confusion, nausea, vomiting, increased rate and depth of respiration or respiration slow and gasping; thyroid, blood changes
NIOSH	NIOSH REL ST	15 minutes	Cyanide, hydrogen	4.7	Short-term exposure level, skin. CNS, cardiovascular system, thyroid [asphyxia, lassitude, headache, confusion, nausea, vomiting, increased rate and depth of respiration or respiration slow and gasping; thyroid, blood changes
NIOSH	IDLH	30 minutes	Nitrogen dioxide	20	Immediately dangerous to life or health. Eyes, respiratory system, cardiovascular system (irritation eyes, nose, throat; cough, mucoid frothy sputum, decreased pulmonary function, chronic bronchitis, dyspnea; chest pain; pulmonary edema, cyanosis, tachypnea, tachycardia
NIOSH	NIOSH REL ST	15 minutes	Nitrogen dioxide	1	Short-term exposure level. Eyes, respiratory system, cardiovascular system (irritation eyes, nose, throat; cough, mucoid frothy sputum, decreased pulmonary function, chronic bronchitis, dyspnea; chest pain; pulmonary edema, cyanosis, tachypnea, tachycardia

Table 3-4 (continued). Plant Worker Acute and Chronic Toxicity Criteria

Agency	Criteria Type	Exposure Time	Chemical	Units- ppmv	Notes
OSHA	OSHA PEL C		Nitrogen dioxide	5	Ceiling. Eyes, respiratory system, cardiovascular system (irritation eyes, nose, throat; cough, mucoid frothy sputum, decreased pulmonary function, chronic bronchitis, dyspnea; chest pain; pulmonary edema, cyanosis, tachypnea, tachycardia
Chronic					
OSHA	OSHA PEL TWA	8 hr	CO_2	5,000	Time-weighted average. Headache, dizziness, restlessness, paresthesia; dyspnea (breathing difficulty); sweating, malaise (vague feeling of discomfort); increased heart rate, cardiac output, blood pressure; coma; asphyxia; convulsions; frostbite (liquid, dry ice)
ACGIH	TWA	8 hr	CO	25	Time-weighted average; BEI; anoxia, CVS, CNS, reproductive effects
					NIOSH Time-weighted average: Headache, tachypnea, nausea, lassitude (weakness, exhaustion), dizziness, confusion, hallucinations; cyanosis; depressed S-T segment of electrocardiogram, angina, syncope
ACGIH	TWA	8 hr	H_2S	10	Time-weighted average; irritation eyes, respiratory system; apnea, coma, convulsions; conjunctivitis, eye pain, lacrimation (discharge of tears), photophobia (abnormal visual intolerance to light), corneal vesiculation; dizziness, headache, lassitude (weakness, exhaustion), irritability, insomnia; gastrointestinal disturbance; liquid: frostbite
OSHA	OSHA PEL TWA	8 hr	SO_2	5	NIOSH Time-weighted average: Irritation eyes, nose, throat; rhinorrhea (discharge of thin mucus); choking, cough; reflex bronchoconstriction; liquid: frostbite
ACGIH	TWA	8 hr	CH_4	1,000	Time-weighted average (as aliphatic hydrocarbon [alkane, C_1-C_4] gases); CNS, depression, cardiac sensitization
OSHA	OSHA PEL TWA	8 hr	Cyanide, hydrogen	10	Time-weighted average, skin. CNS, cardiovascular system, thyroid [asphyxia, lassitude, headache, confusion, nausea, vomiting, increased rate and depth of respiration or respiration slow and gasping; thyroid, blood changes
ACGIH	TWA	8 hr	Nitrogen dioxide	3	Time-weighted average; irritation eyes, nose, throat; cough, mucoid frothy sputum, decreased pulmonary function, chronic bronchitis, dyspnea (breathing difficulty); chest pain; pulmonary edema, cyanosis, tachypnea, tachycardia

3.3.2 GENERAL POPULACE

The general population surrounding the power plant, CO_2 pipeline, injection site(s), and potentially located within the plume area could contain receptor groups more sensitive to CO_2 and trace gas releases than the power plant workers. In addition to a wide-range of age groups, from children to the elderly, the general population could contain hospitalized or otherwise medically challenged groups. For these reasons and to be health protective, the toxicity criteria established for the general populace are typically lower than those for industrial workers. The following describes the toxicity criteria used to characterize potential health effects due to releases of CO_2 and trace gas prior to and after geological post-sequestration.

3.3.2.1 Short-term Inhalation Exposures

As discussed above, short-term release scenarios during plant operations could consist of the rupture of a carbon separation unit, gas compression unit, a pipeline, or possibly wellhead equipment. These scenarios are likely to result in rapid releases of gases, lasting in the range of minutes to at most hours (see Table 3-3). Based on the available toxicity criteria, two sets of toxicity values were identified for evaluating potential CO_2 and trace gas exposures for either end of the range (i.e., minutes compared to a few hours). The toxicity criteria considered applicable for evaluating the potential health effects of these types of releases on the general populace are shown in Table 3-5 and Table 3-6.

In addition to identifying toxicity criteria appropriate for two separate short-term exposure durations, three levels of potential health effects were identified for each set of exposure durations. This approach follows the methodology used previously for evaluating CO_2 exposures from carbon sequestration sites (e.g., Saripalli et al., 2003), with effects levels classified as Low, Moderate, and Severe.

The three levels of effects are also generally consistent with acute exposure guideline levels (AEGLs) developed by the U.S. EPA and are used by US DOE and other agencies for evaluating emergency releases. Accordingly, regulatory-derived criteria, where available, were used to define concentrations for evaluating three levels of potential health effects from predicted gas exposures:

- Adverse - Maximum concentration without mild transient adverse health effects or possible perception of an objectionable odor;

- Irreversible Adverse - Maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action; and

- Life Threatening - Maximum concentration without life-threatening health effects.

Each of these three criteria is used to evaluate the severity of each short-term release that could potentially impact the general populace.

Table 3-5. Acute Toxicity Criteria 15-minute Exposure Duration

Agency	Criteria Type	Exposure Time	Chemical	Units-ppmv	Notes
US DOE - ESH	TEEL-1	15 minutes	CO_2	30,000	Maximum concentration without mild transient adverse health effects or possible perception of an objectionable odor.
USEPA (2000)	Maximum Exposure Limit	20 minutes	CO_2	30,000	3 percent; for healthy males under exercising conditions
USEPA (2000)		1 hour	CO_2	30,000	Mild headache, sweating, and dyspnea at rest; respiratory stimulant (i.e., increasing pulmonary ventilation, cardiac output, etc.)
US DOE - ESH	TEEL-2	15 minutes	CO_2	30,000	Maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action
US DOE - ESH	TEEL-3	15 minutes	CO_2	40,000	Maximum concentration without life-threatening health effects
USEPA (2000)	Maximum Exposure Limit	Less than 3 minutes.	CO_2	70,000	Unconsciousness; longer time or higher concentration (e.g., >100,000 ppmv) = death
US DOE - ESH	TEEL-1	15 minutes	CO	83	Mild transient adverse health effects or possible perception of an objectionable odor
US DOE - ESH	TEEL-2	15 minutes	CO	83	Maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action
US DOE - ESH	TEEL-3	15 minutes	CO	330	Maximum concentration without life-threatening health effects
US DOE - ESH	TEEL-1	15 minutes	H_2S	0.51	Mild transient adverse health effects or possible perception of an objectionable odor
US DOE - ESH	TEEL-2	15 minutes	H_2S	27	Maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action
US DOE - ESH	TEEL-3	15 minutes	H_2S	50	Maximum concentration without life-threatening health effects
US DOE - ESH	TEEL-1	15 minutes	SO_2	0.20	Maximum concentration without mild transient adverse health effects or possible perception of an objectionable odor
US DOE - ESH	TEEL-2	15 minutes	SO_2	0.75	Maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action
US DOE - ESH	TEEL-3	15 minutes	SO_2	27	Maximum concentration without life-threatening health effects
US DOE - ESH	TEEL-1	15 minutes	SO_3	0.60	Maximum concentration without mild transient adverse health effects or possible perception of an objectionable odor

Table 3-5 (continued). Acute Toxicity Criteria 15-minute Exposure Duration

Agency	Criteria Type	Exposure Time	Chemical	Units-ppmv	Notes
USEPA	AEGL 1	10 minutes	SO_3	0.06	Maximum concentration without mild transient adverse health effects or possible perception of an objectionable odor
US DOE - ESH	TEEL-2	15 minutes	SO_3	2.98	Maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action
US DOE - ESH	TEEL-3	15 minutes	SO_3	8.93	Maximum concentration without life-threatening health effects
US DOE - ESH	TEEL-1	15 minutes	CH_4	2,000	Maximum concentration without mild transient adverse health effects or possible perception of an objectionable odor
US DOE - ESH	TEEL-2	15 minutes	CH_4	5,000	Maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action
US DOE - ESH	TEEL-3	15 minutes	CH_4	25,000	Maximum concentration without life-threatening health effects
US DOE - ESH	TEEL-1	15 minutes	Cyanide, hydrogen	2	Maximum concentration without mild transient adverse health effects or possible perception of an objectionable odor
US DOE - ESH	TEEL-2	15 minutes	Cyanide, hydrogen	7.1	Maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action
US DOE - ESH	TEEL-3	15 minutes	Cyanide, hydrogen	15	Maximum concentration without life-threatening health effects
US DOE - ESH	TEEL-1	15 minutes	Nitrogen dioxide	0.5	Maximum concentration without mild transient adverse health effects or possible perception of an objectionable odor
US DOE - ESH	TEEL-2	15 minutes	Nitrogen dioxide	12.5	Maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action
US DOE - ESH	TEEL-3	15 minutes	Nitrogen dioxide	20	Maximum concentration without life-threatening health effects
AIHA	ERPG-1	1 hour	Mercury vapor	NA	Maximum concentration without mild transient adverse health effects or possible perception of an objectionable odor
AIHA	ERPG-2	1 hour	Mercury vapor	0.25	Maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action
AIHA	ERPG-3	1 hour	Mercury vapor	0.5	Maximum concentration without life-threatening health effects
Health Canada	ASTER	1 hr average	Nitrogen dioxide	<0.25	The results of clinical studies indicate that both normal and asthmatic subjects can experience detrimental respiratory effects when exposed for brief periods to concentrations of approximately 960 $\mu g/m^3$ (0.5 ppm). Applied a safety factor of 2.

Table 3-6. Acute Toxicity Criteria >3 hour Exposure Duration

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units-ppmv	Notes
USEPA (2000)	Maximum Exposure Limit		480 minutes	CO_2	15,000	1.5 percent; for healthy males under exercising conditions
USEPA (2000)	Headache, etc.	Acute	Several hours	CO_2	20,000	Headache, dyspnea upon mild exertion; possible respiratory stimulant
USEPA (2000)	Tremors	Acute	Several hours	CO_2	60,000	Tremors
USEPA (2000)	Maximum Exposure Limit	Acute	Less than 3 minutes.	CO_2	70,000	Unconsciousness; longer time or higher concentration (e.g., >100,000 ppmv) = death; AIHA [1971] reported that 100,000 ppm of CO_2 is the atmospheric concentration immediately dangerous to life. In addition, Hunter [1975] noted that exposure to 100,000 ppm for only a few minutes can cause loss of consciousness
USEPA	NAAQS	Primary	8 hr average	CO	9	Not to be exceeded more than once per year
USEPA	AEGL 2	Acute	8 hr	CO	27	Interim AEGL (6/11/01)
USEPA	AEGL 3	Acute	8 hr	CO	130	Interim AEGL (6/11/01)
ATSDR	MRL - inh. Acute	Acute	1-14 days	H_2S	0.2	Respiratory effect
USEPA	AEGL 1	Acute	8 hr	H_2S	0.33	Interim AEGL (9/10/02)
USEPA	AEGL 2	Acute	8 hr	H_2S	17	Interim AEGL (9/10/02)
USEPA	AEGL 3	Acute	8 hr	H_2S	31	Interim AEGL (9/10/02)
USEPA	NAAQS	Acute/Secondary	3-hour	Sulfur oxides	0.5	Not to be exceeded more than once per year
USEPA	NAAQS	Primary	24-hour	Sulfur oxides	0.14	Not to be exceeded more than once per year
USEPA	AEGL 1	Acute	8 hr	SO_2	0.2	Interim AEGL (10/25/04)
USEPA	AEGL 2	Acute	8 hr	SO_2	0.75	Interim AEGL (10/25/04)
USEPA	AEGL 3	Acute	8 hr	SO_2	16	Interim AEGL (10/25/04)
USEPA	AEGL 1	Acute	8 hr	SO_3	0.06	Proposed AEGL

Table 3-6 (continued). Acute Toxicity Criteria >3 hour Exposure Duration

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units-ppmv	Notes
USEPA	AEGL 2	Acute	8 hr	SO_3	2.6	Proposed AEGL
USEPA	AEGL 3	Acute	8 hr	SO_3	27.7	Proposed AEGL
USEPA	AEGL 1	Acute	8 hr	Cyanide, hydrogen	1	Final (2002) (nondisabling)
U EPA	AEGL 2	Acute	8 hr	Cyanide, hydrogen	2.5	Final (2002) (disabling)
USEPA	AEGL 3	Acute	8 hr	Cyanide, hydrogen	6.6	Final (2002) (lethal)
USEPA	AEGL 1	Acute	8 hr	Nitrogen dioxide	0.5	Interim (12/13/04) (nondisabling)
USEPA	AEGL 2	Acute	8 hr	Nitrogen dioxide	6.7	Interim (12/13/04) (disabling)
USEPA	AEGL 3	Acute	8 hr	Nitrogen dioxide	11	Interim (12/13/04) (lethal)

3.3.2.2 Long-term (chronic) Inhalation Exposures

Long-term, low levels of CO_2 and trace gas releases may occur during plant operations and from the sequestered gas reservoir. During pre-injection operations, long-term releases could occur as a result of fugitive emissions from the carbon separation unit, gas compression unit, valves on plant units, pipeline corrosion, or from a wellhead structure (see Figure 2-18). Long-term releases are the primary concern for post-injection conditions, including upward leakage through the caprock, release through faults or abandoned wells, and lateral or vertical leakage into non-target aquifers with eventual releases to the surface (Figure 2-18). In order to characterize the potential for adverse health effects from these long-term releases, toxicity values were identified for levels where there would be no health effects over a lifetime of exposure. These toxicity criteria are shown in Table 3-7 and include:

- National ambient air quality standards;
- Chronic effects levels developed by the U.S. EPA; and
- Indoor air quality criteria developed by Health Canada.

In addition to these criteria, for CO_2 exposures, toxicity criteria were identified that could be used to differentiate potentially low, moderate, or severe health effects (as done for previous carbon sequestration evaluations).

3.3.3 SURFACE WATER AND GROUNDWATER EXPOSURES

CO_2 and trace gas releases could potentially affect surface waters during pre- or post-injection conditions, as indicated in Figure 2-18. Groundwater may also be impacted during post-injection conditions due to lateral or vertical leakage into non-target aquifers. Consequently, toxicity criteria were also compiled in order to determine the potential human health effects from releases potentially affecting surface or ground waters. Water quality criteria were primarily obtained from U.S. EPA sources that have developed chronic water quality criteria and regulatory levels protective of human uses of water. In addition to direct health effects, criteria were also identified for determining potential aesthetic (e.g., taste and odors), acidity (i.e., pH), salinity (i.e., TDS), or corrosion effects that could reduce the value of waters used for potable, industrial, or irrigation purposes. Further, to address the potential for CO_2 or trace gases to displace or otherwise affect radon gas levels in groundwater, criteria were also identified for acceptable radon levels in groundwater. All of the potentially applicable water quality criteria are listed in Table 3-7.

Table 3-7. Chronic Toxicity Criteria Inhalation and Water Exposures

Agency	Criteria Type	Exposure Time	Chemical	Units	Notes
Air/Inhalation Exposure				PPMV	
Health Canada	ALTER	Long-term	CO_2	3,500	Indoor air guideline
Health Canada		Long-term	CO_2	7,000	The lowest concentration at which adverse health effects have been observed in humans is 12,600 mg/m^3 (7,000 ppm), at which level increased blood acidity has been observed after several weeks of continuous exposure
USEPA (2000)	Maximum Exposure Limit	Indefinite	CO_2	5,000	0.5 percent; for healthy males under exercising conditions
USEPA (2000)	Maximum Exposure Limit	Indefinite	CO_2	10,000	1 percent; for healthy males under exercising conditions
USEPA (2000)		Few minutes	CO_2	70,000 to 100,000	Unconsciousness
USEPA (2000)		1 to several minutes	CO_2	>100,000 to 150,000	dizziness, drowsiness, severe muscle twitching, unconsciousness
USEPA (2000)		1 to 2 minutes	CO_2	60,000	Headache, dyspnea; Hearing and visual disturbances
USEPA (2000)		Several hours	CO_2	60,000	Tremors
USEPA (2000)	Headache, dizziness, etc	Within a few minutes	CO_2	40,000 to 50,000	Headache, dizziness, increased blood pressure, uncomfortable dyspnea; possible respiratory stimulant
Saripalli et al. 2003	Low	Human	CO_2	10,000	human, discomfort
Saripalli et al. 2003	Moderate	Human	CO_2	50,000	human, injury
Saripalli et al. 2003	Severe	Human	CO_2	100,000	human, lethal
USEPA	NAAQS	8 hr average	CO	9	Not to be exceeded more than once per year
ATSDR	MRL - inh. Int	>14-365 days	H_2S	0.02	Respiratory effect
USEPA IRIS	RfC		H_2S	0.0014	Nasal lesions of the olfactory mucosa (7/28/2003)

Table 3-7 (continued). Chronic Toxicity Criteria Inhalation and Water Exposures

Agency	Criteria Type	Exposure Time	Chemical	Units	Notes
LEL	10 percent Explosive Limit		H_2S	4,000	
Health Canada	ALTER	8 hr average	SO_2	<0.019	Increased prevalence of acute and chronic respiratory symptoms and impaired pulmonary function
USEPA	NAAQS	Annual (Arith. Mean)	Sulfur oxides	0.03	
USEPA	NAAQS	24-hour	Sulfur oxides	0.14	Not to be exceeded more than once per year
ACGIH	TWA	8 hr	CH_4	1000	(as aliphatic hydrocarbon [alkane, C_1-C_4] gases); CNS, depression, cardiac sensitization
USEPA IRIS	RfC		Cyanide, hydrogen	0.0027	CNS symptoms and thyroid effects
LEL	10 percent Explosive Limit		Cyanide	5,600	5.60 percent
AIHA	ERPG-2	1 hour	Mercury vapor	0.25	
USEPA	NAAQS	Annual (Arith. Mean)	Nitrogen dioxide	0.053 ppm	(100 $\mu g/m^3$)
NAS (1999)	Action Level		Radon	4 pico Curies per liter (pCi/L)	The USEPA has set 4 pCi/L as the Action Level, the level at which residents should take steps to reduce radon levels. (NAS) National Academy of Sciences. Health Effects of Exposure to Radon: BEIR VI
Water Exposure				mg/L	
Saripalli et al. 2003	Severe		CO_2	>6 percent	Groundwater; acidity, well corrosion, irrigation loss
Saripalli et al. 2003	Moderate		CO_2	>2 percent	Groundwater; mild acidity and corrosion
Saripalli et al. 2003	Low		CO_2	>0.2 percent	Groundwater; elevated, low acidity without significant impacts
Saripalli et al. 2003	Normal		CO_2	10-4M or 0.2 percent	Groundwater

Table 3-7 (continued). Chronic Toxicity Criteria Inhalation and Water Exposures

Agency	Criteria Type	Exposure Time	Chemical	Units	Notes
Saripalli et al. 2003	Severe		CO_2	>2 percent	Surface water; acidity, CO_2 explosion, fish kills
Saripalli et al. 2003	Moderate		CO_2	>1 percent	Surface water; higher acidity, mild toxicity effect on irrigation
Saripalli et al. 2003	Low		CO_2	>0.022 percent	Surface water; elevated, low acidity with no significant impacts
Saripalli et al. 2003	Normal		CO_2	10-5M or 0.022 percent	Surface water
USEPA	Secondary MCL		H_2S	0.000029	Taste and Odor Threshold (National AWQC). Water-dilution odor threshold calculated from air odor threshold using equilibrium distributions
USEPA	MCL	Lifetime	Cyanide (as free cyanide)	0.2	Nerve damage or thyroid problems
USEPA	MCL	Lifetime	Mercury (inorganic)	0.002	Final 1987; kidney damage
USEPA	Health Advisory	Lifetime	Mercury (inorganic)	0.04	Final 1987
USEPA	Health Advisory	DWEL	Mercury (inorganic)	0.01	Final 1987
USEPA	Human health consumption	Lifetime	pH	5 to 9	Human health consumption of water + organism
USEPA	Secondary MCL	Lifetime	pH	6.5 to 8.5	Gold Book 1986; USEPA 2006
USEPA	Human health consumption	Lifetime	TDS	250	Human health consumption of water + organism; for solids dissolved and salinity (originally in Red Book; same criterion in Gold Book, USEPA 1986)
USEPA	Secondary MCL		TDS	500	Final; 2006
USEPA	MCLG		Radon	300 pCi/L	300 pico Curies per liter
USEPA	AMCL		Radon	4,000 pCi/L	Alternative Maximum Contaminant Level
USEPA	Drinking Water Health Advisory		Radon	150 pCi/L	at cancer risk of 1×10^{-6} (one in a million)

3.4 Ecological Reference Toxicity Values

Biological receptors present in the environment around the plant, pipeline, and sequestered gas plume sites may also be exposed to CO_2 and trace gases released during plant operation and under post-injection conditions. Effects on biota could occur as a result of gaseous releases to the atmosphere, to surface waters, and through upward leakage of sequestered gases to surface soils. Accordingly, reference toxicity values (TRVs) were also identified to aid in determining potential effects to biota from atmospheric, surface water, and soil exposures (Table 3-8).

Criteria protective of biota exposures to airborne gases were identified for both physiological and behavioral effects. Levels were identified for respiratory effects of atmospherically dispersed gases on animals, including insects, and plants. For plants, the effects also include levels at which there could be increased growth and biomass. Behavioral effects were identified for olfactory sensation leading to changes in insect locomotion, social and prey location, and searching behavior. The criteria for these effects are shown in Table 3-8.

Biological receptors, such as fish, could be exposed to gas releases into surface waters, either directly through a pipeline rupture or discharge of groundwater from a non-target aquifer affected by leakage from sequestered gases. The impacts to biota in these surface waters could include both toxic and physical effects. The criteria identified for evaluating these effects are shown in Table 3-8 and include continuous concentration criteria protective of aquatic biota as well as the range of CO_2 effects identified by Saripalli et al. (2003) on aquatic biota. The normal levels of CO_2 in water are also shown for comparison purposes.

The upward leakage of sequestered gases could eventually reach the surface. As a consequence, biota could be exposed to gases in soils prior to release to the atmosphere. The effects of gases on animals and plants in soils, including the effects of changes in soil acidity on plants are shown in Table 3-8.

Table 3-8. Chronic Toxicity Criteria Biota- Surface Water and Soil Exposures

Criteria Type	Timeframe	Chemical	Units-ppmv	Units-other	Notes
Threshold, animals		CO_2	>1,000		All animals, respiratory stimulation
Threshold, animals		CO_2	>50,000		All animals, respiratory poisoning
Threshold, fungi		CO_2	>10,000		Abnormal growth and reduced reproductive fitness
Threshold, plants		CO_2	>700		Variable increases and decreases in plant respiration
Threshold, plants		CO_2	>380		Increased growth, biomass, reduced carbon to nitrogen ratios in biomass
Threshold, insects		CO_2	>10,000		Regulation of spiracle aperture
Behavioral, insects		CO_2	10 to 500		Olfactory sensation/activation (mosquitoes, ticks, fire bugs, tsetse flies); changes in CO_2 result in signaling of responses including locomotion, social location, prey location, and flight or searching behavior
Behavioral, insects		CO_2	1,000		Olfactory sensation/locomotion (mosquitoes, ticks, fire bugs, tsetse flies)
Behavioral, insects		CO_2	5,000		Olfactory sensation (ants, bees, termites)
Behavioral, insects		CO_2	5,000		Olfactory sensation (beetles, nematodes)
Behavioral, insects		CO_2	0.5 to 300		Olfactory sensation (moths, butterflies)
Severe	Chronic-Biota	CO_2		>4 percent	Aquatic biota, O_2 depletion, lethal
Moderate	Chronic-Biota	CO_2		>2 percent	Aquatic biota, Injure life functions
Low	Chronic-Biota	CO_2		>0.5 percent	Aquatic biota, Mild toxicity
Normal	Normal, biota	CO_2		0.022 percent	Normal for aquatic biota (10-5M)
Freshwater CCC	Chronic	Cyanide		5.2 g (CN)/L	g free cyanide (as CN/L) (EPA-820-B-96-001, September 1996). Does not account for uptake via the food chain
Freshwater CCC	Chronic	H_2S	0.002		Unassociated H_2S for fish and other aquatic life
Freshwater CCC	Chronic	Mercury	0.000012		EPA 440/5-84-026, January 1985; protective of bioaccumulative impacts
Freshwater CCC	Chronic	pH		6.5 to 9	U.S. EPA "Gold Book" 1986
Severe	Chronic	CO_2		>8 percent	Low pH, tree kills, animal deaths
Moderate	Chronic	CO_2		>3 percent	Moderate acidity, tree/crop/soil cover loss

Table 3-8 (continued). Chronic Toxicity Criteria Biota- Surface Water and Soil Exposures

Criteria Type	Timeframe	Chemical	Units ppmv	Units-other	Notes
Low	Chronic	CO_2		>2 percent	Mild suppression in pH with no significant impacts
Normal	Normal	CO_2		1-2 percent	Normal concentration
Harmful, plants		CO_2		> 5 percent	Root asphyxiation in the root zone
Phytotoxic		CO_2		> 20 percent	Root asphyxiation in the root zone

4.0 PRE-INJECTION RISK ASSESSMENT

4.1 Conceptual Plant Design and Assumptions

4.1.1 OVERVIEW OF FUTUREGEN PLANT

A conceptualization of the plant and aboveground facilities for separating, compressing and transporting CO_2 to the injection site was used to determine where releases could occur. For each possible type of release, estimates were developed for release probabilities, volumes, and the chemical concentrations of the released substances for the aboveground engineered system. In the absence of a specific preliminary design at this stage, a schematic of the major process units of the FutureGen Project has been developed from existing information (Figure 4-1). This served as a starting point for estimating types of releases.

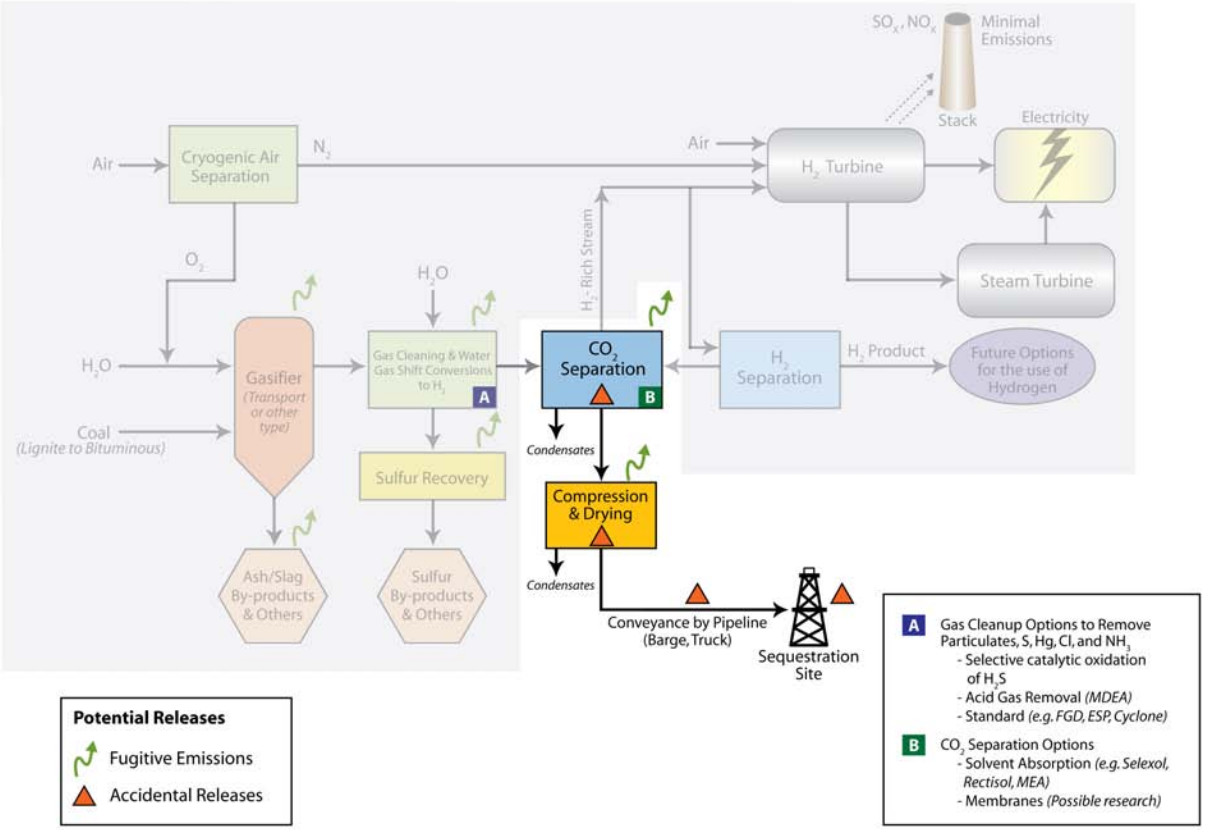


Figure 4-1. Schematic of FutureGen Project Coal-fueled IGCC Plant with Products and Potential Releases

(Based on U.S. DOE, Office of Fossil Energy, 2004 and updated in 2006). Process elements that are screened out will not be considered in this risk assessment. Locations of accidental releases are shown with the orange triangles.

At the core of the FutureGen Project will be an advanced coal gasifier, although the specific type of gasifier has not yet been selected. Rather than burning coal directly, gasification breaks down coal into its basic chemical constituents. The raw gas from the gasifier is composed of predominantly CO, hydrogen (H_2), CO_2, water vapor, and CH_4. The next step is to enrich the concentration of hydrogen gas using a catalyzed shift gas reaction which produces H_2 from CO and steam. Next, H_2S and CO_2 are removed using glycol adsorption. The H_2S is then converted to elemental sulfur in a Claus furnace. The furnace oxidizes 1/3 of the H_2S to SO_2. The SO_2 then reacts with the remaining H_2S in downstream catalytic converters to produce elemental sulfur. The CO_2 is compressed and sent to injection well(s) by pipeline for subsurface injection and sequestration. The overall process yields CO_2 with traces of other gases (e.g., H_2S) and hydrogen-rich gas for use in gas turbines to produce electricity or to serve as hydrogen fuel for transportation. Excess heat will be converted to steam to generate additional electricity. The separated CO_2 may contain other compounds besides H_2S (see Section 2.4).

4.1.2 CARBON SEPARATION AND COMPRESSION UNITS

Fugitive emissions from the carbon separation unit and the CO_2 compressor at the plant have not been provided in the preliminary design information provided for use by the FutureGen team. The compressor unit is planned to be located at the plant site based on the available information.

4.1.3 PIPELINE CHARACTERISTICS

Transport of the captured gas stream to a location for injection underground is planned to occur via pipeline, as shown conceptually in Figure 4-1. The distance of transport, the size of the pipeline, and the belowground placement of the pipeline is based on information available from the final EIV. The distance of transport from the plant site to the injection point varies from less than 1 to 61.5 miles (1.6 to 99 kilometers) for the four candidate sites as shown in Table 4-1. The pipelines from the plant to the injection site(s) are expected to be buried to a typical depth of 3.3 feet (1 meter) (IPCC, 2005). Any pipeline releases are expected to discharge to the atmosphere. Maps showing the location of the plant and injection sites are provided in Section 2.

Table 4-1. Pipeline Dimensions and Conditions

Parameter	Jewett	Odessa	Mattoon	Tuscola
Pipeline Inner Diameter, inches (centimeters)	19.3 (49)	12.8 (32.5)	***14.4 (36.7)***	***14.4 (36.7)***
Pipeline Temperature, °F (°C)	95 (35)	95 (35)	95 (35)	95 (35)
Pipeline Pressure, psi	2,200	2,200	2,200	2,200
Distance to Injection Wells, miles (kilometers)	Woodbine 52-59 (84-95); Travis Peak 52 (84)	61.5 (99)	0.5 (0.8)	11 (18)

The above information is from the final EIV.

4.1.4 CAPTURED GAS FROM PLANT: VOLUME AND COMPOSITION

The composition of the captured gas was provided in the EIV for use by the FutureGen team. As shown in Table 4-2, the percent of CO_2, H_2S, and nitrogen in the captured gas were provided.

Risks were estimated for assumed releases of CO_2 and H_2S at the concentration ratio shown above in Table 4-2. The composition of the gas at the Odessa Site may differ, since the gas may be delivered to an existing commercial CO_2 pipeline that serves EOR projects. No specific information on the expected composition was available, although it may have a H_2S concentration of less than100 ppmv. A co-sequestration experiment is being evaluated for the FutureGen plant configuration where the H_2S and CO_2 are removed together and injected for seven days. For this case, the H_2S content of the gas has been assumed to be 2 percent by weight. Information on other compounds that may be present in the gas such as CH_4, CO, mercury, cyanide, SO_X, and NO_X (see Section 2.4) are addressed in the EIS. At another carbon sequestration site, CH_4 in the captured gas was 0.3 to 0.7 percent and CO was 0.1 percent (IPCC, 2005).

Table 4-2. Captured Gas Characteristics and Composition

Parameter	Captured Gas
Pressure, psi	2,200
Temperature, ^{o}F (^{o}C)	95 (35)
CO_2, percent	95
H_2S, percent	0.01
Nitrogen, percent	<0.5
Moisture, ppmv	100 (maximum)

4.2 Overview of Risk Assessment Approach

The risk assessment approach for the pre-injection components is based on qualitative and quantitative estimates of gas releases from aboveground sources under different failure scenarios. Failures of the engineered system can include catastrophic events, leakage, and fugitive releases of captured gases. The transport of the released gas in the air was estimated through modeling, as explained in Section 4.4. The predicted concentrations in air were used to estimate the potential for exposure and any resulting impacts on human receptors, which were considered to also be protective of ecological receptors. The steps involved in conducting the risk assessment are shown schematically in Figure 2-3. The primary release mechanisms, such as releases to air, can lead to direct exposures to humans or ecological receptors inhaling the released gases, or can be responsible for secondary releases to other media, such as discharge to surface water or soil. These secondary releases can then produce exposures of aquatic receptors in nearby surface waters or plants via uptake from soil. The potential for possible adverse ecological or human health effects is also examined for the case of direct releases of gases to surface waters, such as pipeline discharge into a stream. The effects of exposures for both human and ecological receptors are then evaluated and risk estimates provided. The time frame of the pre-injection risk assessment includes the entire pilot and operational periods of CO_2 capture at the plant to plant closure (estimated to be 50 years).

4.2.1 RELEASE SCENARIOS

Releases may occur from the FutureGen Power Plant itself (if any of its proposed components related to gas capture shown in Figure 4-1 fail), from the pipeline, and from the injection wellhead(s). Areas of potential releases in the plant are indicated on the facility conceptual diagram in Figure 4-1 using orange triangles for failures and green arrows for fugitive emissions. Only releases related to CO_2 sequestration are considered in this risk assessment; the other plant components are evaluated in the EIS.

Potential releases from the FutureGen Project and associated pipelines considered in the pre-injection risk assessment are listed in Table 4-3. For each release scenario included in this table, information is provided on the release mechanism, estimated duration of the release, initial exposed media and receptors, and secondary media that could be affected by migration of gases from the initial release to another location or to a different media. Receptors that could be affected by these secondary releases are also listed in the table. The types of releases considered include:

- Fugitive emissions from the carbon separation and compressor units
- Rupture of the carbon separation and compressor units
- Rupture of the captured gas pipeline within the plant boundary or between the boundary and the injection site

- Leakage of captured gas from the pipeline within the plant boundary or between the boundary and the injection site
- Failure of wellhead injection equipment causing release of gas in wellbore
- Fugitive emissions from wellhead injection equipment

For each release scenario, the volume and mass of gas released has been estimated as discussed in Section 4.4. The accidental rupture of the carbon sequestration and compressor unit is addressed in the plant risk assessment (Quest, 2006). Fugitive emissions and leaks from this unit are considerably less than the pipeline rupture case based on using 1 percent of the CO_2 volume released during a trip event of this unit (Battelle, 2006), so releases from this unit are not reported separately in the risk result tables discussed in Section 4.5. Pipeline length, distance between emergency shutdown valves, diameter, and temperature and pressure of gas present in the pipeline have been used to compute the volume of captured gas that may be accidentally released. Information on the diameter and length of the injection wells was provided in the EIV and used to estimate the volumes of gas released from the aboveground injection equipment. The estimated volumes of key release scenarios were used as input to models to predict concentrations in air from these releases, as discussed in Section 4.4. The results of the modeling effort are discussed in Section 4.5.

4.2.2 FREQUENCY OF FAILURE OF ABOVEGROUND ENGINEERED SYSTEMS

Failure rates for the key release scenarios that were simulated were estimated from historical operational data where available 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. DOE chose to categorize the two accidents with the largest CO_2 releases (4000 barrels and 7408 barrels) as rupture type releases, and the next four highest releases (772 barrels to 3600 barrels) as puncture type releases. For comparison, five miles of FutureGen pipeline contains about 6500 barrels, depending on the pipeline diameter. Assuming the total length of pipeline involved was approximately 1,616 miles (2,600 kilometers) based on data in Gale and Davison (2004), the rupture and puncture failure frequencies were calculated to be 9.55×10^{-5}/miles-year (5.92×10^{-5}/[kilometer-year]) and 1.9×10^{-5}/miles-year (1.18×10^{-4}/[kilometer-year]), respectively.

The failure rate of an injection well during operation is estimated as 2.02×10^{-5} per well per year based on experience with natural gas injection wells from an IEA GHG Study (Papanikolau et al., 2006). The estimated incidence of failure at each site based on the length of pipeline at each site and the number of injection wells and the possible number of incidents over the estimated 50-year operational period are shown in Table 4-4.

Table 4-3. Release Scenarios for Pre-Injection Risk Assessment

Release Mechanism and Location	Exposure Duration	Initial Exposed Media	Initial Potential Receptors	Secondary Exposure Media	Later Potential Receptors
Fugitive emissions from carbon separation unit	Low release rate due to small leaks	Air	Plant workers	None	None
Rupture of carbon separation unit	Few minutes for unit to empty	Air	Nearby plant workers	Floor of plant building*	None, unless air control system fails
Fugitive emissions from gas compression unit	Low release rate due to small leaks	Air	Plant workers	None	None
Rupture of gas compression unit	Few minutes for unit to empty	Air	Nearby plant workers	Floor of plant building*	None, unless air control system fails
Fugitive emissions from valves on plant units	Low release rate due to small leaks	Air	Plant workers	None	None
Pipeline failure after compression unit, but still on plant site	Continuous until gas is shut-off, or few minutes needed for pipeline section to empty	Air	Nearby plant workers	Soil	Off-site residents depending on air modeling results
Pipeline failure between plant site and injection site	Few minutes needed for pipeline section to empty in-between safety shutoff values located every 5 miles	Air and Soil	Offsite people, if present; Ecological exposure route in soil	Air and Surface Water	Ecological exposure route in surface water, if nearby Plant workers and off-site residents depending on air modeling results
Pipeline puncture between plant site and injection site	Few hours for gas to escape out of small leak	Air and Soil	Offsite people, if present; Ecological exposure route in soil	Air and Surface Water	Ecological exposure route in surface water, if nearby Plant workers and off-site residents depending on air modeling results

Table 4-3 (continued). Release Scenarios for Pre-Injection Risk Assessment

Release Mechanism and Location	Exposure Duration	Initial Exposed Media	Initial Potential Receptors	Secondary Exposure Media	Later Potential Receptors
Pipeline puncture of buried section between plant site and injection site when ground is frozen or upward gas migration is inhibited (may not be possible or likely at all sites)	Few hours for gas to escape out of small leak	Air and Soil	Offsite people, if present; Ecological exposure route in soil	Air and Groundwater	Plant workers and off-site residents depending on air modeling results Offsite residents if drink groundwater Ecological exposure route in surface water, if groundwater discharges to surface water
Pipeline puncture in section under or near surface water (may not be possible or likely at all sites)	Few hours for gas to escape out of small leak	Surface Water and Air	Offsite people, if present; Ecological exposure route in surface water	Surface Water and Groundwater	Ecological exposure route in surface water Human users of surface water: recreational and/or potable If recharge to groundwater, then human users if potable
Rupture of aboveground equipment at wellhead injection site	Few minutes needed for wellbore and aboveground equipment to empty	Air and Soil	Nearby plant workers, if present	Air	Plant workers and off-site residents depending on air modeling results Ecological exposure route in soil
Fugitive emissions from aboveground equipment at wellhead injection site	Low release rate due to small leaks	Air	Nearby plant workers, if present	None	None

*Plant units are proposed to be contained inside a structure; details of construction are not known at this time.

Table 4-4. Failure Rate Frequencies for Pipelines and Injection Wells

Parameter	Jewett		Odessa	Mattoon	Tuscola
	Woodbine	Travis Peak			
Pipeline Length, miles (kilometers)	59 (95)	52 (84)	61.5 (99)	0.5 (0.8)	11 (18)
Frequency of Failure by Rupture per year*	0.0056	0.0050	0.0059	0.00005	0.0011
Probability of at least one failure by rupture over lifetime	0.24	0.22	0.25	0.002	0.05
Frequency of Failure by Puncture per year*	0.0112	0.0099	0.0117	0.00009	0.0021
Probability of at least one failure by puncture over lifetime	0.43	0.39	0.48	0.005	0.10
Number of Injection Wells	2	1	10	1	1
Frequency of Failure per year**	4.04E-05	2.02E-05	2.02E-04	2.02E-05	2.02E-05
Probability of at least one failure by puncture over lifetime	2.02E-03	1.01E-03	1.01E-02	1.01E-03	1.01E-03

*Based on estimated pipeline rupture rate of 5.92×10^{-5} and puncture rate of 1.18×10^{-4} failures per kilometer of pipe per year from the Office of Pipeline Safety on-line library (http://ops.dot.gov/stats/IA98.htm).

**Based on estimated injection well failure rate of 2.02×10^{-5} per well per year (Papanikolau et al., 2006).

The estimated probabilities that key release scenarios could occur at each site are discussed in Section 6 of this report.

4.3 Exposure Analysis

Potential human receptor groups that could be affected by releases from the FutureGen plant include plant workers, railroad workers, other onsite workers such as administrative staff, material or equipment suppliers, plant visitors, and offsite residents or other members of the general populace.

4.3.1 HUMAN RECEPTOR GROUPS LIKELY TO BE EXPOSED

4.3.1.1 Onsite Workers

The FutureGen plant will occupy a 62-acre (25-hectare) or 75-acre (30-hectare) footprint (Quest, 2006). There is expected to be a buffer of about 600 feet around the plant footprint out to the property boundary, which encompasses at least 200 acres (81 hectares). The actual area of the plant sites is provided in Section 2. The total number of workers at the plant under operating conditions is estimated to be 200 people, although since there are work shifts all the workers would not be present at the same time (DOE EIS, 2007).

4.3.1.2 Offsite Populations

Offsite populations may be affected by releases to the atmosphere from fugitive emissions from the process units, pipeline punctures or ruptures, and leaks or rupture of the aboveground equipment at the injection site. Maps showing the nearest towns and population density are presented and discussed in Section 2. Sensitive human receptors such as schools, hospitals, and prisons are also shown on these maps. Except for the Mattoon Site, the injection site is located away from the plant site, as listed in Table

4-1. Thus, more offsite populations could potentially be affected at those other sites, since there is more than one area.

The Jewett plant site is located north of the town of Jewett at the juncture of Leon, Limestone, and Freestone counties There are eight small towns located in the vicinity of the proposed pipeline route and sequestration sites, including Turlington, Lanely, Plum Creek, Red Lake, Butler, Sand Hill, Massey Lake, and Harmony. There are two possible injection sites, located 52 and 59 miles (84 and 95 kilometers) away from the plant site. One injection site (52 miles (84 kilometers) away) would have two injection wells that would inject into different formations, the Woodbine and the Travis Peak (see Section 2). Because the Travis Peak Formation is deeper, a recompressor pump would be needed at the injection well being used to inject captured gas into this formation. Four water production wells would also need to be installed around the injection well to extract water from the Travis Peak formation. The furthest injection well to the Woodbine Formation and part of the pipeline to this well are located within the Coffield State Prison Farm; the well is near one of the prisons. Five prison units with approximately 4,115 prisoners are also located in the vicinity of the injection sites (DOE, 2007). There is one school next to the pipeline and several additional schools within 5 miles (8 kilometers) of the CO_2 pipeline corridor. Interstate Highway 45 and several state highways cross the pipeline corridor, while one of the state highways crosses a corner of one of the injection sites. There are a large number of oil and gas production and exploration wells in the vicinity of the sequestration plume footprint, as shown in Figure 2-8.

The Odessa plant site is located about 15 miles (24 kilometers) west of the city of Odessa, TX. A populated area around West Odessa is located about 5 miles (8 kilometers) east of the plant site. There are two schools about 9 miles (14 kilometers) from the plant site. The injection site area is located about 58 miles (93 kilometers) south of the plant site, but the pipeline to the 10 injection wells would be longer. Fort Stockton is about ***13*** miles (***21*** kilometers) west of the injection site, although there may be a shorter distance between the nearest of the 10 injection wells and the town, depending on the exact location of the wells. There are existing oil and gas wells in the vicinity if the injection wells, as shown in Figure 2-11. The town of Imperial and a school are located about 6 miles (10 kilometers) from the CO_2 pipeline corridor. Interstate Highways 10 and 20 and several state highways cross the pipeline corridor. Interstate Highway 10 and two state highways also cross the estimated 50-year sequestration plume footprint.

The Mattoon plant site is about one mile northwest from the town of Mattoon, IL. The injection site is planned to be located in the center of the 444-acre (180-hectare) property. The edge of the estimated 50-year sequestration plume is about 0.5 miles (0.8 kilometers) from the edge of the populated land around the site. The land surrounding the plant site is farmland; there are isolated farm houses within the estimated 50-year sequestration plume footprint. Highway 121 crosses the estimated plume footprint. A school and nursing home are located about 2 miles (3 kilometers) southeast of the plant site.

The Tuscola plant site is about 2 miles (3 kilometers) west from the town of Tuscola, IL. A total of 16 schools and three nursing homes are located within a 10-mile (16-kilometer) radius of the plant site and pipeline. The injection site is located 11 miles (18 kilometers) away from the plant site. The estimated 50-year sequestration plume footprint is about 1 mile (1.6 kilometers) from the town of Arcola. A nursing home and school are located a little more than one mile (1.6 kilometers) away from the edge of the estimated plume. A total of 12 schools and two nursing homes are located within a (10-mile) 16-kilometer radius of the sequestration site. Interstate Highway 57 is located about 2 miles (3.2 kilometers) east of the CO_2 pipeline corridor and runs in an approximately parallel north-south direction.

4.3.2 ECOLOGICAL RECEPTOR GROUPS LIKELY TO BE EXPOSED

Ecological receptor groups have been considered that could be affected by releases to the atmosphere, soil, and at some sites to surface water and ground water.

4.3.2.1 Plant Site

The plant site will become an industrial area after construction of the FutureGen Project. As discussed in Section 4.2.1, the plant facilities will extend over about 62 to 75 acres (25 to 30 hectares), which will be enclosed by a railroad track loop (Quest, 2006). Soil inside this loop will likely be disturbed during construction. Small mammals, soil invertebrates, and insects may be present after construction. The coal pile for a 15-day supply is expected to be stored outside the loop inside an enclosed structure somewhere on the plant property. While the specific species of biota may be different among the sites, because of differences in soil type and vegetation, the general types of biota are likely to be similar on the developed plant site.

4.3.2.2 Pipeline Corridors and Injection Sites

The potential ecological receptor groups near the pipeline and injection sites are discussed separately for each site. A summary of the land use and environmental setting for each of the sites is presented in Section 2 along with maps of each site.

The Jewett plant site has an operating lignite mine on the property. The area surrounding the Jewett plant has four intermittent creeks with small wetlands. Lake Limestone is located about 3 miles (5 kilometers) west of the plant site, and Fairfield Lake is located about 4 miles (6 kilometers) west of the northern part of the pipeline. The CO_2 pipeline corridor crosses several creeks, and the pipeline to the furthest injection site crosses the Trinity River. No endangered aquatic species are known to be present in the pipeline corridor or the injection site. However, there are federally protected terrestrial species such as bald eagles that frequent this general area. The land overlying the 50-year sequestration plume footprint at Jewett (TX) is characterized by open woodlands and savannah ecological habitats and is transected by the Trinity River. The northern portion of the proposed sequestration area has perennial streams and ponds, and is traversed by the Trinity River and its floodplain. Many ephemeral streams occur in this region and fast-growing, opportunistic macrophytes should be expected when flow is present. Permanent creeks, small wetlands, and riverine habitat are also found in the area. Because there are no federally listed species known to occur in the land area above the proposed sequestration reservoir, no critical habitat has been designated by the FWS (see Section 2.5.1).

Most of the land surrounding the Odessa plant site is primarily rangeland with habitat ranging from desert valleys and plateaus to wooded mountain slopes. The Odessa plant site has no wetlands, but both the pipeline corridor and the injection site have wetlands. Some of these wetlands are ephemeral, and form pools following heavy rains. The CO_2 pipeline also crosses the Pecos River, located about 30 miles (48 kilometers) south of the plant site. The land overlying the 50-year sequestration plume footprint at Odessa (TX) is characterized by diverse habitats and vegetation. National Wetland Inventory maps indicate Sixshooter Draw, Monument Draw, Tunas Creek, and several on-channel impoundments as wetland areas potentially subject to Section 404 jurisdiction within the land area above the proposed sequestration reservoir. No known federal or state-listed species are known to be present in the pipeline corridor or the injection site. The endangered pupfish in spring-fed habitats exists well to the north of the planned pipeline. Endangered birds such as bald eagles, peregrine falcons, and whooping cranes may visit the area on a transient basis (see Section 2.5.2).

The land surrounding the Mattoon plant site and overlying the 50-year sequestration plume footprint is mostly farmland where corn and soybeans are grown. About 18 small wetlands have been identified, and several small streams and lakes are present. Healthy aquatic macroinvertebrates and biotic communities are expected in these waterbodies and wetlands. The threatened Eastern Sand Darter may be present, in addition to an endangered Indiana Bat, which lives in caves and mines in the winter in Coles County and in trees in the summer (see Section 2.5.3).

The land surrounding the Tuscola plant site is part industrial and part agricultural. Crops grown are mostly corn and soybeans. About 19 small wetland areas have been identified near the plant and pipeline corridor, comprising a total of 6 to 8 acres (2 to 3 hectares). Scattering Fork Creek is located about 1 mile (1.6 kilometers) east of the plant, which drains into the Embarras River. There are no listed aquatic endangered species. The land overlying the 50-year sequestration plume footprint at Tuscola (IL) is mostly agricultural. Above the sequestration site, no federal or state-listed species are known for those areas. Also, no areas of sensitive or critical habitat for any listed species are known for this area. Aquatic habitat above the sequestration reservoir is limited to a small section of the Kaskaskia River, the adjacent floodplain, and several intermittent drainage ways. The endangered Indiana bat *(Myotis sodalis)* may also be present within the wooded riparian habitat along the rivers or tributaries. This species occupies caves and abandoned mines during the winter. During the remainder of the year, Indiana bats utilize trees with rough or exfoliating bark and/or cavities for roosting (see Section 2.5.4).

4.3.3 EXPOSURE Scenarios

4.3.3.1 Exposure Media

The release scenarios for the pre-injection cases are described in Table 4-3. For most pre-injection scenarios, the primary exposure medium that humans can be exposed to is air. Prior to injection, gas releases could occur from plant equipment, including compression units, or pipelines transporting gases to injection locations, or equipment at the injection sites (e.g., wellheads). The gases will primarily be released to the atmosphere prior to injection. The released gas is likely to be heavier than air.

Gases released to the atmosphere can be transported by wind. These gases in the air may then be inhaled by nearby populations, such as residents or other sensitive receptors, and workers at the plant. It is assumed that for the case of releases to the atmosphere, assessing the potential adverse health effects for human inhalation exposures will be protective of other biota. Therefore, the potential impacts of atmospheric releases focus primarily on human exposures in this report.

Punctures or rupture of the captured gas pipeline would also cause the gas to enter the soil matrix where it would displace the ambient soil gas. If a pipeline puncture or break occurs in a section under a stream or river crossing, then gas could also discharge into surface water. Depending on the relationship between the surface water and groundwater, the contaminated surface water could infiltrate into the groundwater.

4.3.3.2 Exposure Parameters

The durations of the possible releases are included in the description of the release scenarios (see Table 4-3). Estimation of the release volumes are discussed in Section 4.4.1 for pipelines and in Section 4.4.2.2 for wellhead ruptures. These release volumes and durations are then entered into air transport models to estimate the potential levels of gases that workers or offsite residents could be exposed to. The use of air models is discussed in Section 4.4. Toxicity criteria for short-term exposures (e.g., 15 minutes and 8-hours) and long-term, chronic exposure, described in Section 3, were compared to the release-related concentrations of CO_2 and H_2S.

4.4 Exposure Models

A variety of tools can be used to predict the range of atmospheric transport of a given mass or volume of released gas from the plant, pipeline, or wellhead. This includes relatively simple spreadsheet calculations as well as detailed mechanistic models of air dispersion. The preference is to use standard detailed mechanistic models for air dispersion that are used by federal regulatory agencies to estimate the transport distances and resulting concentration of released gases under different meteorological conditions. When appropriate, the models of interest must be able to simulate the three transport phases for denser-than-air gas releases. These models should simulate the physics due to the initial phase of high momentum and air entrainment release processes occurring during the jetting from a puncture or rupture, then the second phase dominated by gravity spreading and reduced turbulent mixing effects acting on the resultant plume, and the final stage of transport governed by the passive effects of atmospheric advection and turbulent diffusion processes (i.e., Gaussian dispersion). Simple cases will also be considered in which gas releases are small enough that only the third phase of passive dispersion needs to be simulated.

The SLAB model was developed by the Lawrence Livermore National Laboratory, and is designed to simulate denser-than-air gas releases for both horizontal jet and vertically elevated jet scenarios. SLAB is approved by U.S. EPA as a hazardous air dispersion model. AERMOD is another model that deserves mention because it was approved for use at the end of 2005 by the U.S. EPA for dispersion modeling, although it cannot allow for denser-than-air gas releases, and for the given problem, can only be applied under certain limiting conditions (i.e., small releases). Its corresponding screening model, called AERScreen, is still in beta testing. Use of this U.S. EPA-approved model for air dispersion is desired but may not be generally applicable to the problem being modeled. It was also not used due to its increased data requirements. Instead, U.S. EPA's existing screening model, called SCREEN3, is used.

The state of the contained captured gas prior to release is important with respect to temperature, pressure, and the presence of other constituents. Release of CO_2 under pressure would likely cause rapid expansion and then reduction in temperature and pressure, which can result in formation of solid-phase CO_2, as explained in Appendix C-III. The estimated quantity of solid-phase formed is 26 percent of the volume released; therefore 74 percent of the volume released from a pipeline rupture or puncture was used as input to the SLAB model for computing atmospheric releases of CO_2 and H_2S. CO_2 is heavier than air and subsequent atmospheric transport and dispersion can be substantially affected by the temperature and density state of the initially released CO_2. The meteorological conditions at the time of the release would also affect the behavior and potential hazard of such a release. Conditions of low wind speed and ground-based inversion conditions at night with fog would be especially hazardous. In areas with significant terrain, cold air drainage at night under such conditions would add to the severity of these conditions under which release of significant CO_2 experiencing rapid expansion would lead to heavier-than-air flows, acidified by the presence of water vapor and droplets in the surrounding air. This meteorological condition is labeled F2, where F is the Pasquill stability class for stable atmospheric conditions with light winds of 2 meters per second (Turner, 1994). On the other hand, meteorological conditions associated with unstable atmospheric conditions and higher wind speeds coupled with smaller CO_2 releases would likely lead to more rapid mixing and dispersion of the release, thus reducing its potential hazards. This meteorological condition is labeled D5, where D is the Pasquill neutral stability condition with winds of 5 meters per second. The D5 and F2 meteorological conditions represent cases for which air concentrations predicted by either SLAB or SCREEN3 remain elevated for much greater distances for ground level receptors. It is also interesting to point out that the UK Health & Safety Executive recommends using the D5 & F2 categories for generic assessments where site specific weather conditions are either not appropriate or not available (DTI, 2003).

Extensive wind speed, wind direction, temperature, and humidity records were found for the four FutureGen sites at nearby airport weather stations, and additional data on Pasquill stability, Monin-Obukhov surface roughness, and other surface meteorological conditions was obtained from the EIV. The SLAB model was run for all seven stability classes to estimate the transport of releases from pipeline ruptures and punctures, as described in Section 4.4.1. The SLAB and SCREEN3 air transport models were run with the D5 and F2 conditions to represent typical and worst-case meteorological conditions in order to develop a range of estimates for transport of released gases for wellhead ruptures as described in Section 4.4.2.2 into areas surrounding the FutureGen Project. Additional simulations using various wind/stability conditions by the models demonstrated that the D5 and F2 conditions reflect the upper end of meteorological extremes. The D5 and F2 conditions were used in estimating airborne gas concentrations and human health and ecological exposures for wellhead releases.

4.4.1 RELEASE RATES FROM PIPELINES

Pressurized gas will flow out of a pressurized portion of the pipeline at the speed of sound (i.e., Mach 1) as long as the pressure within the pipeline remains above a critical pressure value. Gas moving at the speed of sound is called choked or critical flow. The speed of sound of a particular gas depends upon the temperature and pressure of the remaining pressurized gas. Hence, the speed and the emission rate of the gas decreases as the internal pressure decreases in the pipeline, as shown in Appendix C-I.

The formula describing gas emission rate through an orifice in the pipeline is evaluated in Appendix C-1 for both choked and non-choked flow conditions using the formulas of Hanna & Drivas (1987, page 20). It is found that CO_2 will flow out from an orifice in the pipeline at its sonic velocity as the pipeline pressure decreases with time until the absolute pipeline pressure drops below 1.88 atms or 27 psi. The mass flow rate Q_{choked} of CO_2 also steadily decreases with time as the pressure P_{pipe} in the pipeline decreases. The following tables list the mass of CO_2, the choked flow rate of mass and the release duration of CO_2 from a 5 mile (8 kilometer) length of pipeline for the different pipe diameters (Table 4-5) and for a hole in the pipeline (Table 4-6).

Table 4-5. Choked Flow Conditions for CO_2 Released from Severed Sections of Pipeline

Site	ID & Orifice Area	Length	Pipeline Temperature °F (°C)	Absolute Pressure (psi)	CO_2 Mass (kg)	$Q_{choked-CO_2}$* (kg/sec)	Release Duration (sec)
Mattoon, IL	14.438 inch (36.673 cm). 1.141 feet^2 (0.106 m^2)	0.5 mile (0.8 km)	95 (35)	2,200	72,310	4,444	16
Tuscola, IL	14.438 inch (36.673 cm). 1.141 feet^2 (0.106 m^2)	5 mile (8 km)	95 (35)	2,200	723,100	4,444	162
Jewett, TX	19.312 inch (49.052 cm) 2.034 feet^2 (0.189 m^2)	5 mile (8 km)	95 (35)	2,200	1,290,000	7,950	162
Odessa, TX	12.812 inch (32.542 cm) 0.8956 feet^2 (0.0832 m^2)	5 mile (8 km)	95 (35)	2,200	568,000	3,500	162

Supercritical density = 850 kg/m^3 at 35°C and 2,200 psi.

*Choked flow $Q_{choked-CO_2}$ is based on CO_2 properties.

Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release.
ID=inner diameter; m – meter; cm – centimeter; km – kilometer; kg – kilogram; sec – second.

Table 4-6. Simulation Conditions for CO_2 Released from a 3x1 Square Inch Puncture (an Area of 0.00194 m^2) in a Section of Pipeline

Site	Pipeline ID	Length	Pipeline Temperature °F (°C)	Absolute Pressure (psi)	CO_2 Mass (kg)	$Q_{choked-CO_2}$ * (kg/sec)	Release Duration (sec)
Mattoon, IL	14.438 inch (36.673 cm) 1.141 $feet^2$ (0.106 m^2)	0.5 mile (0.8 km)	95 (35)	2,200	72,310	81.4	888
Tuscola, IL	14.438 inch (36.673 cm) 1.141 $feet^2$ (0.106 m^2)	5 mile (8 km)	95 (35)	2,200	723,100	81.4	8880
Jewett, TX	19.312 inch (49.052 cm) 2.034 $feet^2$ (0.189 m^2)	5 mile (8 km)	95 (35)	2,200	1,290,000	81.4	15,800
Odessa, TX	12.812 inch (32.542 cm) 0.8956 $feet^2$ (0.0832 m^2)	5 mile (8 km)	95 (35)	2,200	568,000	81.4	6980

*Choked flow $Q_{choked-CO_2}$ is based on CO_2 properties.

Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release.
ID=inner diameter; m – meter; cm – centimeter; km – kilometer; kg – kilogram; sec – second.

The corresponding mass flow rate of H_2S or any other trace gas mixed with the supercritical CO_2 gas is assumed to be proportional to the mass of H_2S compared to the mass of CO_2 in the pipeline. For example, if the H_2S is assumed to be 0.01 percent of the CO_2 mass, the resultant estimates of mass emissions of H_2S are listed for the different pipeline diameters in Table 4-7 and for a 3”x1” puncture in Table 4-8.

Table 4-7. Choked Flow Conditions for Hydrogen Sulfide (H_2S) Released from Severed Sections of Pipeline

Site	ID & Orifice Area	Length	Pipeline Temperature °F (°C)	Absolute Pressure (psi)	H_2S Mass (kg)	$Q_{choked-H_2S}$* (kg/sec)	Release Duration (sec)
Mattoon, IL	14.438 inch (36.673 cm) 1.141 feet^2 (0.106 m^2)	0.5 mile (0.8 km)	95 (35)	2,200	7.2	0.44	16
Tuscola, IL	14.438 inch (36.673 cm) 1.141 feet^2 (0.106 m^2)	5 mile (8 km)	95 (35)	2,200	72	0.44	162
Jewett, TX	19.312 inch (49.052 cm) 2.034 feet^2 (0.189 m^2)	5 mile (8 km)	95 (35)	2,200	129	0.79	162
Odessa, TX	12.812 inch (32.542 cm) 0.8956 feet^2 (0.0832 m^2)	5 mile (8 km)	95 (35)	2,200	56.8	0.35	162

Supercritical density = 850 Kg/m^3 at 35°C and 2,200 psi.

*Choked flow $Q_{choked-H_2S} = 0.0001 * Q_{choked-CO_2}$ is based on CO_2 properties.

Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release.
ID=inner diameter; m – meter; cm – centimeter; km – kilometer; kg – kilogram; sec – second.

Table 4-8. Simulation Conditions for Hydrogen Sulfide (H_2S) Released from a 3x1 Square Inch Puncture (an Area of 0.00194 m^2) in a Section of Pipeline

Site	Pipeline ID	Length	Pipeline Temperature °F (°C)	Absolute Pressure (psi)	H_2S Mass (kg)	$Q_{choked-H_2S}$* (kg/sec)	Release Duration (sec)
Mattoon, IL	14.438 inch (36.673 cm)	0.5 mile (0.8 km)	95 (35)	2,200	7.2	0.00814	888
Tuscola, IL	14.438 inch (36.673 cm)	5 mile (8 km)	95 (35)	2,200	72.3	0.00814	8,880
Jewett, TX	19.312 inch (49.052 cm)	5 mile (8 km)	95 (35)	2,200	129	0.00814	15,800
Odessa, TX	12.812 inch (32.542 cm)	5 mile (8 km)	95 (35)	2,200	56.8	0.00814	6,980

*Choked flow $Q_{choked-H_2S} = 0.0001 * Q_{choked-CO_2}$ is based on CO_2 properties.

Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release.
ID=inner diameter; cm - centimeter; km – kilometer; kg – kilogram; sec – second.

4.4.2 MODELS FOR RELEASES TO OUTDOOR AIR FROM RAPID RELEASES-SLAB

4.4.2.1 Estimating Pipeline Emission Rates During Catastrophic Failure

Catastrophic simulations involve hypothetical releases from either the pipeline transmission line or directly from the well head during underground injection. Only emissions of CO_2 and H_2S were considered since approximately 95 percent of the sequestrated gas is CO_2 and H_2S is considered likely to be the most potent component in the remaining 5 percent of the sequestrated gases. The pipeline pressure of the CO_2 in the transmission lines is assumed to be approximately 2,200 psi and at approximately 95°F (35°C) (from the EIV). This means the CO_2 will move in the transmission pipeline as a gas in a supercritical state (IPCC, 2005). Supercritical CO_2 has a very low viscosity but is also heavier than air. The CO_2 will escape through an open orifice in the pipeline as a gas moving with the speed of sound, which is called choked or critical flow (Bird et al., 2002). Choked flow is the maximum rate as which a gas can escape through an orifice without being accelerated by an explosion. The fact that the supercritical CO_2 is a heavier-than-air gas means that the CO_2 will not immediately diffuse upwards into the atmosphere if vented from the pipeline but instead will sink to the ground, and part of it can freeze or become a liquid. The dispersal of the supercritical CO_2 will be initially governed by equations based on gravity flow. The discharged CO_2 will eventually mix with the atmosphere and henceforth move as a neutrally buoyant gas. The SLAB air dispersion model (Ermak, 1990) is used to simulate the emission of CO_2 for various release scenarios involving the pipeline and injection well head when the gas is in a supercritical gas state.

Pipeline release simulations were evaluated for a "hole-puncture" and a complete severing of the pipeline. A hole-puncture, specifically a 3 inch by 1 inch (8 by 3 centimeter) hole, is used to represent an accidental cut into the CO_2 transmission pipeline by a 30-60 ton (27-54 metric ton) excavator. The blades or teeth of a 30-60 ton (27-54 metric ton) excavator are typically 4 inches (10 centimeters) wide by 1 inch (3 centimeters) thick. The transmission pipeline diameter was assumed to range from 12.8 inches (32.5 centimeters) to 19.3 inches (49 centimeters) inside diameter and with pipe wall thicknesses of approximately one-half inches of steel (Battelle, 2006). Hence, a 3 inch by 1 inch (8 by 3 centimeter) hole is assumed to represent what happens if a 30-60 ton (27-54 metric ton) excavator bucket is either thrust or clamped against the pipeline. The complete severing of the pipeline scenario is used to represent an incident in which a heavy piece of equipment such as a bulldozer runs into the transmission pipe. The complete severing scenario could also represent a rail derailment incident in which a portion of a derailed train plows into the buried pipe. In all cases, the escaping gas from the transmission line is assumed to escape as a horizontal jet at ground level. A ground release as a horizontal jet is typically the worst case event for heavier-than-air gases (Hanna and Drivas, 1987).

An automated "pipeline-walk" approach was developed to evaluate the effects of thermodynamically determined gas-phase releases along the entire length of the pipeline at each site. The five main steps in this approach are described below. A detailed description of the analyses, atmospheric input data, and the simulation results is presented in Appendix C-IV.

Step 1. Summarize Meteorological Conditions that Affect Plume Transport. The meteorological data from the EIVs were used to characterize atmospheric conditions at each site. The proportion of time over a year in each of 112 atmospheric states (combinations of 16 wind directions and 7 stability conditions) was defined. The information for the Jewett Site is provided in Table 4-9. The meteorological data for the other sites are presented in Appendix C-IV.

Step 2. Simulate the Area Potentially Affected by a Pipeline Release. The SLAB model was run to determine the area of the potential impact zone for each of the 112 defined atmospheric states. This step was repeated every 984 feet (300 meter) along the length of the pipeline for the release conditions corresponding to both a pipeline puncture and pipeline rupture. 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. For a pipeline puncture, the gaseous impact zone or footprint was determined for five concentration levels corresponding to selected health-effect levels for 8-hour exposure durations: 0.33 ppmv H_2S, 17 ppmv H_2S, 31 ppmv H_2S, 20,000 ppmv CO_2, and 40,000 ppmv CO_2.

Step 3. Estimate Population Affected for Each Atmospheric State. The digital image of each predicted exposure zone defined in Step 2 for each of the 112 atmospheric states was superimposed onto a map containing the digitized census-tract data. The exposure zone was then subdivided into areas having uniform population density. The total affected population in each exposure zone (p_j) was estimated as the sum of the products of the area of each unique sub-portion of the exposure zone (A_k) and the corresponding population density (ρ_k), where k = the index for the census blocks within the area of the plume.

$$p_j = \sum_{k=1}^{m} \rho_k A_k \qquad \text{(Equation 4.1)}$$

where: m= total number of distinct census tracts in impact zone

j = number of defined atmospheric states

= 112

Step 4. Determine the Expected Number of Individuals Potentially Affected at the Specified Release Points. The affected population in each exposure zone (p_j) was next multiplied by the proportion of the time (relative importance) in each atmospheric state (atm_j). Since atm_j for all j = 112 sums to 1, the sum of these products provides the expected number of affected individuals at any selected point (i) along the pipeline (P_i):

$$P_i = \sum_{j=1}^{112} p_j atm_j \qquad \text{(Equation 4.2)}$$

or combining Equations 1 and 2:

$$P_i = \sum_{j=1}^{112} atm_j \sum_{k=1}^{m} \rho_k A_k \qquad \text{(Equation 4.3)}$$

Step 5. Characterize the Potential Exposure Along the Entire Pipeline. Tabular and graphical summaries of the expected number of affected individuals (P_i) at all points along the pipeline provide a comprehensive summary of potential health effects from a pipeline release and, as described below, a basis for comparisons between sites. For example, Figure 4-2 shows the results of the analysis of the estimated population exposed to H_2S concentrations (0.51 ppmv) that can result in adverse effects at the Jewett Site. Along much of the pipeline (37 miles [59 kilometer]), near zero or less than 10 individuals would be expected to be exposed to H_2S above 0.51 ppmv from a pipeline rupture. At about 39 miles (62 kilometers) along the pipeline, the potentially exposed population increases to greater than 30 and up to 52 individuals.

The wind rose for Jewett, TX site is based on combined data from Waco/Huntsville Regional Airports from Jan 1, 2005 through Dec 31, 2005. Table 4-9 shows the percent of time per year that wind blows from one of sixteen directions and with one of seven wind speed categories. Pasquill stability category is shown along the top line of the table. Its value is based on the corresponding wind speed and the assumption of moderate insolation (Turner, 1994, page 2-7). For example, category B03 means a 3 meter/second wind with a Pasquill stability class B, etc.

Table 4-9. Wind Rose for Jewett, TX

	F02	A01	A02	B03	B04	C06	D08
From	**Calm (%)**	**2.6 to 3.09 mph (4.2 to 4.97 kmph) (%)**	**3.09 to 5.14 mph (4.97 to 8.27 kmph) (%)**	**5.14 to 8.23 mph (8.27 to 13.24 kmph) (%)**	**8.23 to 10.8 mph (13.24 to 17.4 kmph) (%)**	**10.8 to 15 mph (17.38 to 24 kmph) (%)**	**>=15mph (24kmph) (%)**
S	1.3	1.125	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		2.625	2.25	1.875

kmph – kilometers per hour

4.4.2.2 Predicting Air Concentrations for Wellhead Rupture Scenarios

The rupture of the aboveground equipment at an injection well was also simulated using SLAB as a well-head blowout scenario. The well-bore diameters and depths varied among sites. The mass of CO_2 from a rupture of wellhead equipment at each site is listed in Table 4-10 and the H_2S mass is given in Table 4-11. These cases were simulated with SLAB, since they act as vertical jet releases upon rupture.

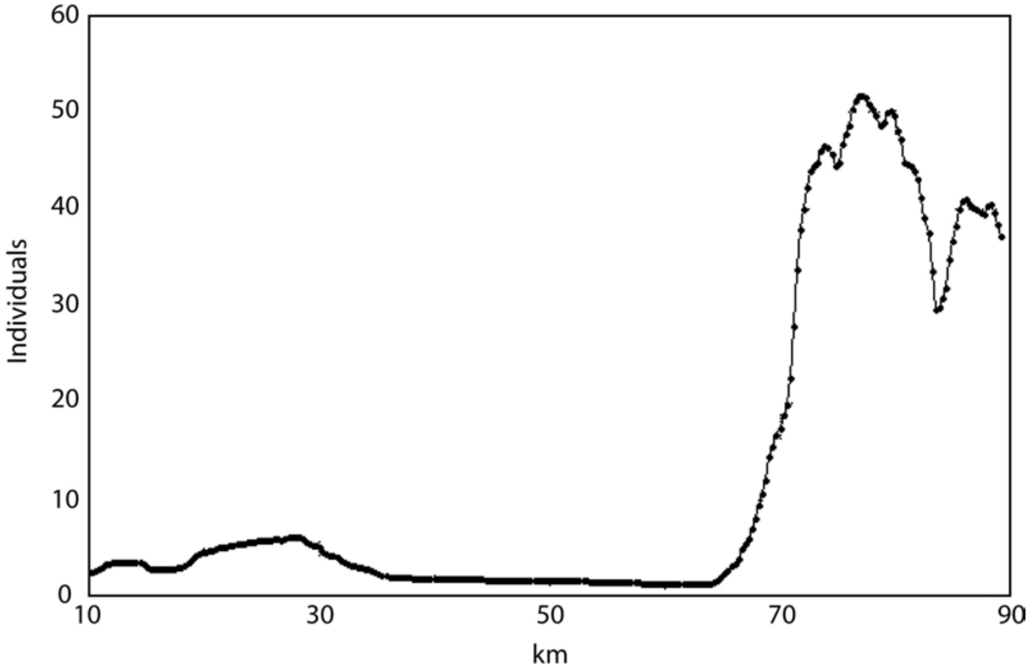


Figure 4-2. Expected Population Impact to 0.51 ppmv H_2S from Pipeline Rupture at Jewett, TX[1]

Table 4-10. Choked Flow Conditions for CO_2 Released from Injection Wellheads

Site	Injection Zone	Tubing ID, inches (centimeters)	Tubing Depth, feet (meters)	Total Depth, feet (meters)	Well Volume*, feet^3 (meters^3)	Mass CO_2 (tonne) @2200 psi, 95°F	Mass Rate (Kg/sec)	Duration (sec)
Mattoon, IL	Mt. Simon	3.83 (9.73)	6,950 (2,118)	8,000 (2,438)	681.6 (19.3)	16.4	313	52
Tuscola, IL	Mt. Simon	4.89 (12.42)	6,150 (1,875)	7,750 (2,362)	939.4 (26.6)	22.6	510	44
Jewett, TX	Woodbine	3.83 (9.73)	4,800 (1,463)	5,500 (1,676)	469.7 (13.3)	11.3	313	36
	Travis Peak	3.83 (9.73)	9,200 (2,804)	11,000 (3,353)	939.4 (26.6)	22.6	313	72
Odessa, TX	Mountain	1.99 (5.05)	5,600 (1,707)	5,600 (1,707)	120.1 (3.4)	2.9	84.8	35

*Wellbore volume is based on the total depth of hole. ID=inner diameter

CO_2 density = 850 kg/ m^3 @2200 psi & 95°F.

1 ton = 1 metric ton = 1000 kg.

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[1] Expected population impact at every (984-foot) 300-meter location along the pipeline. Each point on the graph represents the results of a complete simulation of H_2S release from the pipeline described in Steps 1 – 5 of the revised assessment methodology.

Table 4-11. Choked Flow Conditions for Hydrogen Sulfide (H_2S) Released from Injection Wellheads

Site	Injection Zone	Tubing ID, inches (centimeters)	Tubing Depth, feet (meters)	Total Depth, feet (meters)	Well Volume*, feet^3 (meters^3)	Mass H_2S (tonne) @2200 psi, 95°F	Mass Rate Kg/sec	Duration sec
Mattoon, IL	Mt. Simon	3.83 (9.73)	6,950 (2,118)	8,000 (2,438)	681.6 (19.3)	0.00164	0.0313	52
Tuscola, IL	Mt. Simon	4.89 (12.42)	6,150 (1,875)	7,750 (2,362)	939.4 (26.6)	0.00226	0.0510	44
Jewett, TX	Woodbine	3.83 (9.73)	4,800 (1,463)	5,500 (1,676)	469.7 (13.3)	0.00113	0.0313	36
	Travis Peak	3.83 (9.73)	9,200 (2,804)	11,000 (3,353)	939.4 (26.6)	0.00226	0.0313	72
Odessa, TX	Mountain	1.99 (5.05)	5,600 (1,707)	5,600 (1,707)	120.1 (3.4)	0.00029	0.00848	35

*Wellbore volume is based on the total depth of hole. ID=inner diameter

4.4.2.3 Predicting Air Concentrations for Post-Sequestration Release Scenarios

Post-sequestration scenarios of diffusive releases were performed using U.S. EPA's screening model SCREEN3 (U.S. EPA, 1995b). The dimensions of eight area sources being simulated for potential emitters of CO_2 in post-sequestration leakage were determined. Two wind speeds & Pasquill stability classes were selected (F2 and D5). A total of sixteen SCREEN3 runs were made with the different area sources (8 areas X 2 wind categories). The emission flux rate of each area source was simulated with a unit flux rate of 1 gram/square-meter/second value for ground-level releases. Air concentrations were predicted by SCREEN3 at a receptor elevation of 4.9 feet (1.5 meters) above ground every 820 feet (250 meters) down-wind of a source out to 6 miles (10,000 meters). The model simulates only one source at a time so each emission scenario requires a separate run. Air concentrations were also predicted for emissions from abandoned wells. Two SCREEN3 runs were made using point sources (1 well emitter for 2 wind categories) with an emission rate of 1 gram/second. Predictions were also generated for every 820-feet (250-meter) increment down-wind of the well emitter. The final predicted air concentrations were determined by multiplying the unit emission results by the estimated emission rates for each area and point source. Results of the post-sequestration release scenarios are presented in Section 5.

4.5 Consequence Analyses

Human health and ecological effects were evaluated by examining the routes by which people or biological receptors may be exposed to captured gas releases into the atmosphere, surface water, groundwater, or in surface soils. The key exposure routes that have been evaluated for the pre-injection scenarios are inhalation of gases released to the atmosphere and transported by the wind to nearby residential populations and workers at the plant. Humans may also potentially be exposed to released gases if impacted surface water is used as a potable water source, or for recreation or irrigation of crops. These secondary exposure pathways have not been evaluated, as they are less likely to be important than the atmospheric pathway for the short-term releases of concern from the pipelines and wellheads at each site.

Aquatic organisms may be exposed to gases eventually released into the surface water bodies in which they live (e.g., via surface discharge into a stream or lake, contact of the gases with aquatic plants or sediment, deposition of gases on surface water). Changes in surface water quality can occur if releases of captured gases are sufficient to significantly modify the pH of affected surface waters and the TDS can increase. Potential effects on aquatic organisms are evaluated in a qualitative manner. Lastly, gases migrating through the soil column may adversely impact trees and plants by lowering the amount of oxygen available to root systems. The potential for these terrestrial exposure routes is discussed qualitatively.

4.5.1 JEWETT, TX

4.5.1.1 Key Factors Affecting Risk Assessment

A description of the nearby towns and environmental setting and maps are presented in Section 2. Key factors that affect the potential for risks at the Jewett Site include the following:

- Long pipelines to the injection wells;
- Populated areas near one of the injection sites next to the Trinity River;
- Pipeline crossing of the Trinity River for one of the injection sites and multiple tributaries for all injection sites;
- Schools and five prisons near the pipeline corridor; and
- Use of three injection wells and 4 water extraction wells.

4.5.1.2 Risk Results

The predicted atmospheric concentrations of CO_2 and H_2S that plant workers could be exposed to, should a release event occur, are presented in a series of tables for short-term and long-term exposure scenarios at each site. These risk tables include the gas concentrations that workers may be exposed to at two distances (i.e., 66 feet [20 meters] and 820 feet [250 meters]) from a pipeline rupture, pipeline puncture, or wellhead rupture. These concentrations are, in turn, compared to health-protective industrial hygiene criteria, with ratios greater than 1 representing potential health concerns for workers. In contrast, evaluations of nearby residents are described in terms of the distances at which different levels of exposures could occur due to pipeline or wellhead ruptures or punctures. Most importantly, the tables and accompanying figures show the distances that represent levels with only mild or transient health effects for potentially exposed individuals. The risk tables and figures showing areas potentially affected by any releases are provided in Appendix B.

At the Jewett Site, the predicted atmospheric concentrations of CO_2 potentially resulting from a worst-case pipeline rupture and puncture would exceed life-protective criteria for workers (i.e., the IDLH) within a short distance (66 feet [20 meters]) of the release point. However, within a distance of 820 feet (250 meters), predicted concentrations would not cause irreversible or other serious health effects (i.e., would not exceed 30,000 ppmv). CO_2 concentrations that could cause serious health effects would occur only close to the pipeline rupture, about 663 feet (202 meters) from the pipe. For a pipeline puncture, the CO_2 concentrations would decrease to 20,000 ppmv by a distance of 551 feet (168 meters). For a wellhead failure at either a Woodbine or Travis Peak injection well, CO_2 concentrations would be below levels that cause serious health effects, even near the equipment (about 66 feet [20 meters]). A somewhat different pattern of exposures is predicted for H_2S releases. For both the pipeline rupture, life-protective criteria for H_2S (i.e., the Ceiling or maximum concentration allowable at any time [i.e., 10 ppmv] would be exceeded both at a distance of 66 feet [20 meters] and 820 feet [250 meters]). For a pipeline puncture, the H_2S Ceiling concentration would be exceeded at 66 feet (20 meters), but not at 820 feet (250 meters). For a wellhead rupture, the life-protective criteria would not be exceeded by predicted H_2S concentrations at a distance of 820 feet (250 meters). Thus, these results suggest that health effects for workers outside of the immediate vicinity of a release would primarily be related to H_2S exposures should a pipeline rupture or be punctured.

Potential health effects to offsite populations from the CO_2 concentrations predicted for a pipeline rupture or puncture at the plant site are unlikely, 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 near the furthest injection wells, the impact zone with predicted H_2S concentrations at a level (TEEL-2 of 27 ppmv) where there could be more than transient health effects, could extend to a distance of 1,946 feet (593 meters), while the zone with H_2S concentrations causing mild transient effects (TEEL-1 of 0.51 ppmv) could extend out to a distance of 22,589 feet (6,885 meters), which extends into the populated area north of the Trinity River as shown in the series of maps included in Appendix B.

If a pipeline puncture occurred near the injection site, the impact zone with predicted H_2S concentrations causing more than transient health effects (i.e., AEGL-1 of 0.33 ppmv) could extend out to a distance of 7,730 feet (2,356 meters). However, the impact zone would not be as large as for the rupture case.

If a wellhead rupture occurred, the impact zone where predicted H_2S concentrations could cause more than transient health effects (i.e., above the TEEL-1 criteria of 0.51 ppmv) would extend to a distance of 2,585 feet (788 meters) for a Woodbine well and 1,752 feet (534 meters) for the Travis Peak well. These results, therefore, indicate that there is greater likelihood of health effects for offsite populations from H_2S than CO_2 releases from a pipeline or wellhead rupture or pipeline puncture. The impact zone represents the area where individuals could possibly be affected, depending on wind direction and other meteorological conditions at the time of the release. The number of individuals who could actually be affected by any given release is determined by the size, shape, and location of the dispersion plume, which could occupy only a very small portion of the zone of possible impacts. For example, the estimated size of the plume from a wellhead rupture is only 1.2 percent of the entire circular area defined by a radius equal to the maximum downwind distance at which the AEGL-1 is exceeded. Thus the number of individuals that could be exposed to adverse effects of H_2S (i.e., 0.51 ppmv) or CO_2 (30,000 ppmv) is much less than the number of people in the zone of possible impacts. Based on the population density, the estimated number of individuals potentially affected by H_2S from a wellhead rupture is 4. In addition, prisoners and staff located at the prison next to the Woodbine well north of the Trinity River could also be affected. No individuals are expected to be affected by CO_2, since the impact zone is within 33 feet (10 meters) of the injection well.

Tabular and graphical summaries of the expected number of affected individuals (P_i) at all points along the pipeline provide a comprehensive summary of potential health effects from a pipeline release and a basis for comparisons between sites. For a pipeline rupture, Figure 4-2 shows the results for a pipeline rupture of the analysis of the estimated population exposed to H_2S concentrations (0.51 ppmv) that can result in adverse effects at the Jewett Site. Along much of the pipeline (59 miles [95 kilometers]), near zero or less than 10 individuals would be expected to be exposed to H_2S above 0.51 ppmv from a pipeline rupture. At about 45 miles (72 kilometers), the potentially exposed population increases to greater than 30 and up to 52 individuals. The length of pipeline along which specified numbers of individuals could be affected is shown in Table 4-12. For Jewett, the greatest number of individuals affected could occur along a 1.7 miles (2.7 kilometers) segment of the pipeline located along the pipeline segment north of the Trinity River. The length of pipeline with greater than 10 individuals potentially affected was 13 miles

(21 kilometers) out of the total length of 59 miles (95 kilometers). Additional mitigation methods could be considered for these portions of the pipeline to reduce the potential for effects on offsite populations.

Table 4-12. Pipeline Lengths (miles [kilometers]) 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 (miles [kilometers])***			
	Mattoon	**Tuscola**	**Jewett**	**Odessa**
<1	0.5 (0.8)	2.6 (4.2)	0 (0)	61.5 (99)
1 - 10		8.4 (13.5)	46 (74)	
11 - 20		-	1.5 (2.4)	-
21 - 30	-	-	0.7 (1.2)	-
31 - 40	-	-	3.2 (5.1)	-
41 - 50	-	-	6.0 (9.6)	-
51- 60	-	-	1.7 (2.7)	-
Total Pipeline Length (miles [kilometers])	0.5 (0.8)	11 (17.7)	59 (95)	61.5 (99)

A similar analysis was conducted for the pipeline puncture scenario. Results are presented in tabular format in Table 4-13. At Jewett, the expected number of individuals potentially exposed to H_2S above 0.33 ppmv from a pipeline ***puncture*** was less than 1 individual for 47.1 miles (76.4 kilometers) of the total pipeline (59 miles [95 kilometers]). The expected number of individuals that would be expected to be exposed to adverse effects from H_2S (i.e., 0.33 ppmv) from a pipeline puncture was less than 10 individuals along 11.6 miles (18.6 kilometers) of the pipeline.

Table 4-13. Pipeline Lengths (miles [kilometers]) Corresponding to Expected Number of Individuals in Offsite Population Potentially Exposed to 0.33 ppmv Concentrations of H_2S (Adverse Effects) by Pipeline Puncture

Number of Individuals Potentially Affected	***Length of Pipeline Effect (miles [kilometers])***			
	Mattoon	**Tuscola**	**Jewett**	**Odessa**
<1	0.5 (0.8)	8.9 (14.4)	47.5 (76.4)	61.5 (99)
1 - 10	-	2.1 (3.3)	11.6 (18.6)	-
11 - 20	-	-	-	-
21 - 30	-	-	-	-
31 - 40	-	-	-	-
41 - 50	-	-	-	-
51- 60	-	-	-	-
Total Pipeline Length (miles [kilometers])	0.5 (0.8)	11 (17.7)	59 (95)	61.5 (99)

4.5.1.3 Ecological Risk Results

Because the pipeline to the injection sites crosses streams and the Trinity River, there is a potential for the captured gas to be released into surface water. The volume of released gas would first displace ambient soil gas and then be released into the surface water. Both CO_2 and H_2S would dissolve in the water up to their respective solubilities, given the pH, salinity, and temperature of the water at the time of the leak. The solubility of H_2S is greater in alkaline waters than below a pH of 5. For example, at a pH of 8 the H_2S concentration in the water would be 3.4×10^{-8} mg/L. H_2S concentrations in the water are predicted to be less than the criterion protective of freshwater aquatic biota (0.002 mg/L). When CO_2 gas dissolves in the water, the pH is decreased due to the formation of carbonic acid and the subsequent production of bicarbonate ions. As the TDS of the water increases, the amount of CO_2 that can dissolve decreases. Depending on the relative flux rate of the release to the volume of water in the reach where the event occurs and the flow rate, some of the gases may bubble up through the water into the atmosphere. The CO_2 concentration in the water is unlikely to reach 2 percent (i.e., when injuries to aquatic life can occur; see the risk table for biota in Appendix B), since the solubility of CO_2 at typical atmospheric conditions would keep the concentration less than about 0.2 percent.

The pipeline is expected to be buried to a depth of about 1 meter. Thus, if a leak or rupture occurred, the released gas would first migrate into the soil gas and displace the ambient air. Respiratory effects to biota due to atmospheric CO_2 concentrations are unlikely to occur, except immediately in the vicinity of the pipeline where the rupture or leak occurred, since the predicted airborne concentrations are less than 1 percent. Soil gas concentrations can be higher depending on soil type, so effects on soil invertebrates or plant roots could occur close to the segment where the pipe failed or leaked.

4.5.2 ODESSA, TX

4.5.2.1 Key Factors Affecting Risk Assessment

A description of the nearby towns and environmental setting and maps are presented in Section 2. Key factors that affect the potential for risks at the Odessa Site include the following:

- One injection site with a long pipeline (i.e., 60 miles [97 kilometers]);
- Populated areas within 8 miles (13 kilometers) of the injection site;
- Pipeline crossing of the Pecos River;
- Pipeline crossing of Interstate Highway 10; and
- Use of multiple injection wells.

The composition of the gas injected at the Odessa Site may differ from the other sites, if the gas is delivered to an existing commercial CO_2 pipeline that serves EOR projects. The pipeline company would be responsible for the pipeline crossings of the river and highways.

4.5.2.2 Risk Results

The predicted atmospheric concentrations of CO_2 and H_2S that plant workers could be exposed to, should a release event occur, are presented in a series of tables for short-term and long-term exposure scenarios at each site. These risk tables include the gas concentrations that workers may be exposed to at two distances (i.e., 66 feet [20 meters] and 820 feet [250 meters]) from a pipeline rupture, puncture, or wellhead rupture. These concentrations are, in turn, compared to health-protective industrial hygiene criteria, with ratios greater than 1 representing potential health concerns for workers. In contrast, evaluations of nearby residents are described in terms of the distances at which different levels of exposures could occur due to pipeline or wellhead ruptures or punctures. Most importantly, the tables and accompanying figures show the distances that represent levels with only mild or transient health effects for potentially exposed individuals. The risk tables and figures showing areas potentially affected by any releases are provided in Appendix B.

At the Odessa Site, the predicted atmospheric concentrations of CO_2 potentially resulting from a worst-case pipeline rupture or puncture would exceed life-protective criteria for workers (i.e., the IDLH) within a short distance (20 m) of the release point. However, within a distance of 250 m, predicted concentrations would not cause irreversible or other serious health effects (i.e., would not exceed 30,000 ppmv). CO_2 concentrations that could cause serious health effects would occur only close to the pipeline rupture, about 397 feet (121 meters) from the pipe. For a pipeline puncture, the CO_2 concentrations would decrease to 20,000 ppmv by a distance of 627 feet (191meters). For a wellhead failure, CO_2 concentrations would be below 30,000 ppmv even near the equipment (about 66 feet [20 meters]). A somewhat different pattern of exposures is predicted for H_2S releases. For both the pipeline rupture and puncture, life-protective criteria for H_2S (i.e., the Ceiling or maximum concentration allowable at any time) would be exceeded at a distance of 66 feet (20 meters), but the concentration would exceed the criteria at 820 feet (250 meters) only for a pipeline rupture. For a wellhead rupture, the H_2S concentrations are predicted to be about 22 ppmv (i.e., exceeding the Ceiling criterion of 10 ppmv) at a distance of 66 feet (20 meters) from the wellhead equipment, while the life-protective criteria would not be exceeded by predicted H_2S concentrations at a distance of 820 feet (250 meters). Thus, these results suggest that health effects for workers outside of the immediate vicinity of a release would primarily be related to H_2S exposures should a pipeline rupture or be punctured.

Potential health effects to the offsite populations from the CO_2 concentrations predicted for the three types of pipeline or wellhead failures are unlikely, since the CO_2 concentrations outside the plant site (i.e., more than 820 feet [250 meters]) from the release points are less than a level (30,000 ppmv) below which there would be only mild or transient health effects. In contrast, if a pipeline rupture occurred, the impact zone with predicted H_2S concentrations at a level above which there could be serious, life-threatening effects (TEEL-2 of 27 ppmv) could extend to about 269 feet (82 meters). The nearest population center to the plant is outside the area where there could be mild transient health effects (above the TEEL-1 criterion of 0.51 ppmv) at a distance of 2,585 feet (788 meters), as shown in the maps in Appendix B. The nearest population center is about 8 miles (13 kilometers) away from the injection site, which is also outside the zone with H_2S concentrations where mild transient health effects could occur from a pipeline rupture. Nevertheless, if a pipeline puncture occurred near the injection site, the impact zone with predicted H_2S concentrations above the level at which serious, life-threatening effects could occur (i.e., the AEGL-3 criterion of 31 ppmv) could extend to about 381 feet (116 meters). If a wellhead rupture occurred, the impact zone with predicted H_2S concentrations that could result in mild transient health effects would be close to the wellhead (e.g., 951 feet [290 meters] away). The distance of the impact zone represents the area where individuals could potentially be affected, depending on wind direction and other meteorological conditions at the time of the release. The number of individuals who could actually be affected by any given release is determined by the size, shape, and location of the dispersion plume, which could occupy only a very small portion of the zone of possible impacts. For example, the estimated size of the plume from a wellhead rupture is only 1.2 percent of the entire circular area defined by a radius equal to the maximum downwind distance at which the AEGL-1 is exceeded. Thus. the number of individuals that could be exposed to adverse effects of H_2S (i.e., 0.51 ppmv) or CO_2 (30,000 ppmv) is much less than the number of people in the zone of possible impacts. Based on the population density, the estimated number of individuals potentially affected by H_2S from a wellhead rupture is none for both H_2S or CO_2 exposure. These results, therefore, indicate that there is greater likelihood of health effects for nearby populations from H_2S than CO_2 releases from a pipeline or wellhead rupture or pipeline puncture.

Tabular and graphical summaries of the expected number of affected individuals (P_i) at all points along the pipeline provide a comprehensive summary of potential health effects from a pipeline release and a basis for comparisons between sites. Figure 4-3 shows the results of the analysis for a pipeline rupture of the estimated population exposed to H_2S concentrations (0.51 ppmv) that can result in adverse effects at the Odessa Site. Along the entire pipeline (61.5 miles [99 kilometers]), near zero or less than 1 individual would be expected to be exposed to H_2S above 0.51 ppmv from a pipeline rupture.

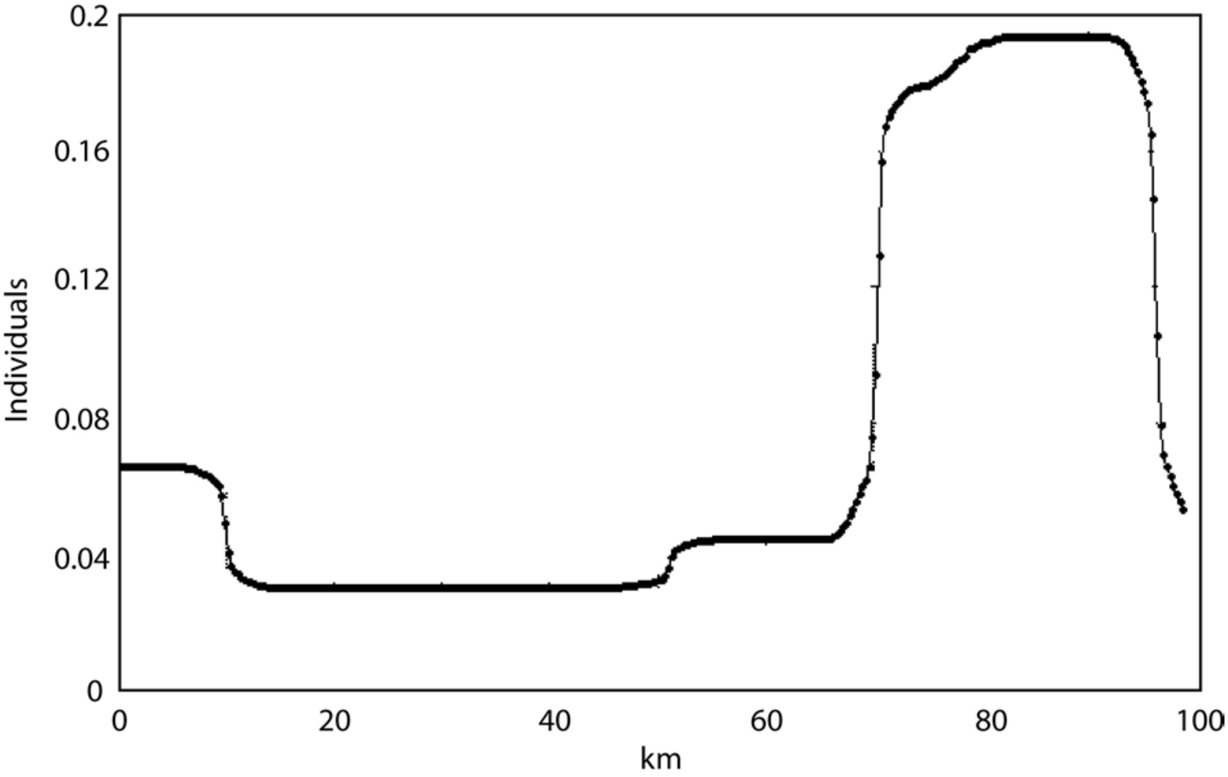

Figure 4-3. Expected Population Impact to 0.51 ppmv H_2S from Pipeline Rupture at Odessa, TX[2]

The length of pipeline along which specified numbers of individuals could be affected is shown in Table 4-12. For Odessa, the greatest number of individuals affected is less than one individual for the entire length of the pipeline. A similar analysis of the pipeline puncture scenario showed that for Odessa, there were less than one individual potentially exposed to H_2S concentrations above the levels that can result in adverse effects (0.33 ppmv) along the entire pipeline (see Table 4-13).

4.5.2.3 Ecological Risk Results

Because the pipeline to the injection sites crosses the Pecos River, there is a potential for the captured gas to be released into surface water. The commercial pipeline company accepting the captured gas would have the responsibility for the pipeline, and could take additional measures in this area to protect the pipeline. There are also wetlands overlying the injection site. Any released gas volume would first displace ambient soil gas and then be released into the surface water. Both CO_2 and H_2S would dissolve in the water up to their respective solubilities, given the pH, salinity, and temperature of the water at the time of the leak. When CO_2 gas dissolves in the water, the pH is decreased due to the formation of carbonic acid and the subsequent production of bicarbonate ions. As the TDS of the water increases, the amount of CO_2 that can dissolve decreases. Depending on the relative flux rate of the release to the volume of water in the reach where the event occurs and the flow rate, some of the gases may bubble up through the water into the atmosphere. The CO_2 concentration in the water is unlikely to reach 2 percent

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[2] **Expected population impact at every 984-foot (300-meter) location along the pipeline. Each point on the graph represents the results of a complete simulation of H_2S release from the pipeline described in Steps 1 – 5 of the revised assessment methodology.**

(i.e., when injuries to aquatic life can occur), since the solubility of CO_2 at typical atmospheric conditions would keep the concentration less than about 0.2 percent. H_2S concentrations in the water are predicted to be less than the criterion (0.002 mg/L) protective of freshwater aquatic biota.

The pipeline is expected to be buried to a depth of about 1 meter. Thus, if a leak or rupture occurred, the released gas would first migrate into the soil gas and displace the ambient air. Respiratory effects to biota due to atmospheric CO_2 concentrations are unlikely to occur, except immediately in the vicinity of the pipeline where the rupture or leak occurred, since the predicted concentrations are less than 1 percent. Soil gas concentrations can be higher depending on soil type, so effects on soil invertebrates or plant roots could occur close to the segment where the pipe failed or leaked. The primary biota of concern at the injection site are endangered birds, which may visit the wetlands overlying the plume for short periods of time. No effects on the birds would be expected, since they would not be directly exposed to the soil gas.

4.5.3 MATTOON, IL

4.5.3.1 Key Factors Affecting Risk Assessment

A description of the nearby towns and environmental setting and maps are presented in Section 2. Key factors that affect the potential for risks at the Mattoon Site include the following:

- Injection site below the plant site; and
- Populated areas within 1 mile of the estimated injection plume.

4.5.3.2 Risk Results

The predicted atmospheric concentrations of CO_2 and H_2S that plant workers could be exposed to, should a release event occur, are presented in a series of tables for short-term and long-term exposure scenarios at each site. These risk tables include the gas concentrations that workers may be exposed to at two distances (i.e., 66 feet [20 meters] and 820 feet [250 meters]) from a pipeline rupture, puncture, or wellhead rupture. These concentrations are, in turn, compared to health-protective industrial hygiene criteria, with ratios greater than 1 representing potential health concerns for workers. In contrast, evaluations of nearby populations are described in terms of the distances at which different levels of exposures could occur due to pipeline or wellhead ruptures or punctures. Most importantly, the tables and accompanying figures show the distances that represent levels with only mild or transient health effects for potentially exposed individuals. The risk tables and figures showing areas potentially affected by any releases are provided in Appendix B.

At the Mattoon Site, the predicted atmospheric concentrations of CO_2 potentially resulting from a worst-case pipeline rupture would not exceed life-protective criteria for workers (i.e., the IDLH of 30,000 ppmv) within a distance of 66 feet (20 meters) or 820 feet (250 meters). CO_2 concentrations that could cause serious health effects (i.e., exceed 30,000 ppmv) would occur only close to the pipeline puncture, but not 820 feet (250 meters) from the pipeline. The duration of the release for a pipeline rupture is less than for a puncture. For a short pipeline such as for Mattoon, the duration of a rupture is about 16 seconds (see Table 4-5), which is less than the duration of a puncture, which is about 15 minutes (see Table 4-6). Thus, the estimated CO_2 concentration at a distance of 66 feet (20 meters) from a pipeline rupture is considerably less than from a pipeline puncture, as shown in the tables in Appendix B-1. For a wellhead failure, CO_2 concentrations that could cause serious health effects are predicted only around the equipment (e.g., about 16 feet [5 meters]). A similar pattern of exposures is predicted for H_2S releases. For the pipeline rupture, puncture, and wellhead blowout, life-protective criteria for H_2S (i.e., the Ceiling or maximum concentration allowable at any time) would be exceeded at a distance of 66 feet (20 meters), but would not be at 820 feet (250 meters). Thus, these results suggest that health effects for workers outside of the immediate vicinity of a release would primarily be related to H_2S exposures should a pipeline or wellhead rupture or a pipeline be punctured.

Potential health effects to offsite populations from the CO_2 concentrations predicted for the three types of pipeline or wellhead failures are unlikely, since the CO_2 concentrations outside the plant site are likely to be less than the level where mild transient effects could occur. Similarly, if a pipeline rupture occurred, the impact zone with predicted H_2S concentrations above the criterion (0.51 ppmv) where mild transient health effects could occur would extend to 4,170 feet (1,271 meters). Because the pipeline length is short between the plant and the injection well, the probability of a rupture or failure is less at this site than those with long pipelines. The impact zone for a pipeline puncture that could release H_2S and cause mild transient effects (0.33 ppmv) could extend to a distance of 5,341 feet (1,628 meters). These distances do not extend to the populated area east of the plant or to the school located ***about 9,240 feet (2,816 meters)*** to the southeast near the plant (see maps in Appendix B).

However, if a wellhead rupture occurred, the impact zone for H_2S would extend out to 2,257 feet (688 meters) from the wellhead. The impact zone represents the area where individuals could possibly be affected, depending on wind direction and other meteorological conditions at the time of the release. The number of individuals who could actually be affected by any given release is determined by the size, shape, and location of the dispersion plume, which could occupy only a very small portion of the zone of possible impacts. For example, the estimated size of the plume from a wellhead rupture is only 1.2 percent of the entire circular area defined by a radius equal to the maximum downwind distance at which the AEGL-1 is exceeded. Thus, the number of individuals that could be exposed to adverse effects of H_2S (i.e., 0.51 ppmv) or CO_2 (30,000 ppmv) is much less than the number of people in the zone of possible impacts. Based on the population density, less than 1 individual is estimated to be potentially exposed to levels of H_2S that can cause adverse effects (***0.51*** ppmv) from a wellhead rupture, but none for CO_2. Thus, these results indicate that although there is greater likelihood of health effects for nearby populations from H_2S than CO_2 releases, these may only be mild transient effects.

Tabular and graphical summaries of the expected number of affected individuals (P_i) at all points along the pipeline provide a comprehensive summary of potential health effects from a pipeline release and a basis for comparisons between sites. Figure 4-4 shows the results of the analysis of a pipeline rupture of the estimated population exposed to H_2S concentrations (0.51 ppmv) that can result in adverse effects at the Mattoon Site. Along the entire pipeline (0.5 miles [0.8 kilometers]), near zero or less than 1 individual would be expected to be exposed to H_2S above 0.51 ppmv from a pipeline rupture, as shown in Table 4-12.

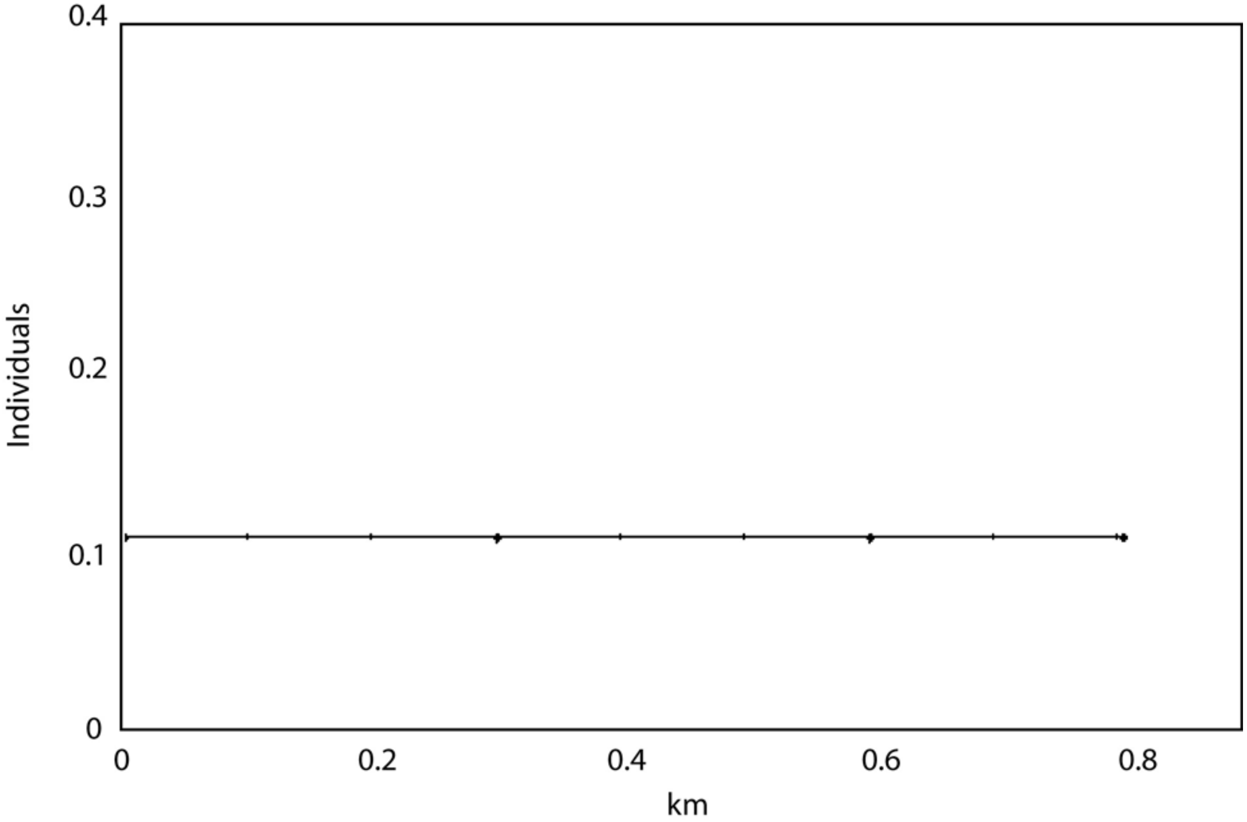

Figure 4-4. Expected Population Impact to 0.51 ppmv H_2S from Pipeline Rupture at Mattoon, IL[3]

A similar analysis was conducted for the pipeline puncture scenario. The results are provided for all four sites in tabular format in Table 4-13. Along the entire pipeline (0.5 miles [0.8 kilometers]), less than 1 individual would be expected to be exposed to H_2S above 0.33 ppmv from a pipeline puncture, as shown in Table 4-13.

4.5.3.3 Ecological Risk Results

About 18 small wetlands have been identified, and several small streams and lakes are present in the vicinity of the 50-year sequestered gas plume footprint. The threatened Eastern Sand Darter may be present, which is a fish that prefers waterbodies with sandy substrates. The endangered Indiana Bat may frequent wooded riparian habitat along the waterbodies. There is only a short pipeline from the plant to the injection well. Thus, a pipeline rupture or leak is unlikely to affect biota outside of the plant property.

There is a low potential for the captured gas to be released into surface water, because the pipeline is short and the injection site is located on the plant property. If the gas discharged into surface water, the CO_2 concentration in the water is unlikely to reach 2 percent (when injuries to aquatic life can occur) since the solubility of CO_2 at typical atmospheric conditions would keep the concentration less than about 0.2 percent. H_2S concentrations in the water are predicted to be less than the criterion (0.002 mg/L) protective of freshwater aquatic biota.

The pipeline is expected to be buried to a depth of about 3.3 feet (1 meter). Thus, if a leak or rupture occurred, the released gas would first migrate into the soil gas and displace the ambient air. Respiratory

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[3] **Expected population impact at every 984-foot (300-meter) location along the pipeline. Each point on the graph represents the results of a complete simulation of H_2S release from the pipeline described in Steps 1 – 5 of the revised assessment methodology.**

effects to biota due to atmospheric CO_2 concentrations are unlikely to occur, except along the pipeline where the rupture or leak occurred, since the predicted offsite concentrations are less than 1 percent. Soil gas concentrations can be higher depending on soil type, so effects on soil invertebrates or plant roots could occur close to the segment where the pipe failed or leaked. One of the primary biota of concern at the injection site is an endangered bat, which may visit the streams and wetlands for short periods of time. No effects on the bats would be expected, since they would not be directly exposed to the soil gas.

4.5.4 TUSCOLA, IL

4.5.4.1 Key Factors Affecting Risk Assessment

A description of the nearby towns and environmental setting and maps are presented in Section 2. Key factors that affect the potential for risks at the Tuscola Site include the following:

- Pipeline to injection site is about 11 miles (18 kilometers) long
- Populated areas near the plant and injection site
- Wetlands and a small section of the Kaskaskia River overly part of the sequestered gas plume site.

4.5.4.2 Risk Results

The predicted atmospheric concentrations of CO_2 and H_2S that plant workers could be exposed to, should a release event occur, are presented in a series of tables for short-term and long-term exposure scenarios at each site. These risk tables include the gas concentrations that workers may be exposed to at two distances (i.e., 66 feet [20 meters] and 820 feet [250 meters]) from a pipeline rupture, puncture, or wellhead rupture. These concentrations are, in turn, compared to health-protective industrial hygiene criteria, with ratios greater than 1 representing potential health concerns for workers. In contrast, evaluations of nearby residents are described in terms of the distances at which different levels of exposures could occur due to pipeline or wellhead ruptures or punctures. Most importantly, the tables and accompanying figures show the distances that represent levels with only mild or transient health effects for potentially exposed individuals. The risk tables and figures showing areas potentially affected by any releases are provided in Appendix B.

At the Tuscola Site, the predicted atmospheric concentrations of CO_2 potentially resulting from a worst-case pipeline rupture or puncture would exceed life-protective criteria for workers (i.e., the IDLH) within a short distance (66 feet [20 meters]) of the release point. However, within a distance of 820 feet (250 meters), predicted concentrations from a pipeline rupture or puncture would not cause irreversible or other serious health effects (i.e., would not exceed 30,000 ppmv). For a wellhead failure, CO_2 concentrations causing serious health effects are predicted only near the equipment (e.g., about 16 feet [5 meters]). A somewhat different pattern of exposures is predicted for H_2S releases. For both the pipeline rupture, life-protective criteria for H_2S (i.e., the Ceiling or maximum concentration allowable at any time) would be exceeded at a distance of 66 feet (20 meters) but not at 820 feet (250 meters). For a pipeline puncture, life-protective criteria for H_2S (i.e., the Ceiling or maximum concentration allowable at any time) would be exceeded at both a distance of 66 feet (20 meters) and 820 feet (250 meters). For a wellhead rupture, the life-protective criteria would be exceeded by predicted H_2S concentrations at a distance of 66 feet (20 meters) but not at 820 feet (250 meters). Thus, these results suggest that health effects for workers outside of the immediate vicinity of a release would primarily be related to H_2S exposures should a pipeline rupture or be punctured.

Potential health effects to offsite populations from the CO_2 concentrations predicted for a pipeline rupture or puncture at the plant site are unlikely, since the CO_2 concentrations more than 820 feet (250 meters) 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 occurs, the impact zone with predicted H_2S concentrations that could cause serious health effects (i.e., above the TEEL-3 criterion of 50 ppmv) could extend to a distance of about 873 feet (266 meters). This distance would extend into the less densely-populated area around the injection site (see maps in Appendix B.) If a pipeline puncture occurred near the injection site, the impact zone with predicted H_2S concentrations that could cause serious health effects (i.e., above the AEGL-3 criterion of 31 ppmv) could extend to about 381 feet (116 meters). Thus, nearby offsite populations could possibly be affected. If the pipeline rupture or puncture occurs closer to the plant site, the predicted H_2S concentrations causing serious health effects would not extend to the populated area around the town of Tuscola.

If a wellhead rupture occurred, the impact zone with predicted H_2S concentrations that could cause serious health effects (i.e., above the TEEL-3 criterion of 50 ppmv) would be close to the wellhead (e.g, 164 feet [50 meters] away). The distance at which H_2S releases from a wellhead rupture are predicted to cause only mild transient effects (i.e., above the TEEL-1 criteria of 0.51 ppmv) would occur at a distance of about 2,034 feet (620 meters), and thus effects could occur in a populated area, as shown in the maps in Appendix B. The impact zone represents the area where individuals could potentially be affected, depending on wind direction and other meteorological conditions at the time of the release. The number of individuals who could actually be affected by any given release is determined by the size, shape, and location of the dispersion plume, which could occupy only a very small portion of the zone of possible impacts. For example, the estimated size of the plume from a wellhead rupture is only 1.2 percent of the entire circular area defined by a radius equal to the maximum downwind distance at which the AEGL-1 is exceeded. Thus, the number of individuals that could be exposed to adverse effects of H_2S (i.e., 0.51 ppmv) or CO_2 (30,000 ppmv) is much less than the number of people in the zone of possible impacts. Based on the population density, no individuals are estimated to be potentially affected by CO_2 from a wellhead rupture, and less than one individual could be exposed to adverse effects of H_2S (i.e., 0.51 ppmv). These results, therefore, indicate that there is greater likelihood of health effects for nearby populations from H_2S than CO_2 releases from a pipeline or wellhead rupture or pipeline puncture.

Tabular and graphical summaries of the expected number of affected individuals (P_i) at all points along the pipeline provide a comprehensive summary of potential health effects from a pipeline release and a basis for comparisons between sites. Figure 4-5 shows the results of the analysis of a pipeline rupture of the estimated population exposed to H_2S concentrations (0.51 ppmv) that can result in adverse effects at the Tuscola Site. For the section of the pipeline beginning at the plant and extending to about 7.5 miles (12 kilometers) less than 3 individuals would be expected to be exposed to H_2S above 0.51 ppmv from a pipeline rupture. Between the pipeline segments from about 7.5 to 9.3 miles (12 to 15 kilometers), the number of individuals that would be expected to be exposed to H_2S above 0.51 ppmv from a pipeline rupture increases to about 7 individuals. The portion of the pipeline where between one and ten individuals could be affected by a pipeline rupture due to H_2S above 0.51 ppmv is 8.4 miles (13.5 kilometers) out of the 11-mile (17.7-kilometer) long pipeline, as shown in Table 4-12. This pipeline segment is near the town of Arcola as shown in the maps in Appendix B. Additional mitigation measures for the pipeline could be implemented along this segment to reduce the potential for effects to offsite populations. A similar analysis was conducted for the pipeline puncture scenario. The results are provided for all four sites in tabular format in Table 4-12. A shorter length of pipeline could have between one and ten individuals affected by a pipeline puncture due to H_2S exposure at levels above 0.33 ppmv (2.1-mile (3.3-kilometer) out of the 11-mile (17.7-kilometer) long pipeline), as shown in Table 4-12.

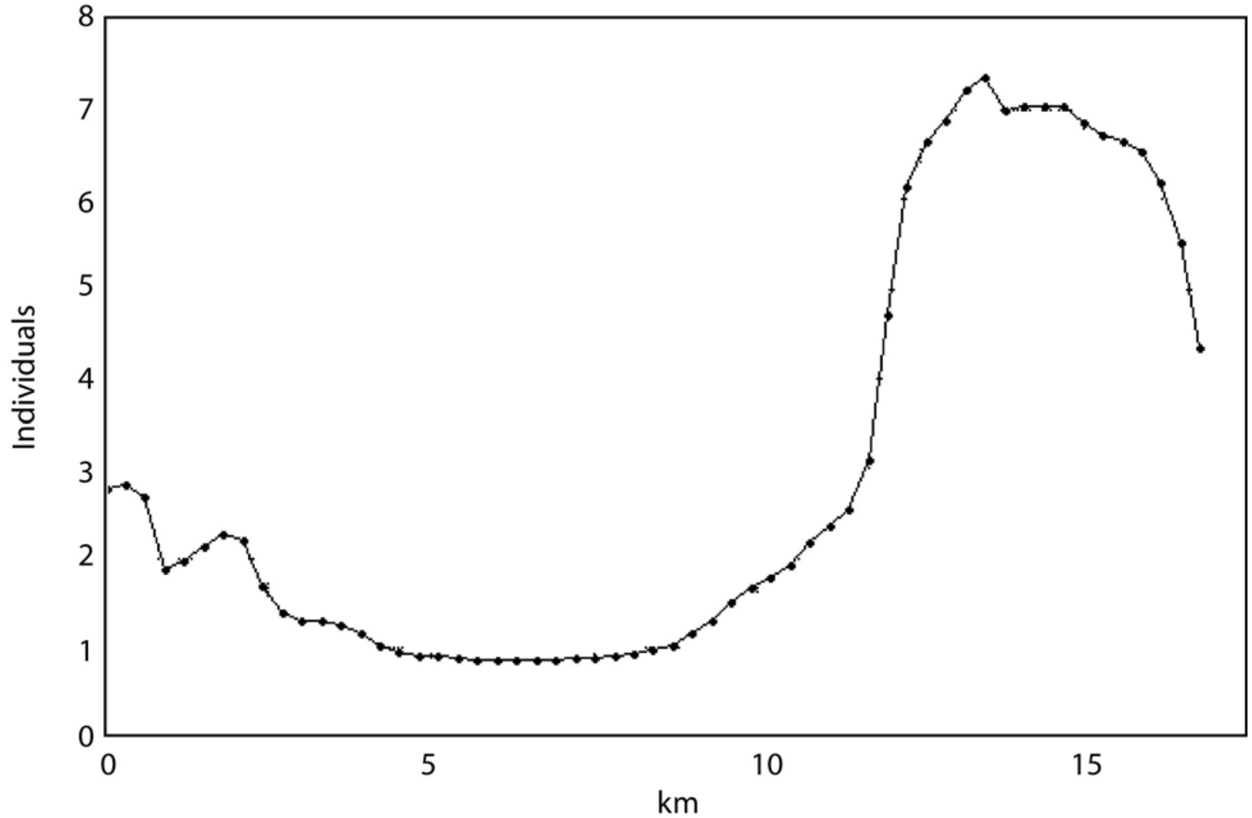

Figure 4-5. Expected Population Impact to 0.51 ppmv H_2S from Pipeline Rupture at Tuscola, IL[4]

4.5.4.3 Ecological Risk Results

Both aquatic biota in the wetlands and Kaskaskia River and the endangered Indiana bat that lives in the wooded riparian habitat are a potential concern. A series of wetlands is located about 2 miles away from the plant site. The Kaskaskia River is located about one mile away from both the plant and injection site, and follows a generally north-south route from 1 to 3 miles (1.6 to 4.8 kilometers) west of the pipeline corridor.

There is a low potential for the captured gas to be released into surface water, because the pipeline does not cross a river, although there could be small ponds or wetlands in the vicinity. The CO_2 concentration in the water is unlikely to reach 2 percent (when injuries to aquatic life can occur; see the risk table for biota), since the solubility of CO_2 at typical atmospheric conditions would keep the concentration less than about 0.2 percent. H_2S concentrations in the water are predicted to be less than the criterion (0.002 mg/L) protective of freshwater aquatic biota.

The pipeline is expected to be buried to a depth of about 3.2 feet (1 meter). Thus, if a leak or rupture occurred, the released gas would first migrate into the soil gas and displace the ambient air. Respiratory effects to biota due to atmospheric CO_2 concentrations are unlikely to occur, except along the pipeline where the rupture or leak occurred, since the predicted offsite concentrations are less than 1 percent. Soil gas concentrations can be higher depending on soil type, so effects on soil invertebrates or plant roots could occur close to the segment where the pipe failed or leaked. One of the primary biota of concern at the injection site is the endangered Indiana bat, which may visit the streams and wetlands for short

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[4] **Expected population impact at every 984-foot (300-meter) location along the pipeline. Each point on the graph represents the results of a complete simulation of H_2S release from the pipeline described in Steps 1 – 5 of the revised assessment methodology.**

periods of time. No effects on the bats would be expected, since they would not be directly exposed to the soil gas.

4.5.5 RISK RESULTS FOR CO-SEQUESTRATION EXPERIMENT

A co-sequestration experiment is planned for the selected site that involves injection of gas for a period of seven days where the H_2S has not been removed. This gas is estimated to contain 95 percent CO_2 and 2 percent H_2S. The starting H_2S concentration would be 20,000 ppmv, compared to the baseline conditions in which the H_2S concentration is 100 ppmv. During transport of the gas to the injection wells, a pipeline rupture or leak could occur at the higher H_2S concentration of 14,800 ppmv, given that 26% of the gas is expected to be in a solid phase, snow, upon release. During co-sequestration the H_2S concentrations in the pipeline would be greater than the NIOSH's IDLH criterion of 100 ppmv for 30-minute exposures and greater than 500 ppmv when knockdowns can occur, where exposed individuals can experience reversible unconsciousness (Guidotti, 1994).

The pipeline walk method, described in Section 4.4.2, was used to estimate the effect of a pipeline rupture and a puncture during the co-sequestration test. These results are included in Appendix C-5, and sensitivity analyses are described in Appendix C-6. The endpoint presented for these analyses is the number of persons potentially affected. Populated areas are present near the plant and injection sites at Jewett, Mattoon, and Tuscola. There are currently populated areas near the plant site at the Odessa Site, but not near the injection site. The distances where people could be exposed to H_2S at levels that could result in adverse effects are significantly greater than for the baseline (100 ppmv H_2S) case. The maximum expected number of people potentially affected by the release of H_2S at 20,000 ppmv from a pipeline rupture and puncture are shown in Table 4-14 below:

Table 4-14. Estimated Expected Number of Individuals Affected by Pipeline Releases during Co-sequestration Test

Site	Distance to Adverse Effects Level for H_2S (0.51 ppmv)	Maximum Individuals Potentially Affected by Pipeline Rupture	Distance to Adverse Effects Level for H_2S (0.33 ppmv)	Maximum Individuals Potentially Affected by Pipeline Puncture
Jewett, TX	F class 85.1 miles (137 km) Other classes ≤ 21.7 miles (35 km)	1,415	F class 38.2 miles (61.4 km) Other classes ≤ 3.7 miles (5.9 km)	447
Tuscola, IL	F class 59.2 miles (95.2 km) Other classes ≤ 18 miles (29 km)	542	F class 37.1 miles (59.8 km) Other classes ≤ 4.0 miles (6.4 km)	178
Odessa, TX	F class 51.1 miles (82. km) Other classes ≤ 14.3 miles (23 km)	55	F class 34.9 miles (56.2 km) Other classes 3.7 miles (5.9 km)	10
Mattoon, IL	F class 16.1 miles (25.9 km) Other classes ≤ 4.2 miles (6.7 km)	123	F class 11.5 miles (18.5 km) Other classes ≤ 2.0 miles (3.3 km)	52

The results shown in Table 4-14 are initial estimates only, and are influenced by four major factors. These factors are: changes in stability class, variable wind speed, varying wind direction, and availability of population data.

- ***Changes in Stability Class. The predicted distances of plume transport are dependent upon the meteorological conditions selected and vary substantially by stability class. Classes D & F of the Pasquill stability categories are used to represent the most stable wind conditions; classes A & B of the Pasquill stability categories represent the most unstable wind conditions. The farthest distance to the specified time-averaged concentration criteria is predicted by SLAB for F2 meteorological conditions (i.e., class F wind stability and a 2 m/sec wind speed). The shortest distance to the specified time-averaged concentration criteria is predicted by SLAB for A2 meteorological conditions (i.e., class A wind stability and a 2 m/sec wind speed). The estimated number of people affected listed in the above table is the expected maximum number of people at a location along the pipeline route taking into account the percent of time that a given stability class is likely to occur. The F stability class that results in the longest distance occurs infrequently; the percent of time is 20 % at Jewett, 8.1 % Mattoon, 4.8 % at Odessa, and 4.6 % at Tuscola. The distance a plume is estimated to be transported for the other stability classes is 5 to 9 times less than for the F stability class. Another factor is that the time required to reach the longest distance can be substantial (e.g. 19 hours at Jewett), and it is unlikely that the wind would be maintained at the same stability class, wind speed, and direction to reach a distant population. Thus, the distances that a plume could be transported are likely to be an overestimate for the F2 stability class. The readily available data sets from the NOAA Climatic***

Data Centers at airports provide stability and wind speed only once an hour, rather than on a 15-minute basis. Thus, data to determine how long a given stability class occurs before changing to another were not available.

- *Variable Wind Speed. As seen in the above table, varying the wind speeds for the same stability class influences the results, but not as much as changing the stability class. Six wind speeds were used in the modeling at each site from 1 to 8 m/sec for the Texas sites and from 2 to 12 m/sec for the Illinois sites. As mentioned above, wind speed controls the time to reach a given distance. Longer periods with steady wind speed are necessary to reach the furthest populated areas.*

- *Varying Wind Direction. Plume transport estimates are made for 16 different wind directions at each 300 meter location along the pipeline route. The results for the number of individuals within each plume are weighted by the percent of time each of the 16 wind directions occurs on an annual basis. In some cases, the wind would have to blow steadily within a narrow quadrant to reach a populated area.*

Availability of Population Data. Population data for census tracts were obtained along the pipeline route. The size and shape of the tracts vary, so that the distance out from the pipeline for which population density was available varied at each site and by segment. For some small segments of the pipeline in a given direction, population data were available only for 15 kilometers at Mattoon where the pipeline was shorter and to 25 kilometers at the other sites. Thus, the population estimates in Table 4-14 may be under predicted for the F2 stability class for certain pipeline segments and wind directions out of the 16 directions analyzed. Population census tract data were available for the estimated transport distances for the majority of the other stability classes, and for the higher health criteria for H_2S, as listed in Appendix C-6.
To minimize the potential for releases during the co-sequestration experiment when high H_2S concentrations of 20,000 ppmv would be present in the pipeline, additional protective measures could be implemented including inspection of the pipeline before and after the test and not allowing any excavation along the pipeline route during the test.

If a wellhead equipment failure occurs at an injection well while the co-sequestered gas is being injected, the H_2S concentration could be 20,000 ppmv. Wellhead ruptures after the actual co-sequestration was completed would have lower H_2S concentrations. If a wellhead failure occurs at an injection well sometime after a co-sequestration experiment, the co-sequestered gases could flow from the geologic reservoir back into the well where it would then escape to the atmosphere through the damaged wellhead. However, subsurface modeling conducted by Battelle in the Final EIV shows that the H_2S concentrations would gradually decrease over a 2-year period to less than 100 ppmv. During this interim two-year period, the H_2S concentrations in the co-sequestrated gas close to the well would vary between 100 ppmv and 20,000 ppmv. Wellhead ruptures after two years would be predicted to have similar effects as the standard case. During the interim period, higher concentrations could be released, and could potentially impact larger populations at the Jewett, Mattoon, and Tuscola Sites, and could reach the populated areas west of the Odessa injection wells, depending on the location of the specific well used.

5.0 POST-INJECTION RISK ASSESSMENT

5.1 Introduction

This chapter evaluates the potential impacts from CO_2, and H_2S, after the injection of CO_2 into subsurface reservoirs. Under the right conditions, CO_2 may remain trapped for extremely long time periods in subsurface reservoirs. However, sequestered gases may also be accidentally released through one of the following key mechanisms (Section 2.3) (IPCC, 2005):

- Upward leakage through the caprock due to either catastrophic failure and quick release or gradual failure and slow release;
- Release through existing faults or induced faults due to the effects of increased pressure;
- Lateral or vertical leakage into non-target aquifers due to an unknown structural or stratigraphic connection with the target zone, or due to a lack of geochemical trapping and inadequate retention time in the target zone; and
- Upward leakage through inadequately constructed wells, abandoned wells, or undocumented wells.

The analysis of releases from the geological storage of CO_2 is a new field and there are no well-established methodologies for modeling these releases (IPCC, 2005) or guidance from USEPA. Further, many studies have concluded that it is impossible to confidently quantify the likelihood and magnitude of accidental releases of sequestered CO_2 (Vendrig et al., 2003). Therefore, data from natural and engineered analogs were used to provide a range of emissions estimates for sequestered gases. The available data for natural and engineered analogs are reviewed in Section 5.2. These data are then used to estimate emission rates in Section 5.3.

Following the determination of potential release rates in Section 5.3, this chapter will examine the receptors that could be exposed to potential releases (Section 5.4), estimate the concentrations in environmental media to which receptors may be exposed (Section 5.5), and determine the potential consequences of those exposures (Section 5.6).

5.2 Analog Site Database

The role of the Analog Site Database and ancillary databases in the overall approach for conducting the HSE risk assessment (Risk Assessment) is shown in Figure 5-1. The central task in risk assessment is the development of the CSMs for the proposed site locations. Four key elements of the CSMs are described above in Section 2. A System Model, divided into the biosphere, upper geosphere, site wells and the lower geosphere, is used as the basis for the CSMs. A detailed geological description of the primary and secondary containment provided by the target formation, as well as critical information on the potential attenuation and dispersion in the near-surface and surface environment, was developed. The primary source of information for the System Model was the Geohydrologic Conceptual Model for each site from the EIVs. The System Model utilized the release scenario data base to ensure model completeness. The System Model also includes plant and pipeline design information available in the EIVs and developed by Tetra Tech through their participation in the FutureGen design meetings.

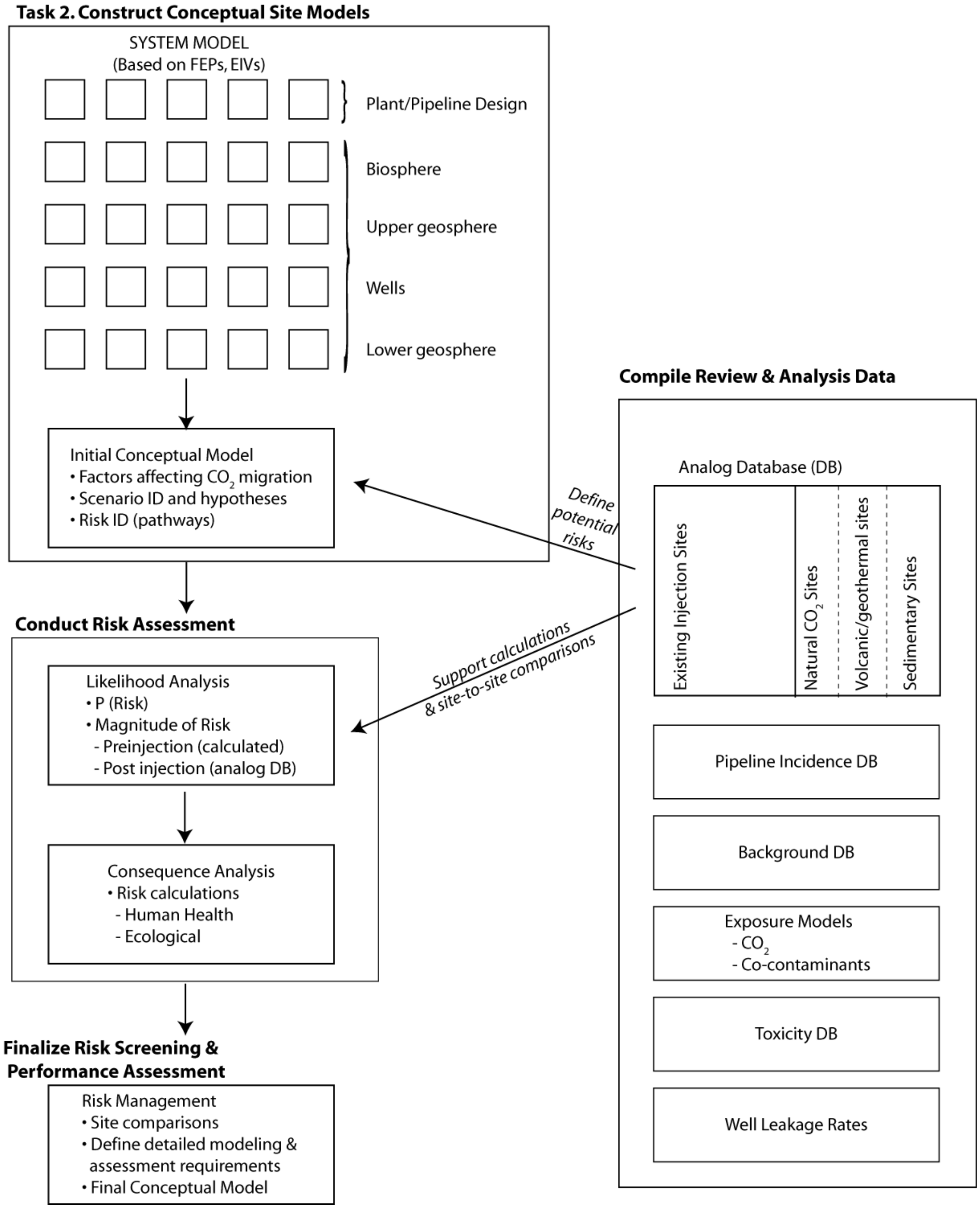

Figure 5-1. Role of the Analog Site Database and Ancillary Databases in the Approach for Conducting the Risk Assessment

5.2.1 BACKGROUND AND RATIONALE

CO_2 can be found in natural reservoirs all over the world in a wide range of geological settings, particularly in sedimentary basins, intra-plate volcanic regions and in faulted areas or in quiescent volcanic structures (IPCC, 2005). These CO_2 accumulations are derived from magmatic sources, the decomposition of organic matter, and the thermal decomposition of carbonate rocks. CO_2 is effectively contained in many of these CO_2 reservoirs, mostly in sedimentary rocks overlain by low permeability strata (i.e., the same types of geologic settings that trap hydrocarbons and form petroleum and/or natural gas reservoirs); however, leaks from CO_2 reservoirs do occur, typically in volcanic, hydrothermal, and metamorphic (VHM) systems. In addition to the leakage of CO_2 from reservoirs, there is a constant flow of CO_2 emitted from organisms in the shallow soils due to the decomposition of organic matter as well as the respiration of organisms living in soils (e.g., plant roots). This process is often called soil respiration or ecosystem efflux. Thus, CO_2 flows from the ground surface into the atmosphere continually all over the world, often dispersing into the atmosphere harmlessly, regardless of its source (Benson et al., 2002).

One way of demonstrating that CO_2 can remain trapped underground for geologically significant timescales is to provide evidence from existing naturally occurring reservoirs, which occur in a variety of geologic environments and can be demonstrated to have stored CO_2 for periods longer than those being considered for CO_2 sequestration. Therefore, many studies are now underway to investigate natural CO_2 reservoirs and what they may tell us about the effectiveness of geologic sequestration (Streit and Watson, 2004; Shipton et al., 2005; IEA Greenhouse Gas R&D Program, 2005 and 2006a).

These studies of natural and industrial analogs for geologic storage of CO_2 (i.e., sites in similar geologic and hydraulic settings with similar anthropogenic influences) provide evidence for the feasibility of geologic containment over the long-term and for characterizing the nature of potential risks from surface leakage, should it occur. Leakage of CO_2 from some of the deep CO_2 sources provides a natural analog for leakage associated with geologic storage of CO_2, should it occur (Benson et al., 2002). These natural analogs provide the strongest basis for understanding and quantifying the emission rates of CO_2 potentially released from the subsurface. To make use of these natural and industrial analogs, the data and findings from these natural CO_2 reservoir investigations were compiled into a database for use in the FutureGen Project Risk Assessment. Oil and gas EOR projects have calibrated and validated complex mathematical models for CO_2 flow and transport processes within target formations for time-scales on the order of 50-100 years. Thus, these types of reservoir models, as presented in the EIVs, can be directly and quantitatively used for defining the FutureGen site subsurface design conditions, and have been used in this manner in this study. However, complex mathematical models to predict CO_2 releases from the target sequestration reservoirs to the surface have not yet been calibrated and validated for the 5,000 year time-scales and processes addressed in a CO_2 sequestration project. As such, quantitative leakage models cannot be solely used to predict leakage from CO_2 sequestration sites. Analog studies supported by leakage model efforts provide the most compelling information regarding leakage at each FutureGen site, and leakage model results, such as those presented in the EIVs, have been used in this manner in this study.

5.2.2 ANALOG SITE DATABASE: DESCRIPTION AND USE

The Analog Site Database was developed to provide information on the release of CO_2 from existing injection sites and natural releases. The analog site database is a compilation of studies performed at other CO_2 storage locations and from sites with natural CO_2 accumulations and releases. Since there is limited information on leakage rates from deep saline injection projects, the analog site search was extended to existing CO_2 injection sites, natural CO_2 sites, and VHM CO_2 emission sites. While it is recognized that, by their very nature, VHM sites are not good analogs for CO_2 releases from sedimentary basins, releases from VHM sites provide valuable information on CO_2 attenuation and dispersion in the near surface and surface environment, and the potential impact of CO_2 emissions on human health and the environment.

The analog site database currently includes information that has been obtained from four existing CO_2 injection sites[1] (i.e., Rangely, Weyburn, In Salah, and Sleipner), 16 natural CO_2 sites in sedimentary rock formations, and 17 sites in VHM areas (Table 5-1). These sites have been identified in several natural analog investigations for CO_2 sequestration (e.g., Benson et al., 2002; IEA Greenhouse Gas R&D Program, 2005 and 2006a; IPCC, 2005; Streit and Watson, 2004).

Table 5-1. Sites Included in Analog Sites Database

Location/Site	Site Type
Existing CO_2 Injection Sites	
Sleipner, North Sea	Sedimentary
Weyburn, CO_2 Project, Canada	Sedimentary
Rangely CO_2 EOR Project, CO	Sedimentary
In Salah, CO_2 Project, Algeria	Sedimentary
Natural CO_2 Sites	
Crystal Geyser-Ten Mile Graben (Fault Zone), UT	Sedimentary
Teapot Dome, WY	Sedimentary
Farnham Dome, UT	Sedimentary
Otway (Penola), Australia	Sedimentary
Otway (Pine Lodge, Permeable Zone), Australia	Sedimentary
Otway (Pine Lodge, Fault), Australia	Sedimentary
Springerville, AZ	Sedimentary
St. Johns Dome, AZ-NM	Sedimentary
Vorderrhon, Germany	Sedimentary
Jackson Dome, MS	Sedimentary
McElmo Dome, CO	Sedimentary
Bravo Dome, NM	Sedimentary
Big Piney – La Barge Area, WY	Sedimentary
Gordon Creek, UT	Sedimentary
Escalante, UT	Sedimentary
Sheep Mountain, CO	Sedimentary

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[1] **Teapot Dome is also an experimental CO_2 injection site, but injection did not start until mid 2005, well after the CO_2 flux measurements were made. Therefore, Teapot Dome is not considered a CO_2 injection site within the context of this analog database.**

Table 5-1 (continued). Sites Included in Analog Sites Database

Location/Site	Site Type
Volcanic/Geothermal Sites	
Mesozoic carbonate, Central Italy	Sedimentary -hydrothermal
Mammoth Tree Kill Area, CA	Volcanic
Matraderecske, Hungary (Permeable Zone)	Volcanic - hydrothermal
Matraderecske, Hungary (Fault)	Volcanic - hydrothermal
Masaya volcano, Nicaragua	Volcanic
Alban Hills, Italy	Volcanic - hydrothermal
Latera, Tuscany, Italy	Volcanic - hydrothermal
Poggio dell'Ulivo, Italy	Volcanic - hydrothermal
Yellowstone volcanic system, WY	Volcanic - hydrothermal
Dixie Valley Geothermal Field, NV	Volcanic - hydrothermal
Poas volcano, Costa Rica	Volcanic
Arenal volcano, Costa Rica	Volcanic
Oldoinyo Lengai volcano, Tanzania	Volcanic
Solfatara crater, Italy	Volcanic
Vulcano Island, Italy	Volcanic
Cerro Negro, Nicaragua	Volcanic
Miyakejima volcano, Japan	Volcanic

The most relevant natural analogs for geologic containment over the long-term are CO_2 and CO_2 -rich natural gas fields (Benson et al., 2002). The types of information collected, listed in Table 5-2, were selected based upon the following criteria:

- Data and information requested in the geologic storage qualifying criteria and geologic storage scoring criteria given in the FutureGen request for proposals;

- Data and information identified as key factors in the geologic carbon sequestration health, safety, and environment screening and ranking framework developed by LBNL (Oldenburg, 2005);

- Data and information defined as key factors controlling the potential for CO_2 leakage and the magnitude of CO_2 leakage in recent CO_2 risk assessments and risk assessment guidelines (Benson et al., 2002; IPCC, 2005); and

- Data and information defined as important factors in recent analog studies (Streit and Watson, 2004; IEA Greenhouse Gas R&D Program, 2005 and 2006a).

Table 5-2. Parameters Compiled in Analog Site Database

General Site Information
Location/Site
General Site Type (Volcanic/Geothermal or Sedimentary)
Area (sq km)
Description of CO_2 Zone
Depth (m)
Areal Extent (sq km)
Structural Closure (m)
Lithology
CO_2 Origin
CO_2 Age (years)
Net Thickness (m)
Gross Thickness (m)
Gas Composition (percent CO_2)
Porosity (Fraction)
Permeability (mD)
Pressure Gradient (psi/ft)
Fracture Gradient (psi/ft)
Reservoir Water Chemistry TDS (mg/L)
Description of CO_2 Flux Rates & Reservoir Volume
CO_2 Zone Regional Flow Rate (m/year)
CO_2 Production Rate (cu m/year)
CO_2 Reservoir Volume (cu m)
Description of Leakage Event
CO_2 Leakage Rate (gm/sq m/day)
Event Triggering Leakage
Pathway for Leakage
Type of Release
Surface Topographic Slope (m per m)
Average Surface Wind Speed (m/sec)
Average Atmospheric Stability Class
Surface Climate Type (arid; semi-arid, etc)
Surface CO_2 Concentration (ppm)
Known Human Impacts from CO_2 Releases
Known Ecosystem Impacts from CO_2 Releases

Table 5-2 (continued). Parameters Compiled in Analog Site Database

Description of Primary and Secondary Seals
Lithology
Zone Areal Extent (sq km)
Zone Gross Thickness (m)
Porosity (fraction)
Permeability (mD)
Capillary Entry Pressure (Mpa)
Description of Secondary Porous Zone
Lithology
Zone Areal Extent (sq km)
Depth (m)
Gross Thickness (m)
Porosity (fraction)
Permeability (mD)
Capillary Entry Pressure (Mpa)
Description of Groundwater (GW)
Regional Flow (m/year)
Pressure (kPA)
TDS (mg/L)
Major Cation (Type-mg/L)
Major Anion (Type-mg/L)
Primary Storage Formation - Regional Flow (m/year)
Description of Vadose Zone
Thickness (m)
Porosity (fraction)
Permeability (mD)
CO_2 Concentration (ppm)
Surface Water Information
Depth (m)
Lake HCO_3 (mg/L)
River HCO_3 (mg/L)
Information on Faults
Number of Tectonic Faults
Number of Normal Faults
Number of Strike-Slip Faults
Fault Permeability (mD)

Table 5-2 (continued). Parameters Compiled in Analog Site Database

Nearby Wells
Number of Deep Wells Number of Shallow Wells Number of Abandoned Wells
Injection Wells
Number of Injection/Disposal Wells Injection Rate (MMT/year) Total Reinjected (MMT)
Radon Information
References

Not all information was pertinent for a given site and not all the information could be obtained. The CO_2 release rates are expressed as g/m^2-year (or micromoles per meter squared-second [µmol/m^2-s]), so that the relative leakage rates could be compared among the sites. References are included in the database.

The Analog Site Database was used to identify sites where CO_2 has been released, and that had measured or estimated release rates, and information on effects on human health and the environment. The database was used to identify realistic CO_2 migration pathways and factors that influence those pathways for use in formulating the conceptual model (Figure 5-2). These pathways provide the basis for the description of potential release scenarios for the FutureGen sites. Comparison of information from the System Model and the parameter values in the Site-Analog Database was then used to identify analogs for the proposed injection sites, which are in turn used to estimate both the probability of releases and the magnitude of releases at the proposed sites.

The first step in applying the Analog Site Database is to conduct a qualitative review of the geologic setting and a quantitative analysis of the FutureGen site database to assess the similarity of each FutureGen site and determine the most appropriate (set of) analog site(s). Then, where known release estimates are available from the selected analog site, the release estimates are extrapolated from the analog site to the candidate site.

5.2.3 OVERVIEW OF THE ANALOG SITE DATABASE

Figure 5-2 shows the CO_2 emission flux values in the analog site database for a total of 28 analog sites that have measurements of deep-sourced CO_2 flux values. Twelve of the sites are located in sedimentary basins, and the remaining 16 sites are in VHM settings. Figure 5-2 also shows the typical range of soil respiration rates of CO_2 from the ground surface (i.e., 0.05 to 20 µmol/m^2-s). The most striking feature of Figure 5-2 is that there is a marked difference between the magnitudes of the CO_2 flux values in sedimentary basins versus those in VHM settings.

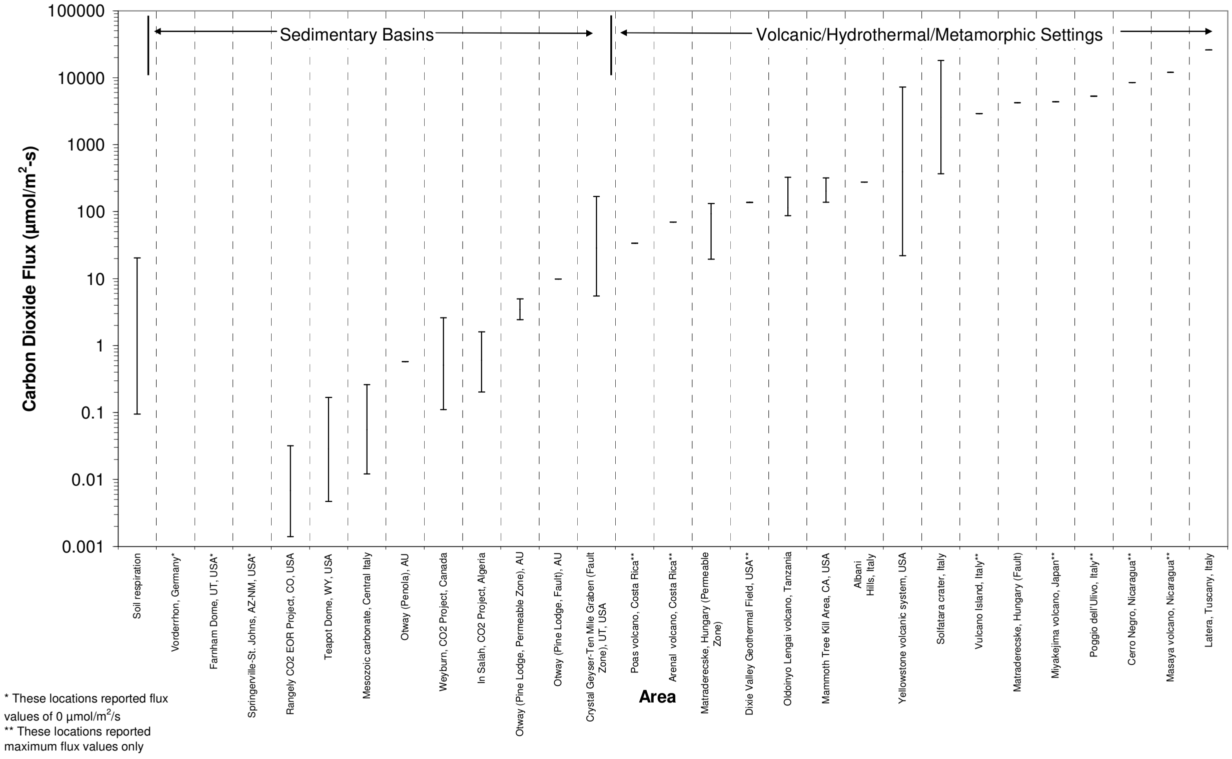

Figure 5-2. Plot of CO_2 Emission Rate for 28 Analog Sites

CO_2 fluxes from both natural and EOR sites in sedimentary basins range as follows:

- Fluxes were measured that are essentially zero at three sites (i.e., Vorderrhon, Germany; Farnham Dome, UT, USA; and Springerville-St. Johns, AZ-NM, USA). Note that in addition, there are several other sedimentary sites (e.g., Jackson Dome, MS and Sleipner, Norway) where it is strongly believed that there are no CO_2 emissions from the CO_2 reservoirs, but there are no flux monitoring data to support that assumption;

- Fluxes were measured at 0.01 to 1 µmol/m²-s at four sites (i.e., Rangely CO_2 EOR Project, CO, USA; Teapot Dome, WY, USA; Mesozoic carbonate, Central Italy; and Otway (Penola), Australia);

- Fluxes were measured at up to 1 to 10 µmol/m²-s at four sites (i.e., Weyburn, CO_2 Project, Canada; In Salah, CO_2 Project, Algeria; Otway (Pine Lodge, Permeable Zone), Australia; and Otway (Pine Lodge, Fault), Australia); and

- Fluxes were measured at 5 to 170 µmol/m²-s at one site (i.e., Crystal Geyser-Ten Mile Graben (Fault Zone), UT, USA).

Thus, flux rates of CO_2 from the sedimentary basin reservoirs are extremely low. At most locations that release CO_2, the rates are well below typical soil respiration rates. The only sedimentary basin reservoir where CO_2 fluxes significantly exceed typical soil respiration rates is associated with discharge from a fault zone (i.e., Crystal Geyser). Note also that (1) the sedimentary sites with the two highest CO_2

emission rates are from measurements associated with fault discharges, and (2) despite the impacts of wells and injection pressure, the fluxes at CO_2 injection sites (i.e., Rangely, Weyburn, and In Salah) are still below typical soil respiration rates. These findings for sedimentary basin sites (see Figure 5-2) are consistent with reports in the literature, which note the following:

- There are many CO_2 fields in sedimentary basins that have held CO_2 for millions of years without any evidence of leakage or environmental impact (IEA Greenhouse Gas R&D Program, 2006a);
- Some CO_2 fields in sedimentary basins do leak, but usually via carbonated springs or dry seeps. This results in either no ecosystem damage or only very localized ecosystem damage (IEA Greenhouse Gas R&D Program, 2006a). Note that since fluxes from most sedimentary basin sites are well below typical soil respiration rates, ecosystem damage would not be expected, since releases from CO_2 reservoirs add very little in the way of emissions;
- Natural accumulations occur in a number of different types of sedimentary rocks (principally limestones, dolomites and sandstones), with a variety of seals (i.e., mudstone, shale, salt, and anhydrite), and a range of trap types, reservoir depths, and CO_2 -bearing phases (IPCC, 2005);
- Fractures seem to control CO_2 migration through the geosphere (IEA Greenhouse Gas R&D Program, 2005);
- CO_2 is also emitted from sedimentary basins, many of which occur in tectonically stable regions with little or no VHM activity. In sedimentary basins, CO_2 is commonly held in porous formations such as sandstones/limestones where the super-critical compressed gas is trapped by overlying layers of impermeable rocks, such as marine shales and salt. This is analogous to the way oil and gas is trapped in sedimentary basins. CO_2 leaks from sedimentary basins through permeable rocks, faults/fissures in rock, and accidentally via wells. In some cases, springs are observed at faults/wells, but more commonly, CO_2 appears at the ground already dispersed to surrounding strata at very low seepage rates (IEA Greenhouse Gas R&D Program, 2006a); and
- Wells that are structurally unsound have the potential to rapidly release large quantities of CO_2 to the atmosphere (Lewicki et al., 2006).

CO_2 fluxes in VHM settings range as follows:

- Fluxes have been measured above the range of typical soil respiration rates (i.e., 0.05 to 20 $\mu mol/m^2$-s) at all VHM sites;
- Fluxes were measured from 20 to 200 $\mu mol/m^2$-s, or roughly one order of magnitude greater than typical soil respiration rates, at seven sites (i.e., Poas volcano, Costa Rica; Arenal volcano, Costa Rica; Matraderecske, Hungary (Permeable Zone); Dixie Valley Geothermal Field, USA; Oldoinyo Lengai volcano, Tanzania; Mammoth Tree Kill Area, CA, USA; and Albani Hills, Italy); and
- Fluxes were measured up to 2,000 to 20,000 $\mu mol/m^2$-s, or roughly two to three orders of magnitude greater than typical soil respiration rates, at nine sites (i.e., Yellowstone volcanic system, USA; Solfatara crater, Italy; Vulcano Island, Italy; Matraderecske, Hungary (Fault); Miyakejima volcano, Japan; Poggio dell'Ulivo, Italy; Cerro Negro, Nicaragua; Masaya volcano, Nicaragua; and Latera, Tuscany, Italy).

Thus, in all of the VHM settings, CO_2 is released from the ground at emission rates above typical soil respiration rates. Also, in both VHM settings and sedimentary basins, fault or fracture structures are the primary pathways that result in high CO_2 release rates. These findings for VHM settings (see Figure 5-2) are consistent with reports in the literature, which note the following:

- There is a well established correlation between high CO_2 emission rates and tectonic zones, seismic activity, and volcanism. As such, most detectable emissions that lead to locally elevated atmospheric CO_2 concentrations, and virtually all hazardous leaks, occur in volcanic areas that are highly fractured and, therefore, unsuitable for CO_2 sequestration (Benson et al., 2002);

- Fractures seem to control CO_2 migration through the geosphere (IEA Greenhouse Gas R&D Program, 2005);

- At some VHM locations in Italy, CO_2 emission rates at quite high, with some cases being directly under housing developments. Yet, there is only a very small increase in indoor air CO_2 concentrations in some of these areas. However, risks do exist in some areas, as demonstrated by livestock kills, ecosystem damage (IEA Greenhouse Gas R&D Program, 2005), and elevated CO_2 concentrations in some VHM settings;

- All of the significant natural CO_2 hazards are associated with volcanism and not with any known sedimentary basin CO_2 reservoirs, and these hazards are only present in geologic settings that would not be considered for CO_2 sequestration (Benson et al., 2002);

- Many natural releases of CO_2 have been correlated with a specific event that triggered the release, such as magmatic fluid intrusion or seismic activity (Lewicki et al., 2006). For example, releases due to earthquakes are well documented at Hyogo-ken Nanbu, Japan; Matushiro, Japan; and, Mammoth Mountain CA, USA.

- Unsealed fault and fracture zones may act as fast and direct conduits for CO_2 flow from depth to the surface. Determining the potential for and nature of CO_2 migration along these structures (Lewicki et al., 2006) is, therefore, important;

- The hazard to human health has been small in most cases of large CO_2 surface releases (Lewicki et al., 2006), excluding two events due to lake overturn in Africa; and

- While changes in groundwater chemistry were related to CO_2 leakage due to acidification and interaction with host rocks along flow paths, waters remained potable in most cases (Lewicki et al., 2006).

5.2.4 WELL FAILURE-RELEASE EVENT DATABASE

In addition to leakage from reservoirs via natural pathways, another major release pathway is via wells (Lewicki et al., 2006). Although data for well leakage are very limited for CO_2 sequestration operations, there is a good deal of data available from the natural gas storage industry (Papanikolau et al., 2006; IEA Greenhouse Gas R&D Program, 2006b) and the oil and gas industry (Holland, 1997). Data on releases from wells at natural CO_2 reservoirs are also available (e.g., Shipton et al., 2005; Bogen et al., 2006). A summary of these well failure data are given in Table 5-3.

Based upon the number, depth, and type of wells within the plume footprint at each FutureGen site, the data presented in Table 5-3 are used in the risk assessment process to estimate the flux rates, durations, and frequencies.

Table 5-3. Well Releases

References	Item	Frequency	Frequency Units	Duration	Duration Units	Flux	Flux Units	Site	CO_2 Source	Geologic model for accumulation	Event triggering leakage	Pathway for leakage	Type of release	Comment
Papanikolau, N., B. M. L. Lau, W. A. Hobbs and J. Gale. 2006. "Safe Storage of CO_2: Experience from the Natural Gas Storage Industry." In *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies (GHGT-8)*, 19 - 22 June 2006. Trondheim, Norway. IEA Greenhouse Gas R&D Program, 2006b	major incident from a natural gas storage facility	8.39E-04	1 /site-year											once every 1,192 years of site operation
Papanikolau, N., B. M. L. Lau, W. A. Hobbs and J. Gale. 2006. "Safe Storage of CO_2: Experience from the Natural Gas Storage Industry." In *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies (GHGT-8)*, 19 - 22 June 2006. Trondheim, Norway. IEA Greenhouse Gas R&D Program, 2006b	major incident from a natural gas storage well	2.02E-05	1 /well-year					NGS well sites Worldwide, particularly North America						once every 49,505 years of well operation
Papanikolau, N., B. M. L. Lau, W. A. Hobbs and J. Gale. 2006. "Safe Storage of CO_2: Experience from the Natural Gas Storage Industry." In *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies (GHGT-8)*, 19 - 22 June 2006. Trondheim, Norway. IEA Greenhouse Gas R&D Program, 2006b	major incident from a natural gas storage well	5.10E-05	1 /well-year					NGS well sites in Europe						European Study with smaller database
Holand P, Offshore blowouts - Causes and controls., Gulf Publishing Company, 1997.	offshore production well blowout frequency	5.00E-05	1 /well-year	0.5 to 5	days (avg of all wells)			US O&G Experience						once every 20,000 well-years
Holand P, Offshore blowouts - Causes and controls., Gulf Publishing Company, 1997.	offshore production well blowout frequency	6.00E-05	1 /well-year	0.5 to 5	days (avg of all wells)			North Sea O&G Experience						
Holand P, Offshore blowouts - Causes and controls., Gulf Publishing Company, 1997.	offshore workover well blowout frequency	1.70E-04	1 /well-year	0.5 to 5	days (avg of all wells)			US O&G Experience						once every 20,000 well-years
Holand P, Offshore blowouts - Causes and controls., Gulf Publishing Company, 1997.	offshore workover well blowout frequency	6.00E-05	1 /well-year	0.5 to 5	days (avg of all wells)			North Sea O&G Experience						
Holand P, Offshore blowouts - Causes and controls., Gulf Publishing Company, 1997.	offshore exploration well drilling blowout frequency	5.93E-03	1 /well drilled	0.5 to 5	days (avg of all wells)			US O&G Experience						
Holand P, Offshore blowouts - Causes and controls., Gulf Publishing Company, 1997.	offshore exploration well drilling blowout frequency	6.66E-03	1 /well drilled	0.5 to 5	days (avg of all wells)			North Sea O&G Experience						
Holand P, Offshore blowouts - Causes and controls., Gulf Publishing Company, 1997.	offshore development well drilling blowout frequency	3.99E-03	1 /well drilled	0.5 to 5	days (avg of all wells)			US O&G Experience						

Table 5-3 (continued). Well releases

References	Item	Frequency	Frequency Units	Duration	Duration Units	Flux	Flux Units	Site	CO2 Source	Geologic model for accumulation	Event triggering leakage	Pathway for leakage	Type of release	Comment
Holand P, Offshore blowouts - Causes and controls., Gulf Publishing Company, 1997.	offshore development well drilling blowout frequency	1.65E-03	1 /well drilled	0.5 to 5	days (avg of all wells)			North Sea O&G Experience						
Bogen, Kenneth, Elizabeth A. Burton, S. Julio Friedmann, and Frank Gouveia, "Source terms for CO2 risk modeling and GIS/simulation based tools for risk characterization", Proceedings of GHGT-8, 8th International Conference on Greenhouse Gas Control Technologies, 19 - 22 June 2006, Trondheim, Norway.	abandoned well					11,000,000	Kilograms / year	Crystal Geyser, UT	Thermal decomposition of carbonates	Reservoirs are vertically stacked, sandstone units, in fault-bounded anticlinal folds, capped by shale/siltstone units	Well blowouts	Well	Cold geysers	Crystal Geyser, UT
Lewicki,Jennifer L., Jens Birkholzer, and Chin-Fu Tsang, 2006. "Natural and Industrial Analogues for Release of CO2 from Storage Reservoirs: Identification of Features, Events, and Processes and Lessons Learned" Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, LBNL-59784, February 2006	Well blowouts							Sheep Mountain, CO, USA	Thermal decomposition of carbonates	Reservoir is anticlinal fold, bounded on one side by thrust fault, sandstone, ave. depth 1500 m, capped by marine sediments and a laccolith.	Well blowouts	Wells	Free flowing CO2 gas from well, CO2 leakage from fractures above drill site	
Lewicki,Jennifer L., Jens Birkholzer, and Chin-Fu Tsang, 2006. "Natural and Industrial Analogues for Release of CO2 from Storage Reservoirs: Identification of Features, Events, and Processes and Lessons Learned" Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, LBNL-59784, February 2006	Well blowouts							Florina Basin, Greece	Thermal decomposition of carbonates	Reservoirs are vertically stacked, limestone and sandstone units (upper unit at 300 m depth), capped by silts and clays.	Well blowouts	Well	CO2 gas leakage from soils, water filled pool formation around well	
Lewicki,Jennifer L., Jens Birkholzer, and Chin-Fu Tsang, 2006. "Natural and Industrial Analogues for Release of CO2 from Storage Reservoirs: Identification of Features, Events, and Processes and Lessons Learned" Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, LBNL-59784, February 2006	Well blowouts					300	tons/hour	Torre Alfina geothermal field, Italy	Geothermal	Geothermal reservoir with a gas CO2 cap at ~660 m depth, capped by sequences of shales, marls, and limestones.	Well blowouts	Well	Free flowing CO2 gas from well, diffuse emissions from ground around well	Total release of 25,000 t of CO2
Lewicki,Jennifer L., Jens Birkholzer, and Chin-Fu Tsang, 2006. "Natural and Industrial Analogues for Release of CO2 from Storage Reservoirs: Identification of Features, Events, and Processes and Lessons Learned" Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, LBNL-59784, February 2006	Well failure					3.00E+06	m3/ year	Leroy Gas Storage Facility, Wyoming, USA	UNG Storage Facility	confined sandstone and dolomite aquifer at 1000 m depth	well casing failed due to corrosion		From well thru formation to adjacent well	1976 to 1981 lost ~3 percent of the total gas stored

Table 5-3 (continued). Well releases

References	Item	Frequency	Frequency Units	Duration	Duration Units	Flux	Flux Units	Site	CO2 Source	Geologic model for accumulation	Event triggering leakage	Pathway for leakage	Type of release	Comment
Lewicki,Jennifer L., Jens Birkholzer, and Chin-Fu Tsang, 2006. "Natural and Industrial Analogues for Release of CO2 from Storage Reservoirs: Identification of Features, Events, and Processes and Lessons Learned" Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, LBNL-59784, February 2006	Well blowout during drilling					45	million cubic feet of gas	Edmundson Trust #1-33 well, Kingfisher, OK, USA	Hydrocarbon gas	Permian Flowerpot shale overlies the Hennesey Group (Cedar Hills sandstone, Hennesey shale, Garber sandstone), underlain by Wellington formation composed of sandstone and several evaporite units				Lost in one month

5.2.5 RELEVANT EXPERIENCE FROM THE NATURAL GAS INDUSTRY

Recently, IEA Greenhouse Gas R&D Program (2006b) published a report summarizing experience from the natural gas industry that is relevant for CO_2 sequestration. An executive summary of these findings is also given by Papanikolau et al. (2006). Similar to the FutureGen Project, natural gas is frequently stored underground in natural reservoirs. At present, the IEA Greenhouse Gas R&D Program (2006b) estimates that there are 634 underground facilities worldwide; with 410 in the USA and 45 in Canada. In 2005, approximately 6,000,000 million feet^3 (169, 901 million meter^3) of natural gas was stored underground in the US (Energy Information Administration, 2006). The Energy Information Administration also estimates that developed underground natural gas storage capacity in the US in 2004 was as follows:

1. Salt caverns: 239,990 million ft^3 (6,796 million m^3)
2. Aquifers: 1,238,158 million ft^3 (35,061 million m^3)
3. Depleted Reservoirs: 6,776,894 million ft^3 (191,900 million m^3)

These storage patterns are representative of the formations used to store natural gas underground around the world (IEA Greenhouse Gas R&D Program, 2006b). In North America, most of the storage formations are considerably shallower than those being considered for use by the FutureGen Project (i.e., natural gas is usually stored at less than 800 m deep). In Europe, however, the formations used for storage are usually deeper than 2,625 feet (800 meters).

The IEA (2006) provided frequency estimates for natural gas well failures from three different data sources:

1. 2.02×10^{-5} major incidents/well-year for natural gas storage wells (estimated from worldwide data from the 1970s onwards);
2. 5.1×10^{-5} accidents/well-year for natural gas storage wells (estimated from European data); and
3. 5.0×10^{-5} blow outs from oil and gas production/well-year (estimated using data from the Netherlands).

These frequencies are similar to those given in the well failure-release event database (Table 5-3) for natural gas storage wells and other industrial wells. Failure rates reported for natural gas storage wells are remarkably similar to those reported in offshore oil and gas wells.

Releases from underground storage were also reported for mechanisms other than well failures, although this was the major release mechanism. From 20,271 cumulative site-years of underground natural gas storage experience, 16 leakage incidents were identified by the IEA Greenhouse Gas R&D Program (2006b). The frequency of significant leakage from all underground mechanisms was estimated at 7.89×10^{-4} significant leaks/site-year for all types of underground natural gas storage facilities (i.e., caverns, aquifers, and depleted reservoirs). Eight of the leaks catalogued by the IEA Greenhouse Gas R&D Program (2006b) were related to subsurface failures of wells used in the underground storage facility (i.e., "well bore failure," "cracked casing," etc.), three leaks were through the caprock, one was from a subsurface pipe leak, one was from an improperly abandoned well that connected to the storage formation, one was from the intrusion of natural gas into an adjoining aquifer used as a drinking water source, one was from release to an adjoining cavern, and the last one was categorized only as an "underground leak."

The leakage mechanisms observed for the natural gas underground storage sites show that release through the caprock, release to nearby aquifers/permeable formations, and release through abandoned wells are all possible. While plausible, the frequencies observed for release through the caprock and release to nearby aquifers/permeable formations should be markedly higher than release frequencies for the underground sequestration of CO_2, as the target formations for CO_2 sequestration are markedly deeper. However, well-related releases (e.g., cracked casings) may be expected to occur at similar frequencies (i.e., 3.95×10^{-4} significant leaks/site-year).

5.2.6 CO_2 LEAKAGE RATES USED IN OTHER CO_2 SEQUESTRATION RISK ASSESSMENTS

Risk Assessments have been conducted for several proposed CO_2 sequestration sites in sedimentary basins in Australia. CO_2 leakage rates at the Australian sites (Table 5-4) were estimated based upon experience in the natural gas and oil and gas industries, natural analog studies, modeling, and the judgment of an expert panel (Hooper et al., 2005). This is very similar to the approach adopted in this risk assessment. While the leakage estimates for the FutureGen sites will vary from those presented for the Latrobe Valley Kingfish and Basin Centre sites (based upon differences in the site's characteristics), production well failure rates (based upon natural gas and oil and gas experience) are likely to be similar for all sites.

Table 5-4. CO_2 Leakage Rates and Frequencies Estimated for Australian Sites

Site	Mechanism	Frequency (1/1,000 year-item)	Loss Rate, tons/year/item (metric tons/year/item)	Number of Items	Duration (Years)
Basin Center, Latrobe Valley, Australia					
	Compressor failure	0.07	4,409,245 (4,000,000)	12	0.001
	Earthquake	0.0001	1,102 to 6.6 (1,000 to 6)	1	0.083 to 1,000
	Exceed spill point	0.000001	2,204,623 (2,000,000)	1	200
	Leaky exploratory wells	0.1	220 (200)	15	500
	Leaky injection wells	0.001	220 (200)	20	500
	Leaky production wells	0.01	220 (200)	63	500
	Local over-pressure	0.01	33 (30)	20	0.02
	Migration direction error	0.0001	2,204,623 (2,000,000)	1	200
	Pipeline failure	0.07	NA	1	0.083
	Platform failure	0.005	22,046,230 (20,000,00)	1	0.003
	Regional over-pressure	0.00001	6.6 (6)	1	1
	Seal Leak, Fault	0.0001	6.6 (6)	4	100
	Seal Leak, Perm Zone	0.000001	0.011 (0.01)	1	1000
Kingfish, Latrobe Valley, Australia					
	Compressor failure	0.07	4,409,245 (4,000,000)	12	0.001
	Earthquake	0.0001	1,102 to 6.6 (1,000 to 6)	1	0.083 to 1,000
	Exceed spill point	0.000001	1,653,457 (1,500,000)	1	200
	Leaky exploratory wells	0.1	220 (200)	14	500
	Leaky injection wells	0.001	220 (200)	15	500
	Leaky production wells	0.01	220 (200)	91	500
	Local over-pressure	0.01	33 (30)	15	0.02
	Migration direction error	0.0001	1,653,457 (1,500,000)	1	200
	Pipeline failure	0.07	NA	1	0.083
	Platform failure	0.005	16,534,670 (15,000,000)	1	0.003
	Regional Over-Pressure	0.00001	6.6 (6)	2	1
	Seal Leak, Fault	0.0001	6.6 (6)	2	200
	Seal Leak, Perm Zone	0.000001	0.011 (0.01)	1	800

5.3 Sequestered Gas Leakage Analyses

Risk Screening and Ranking

As outlined in the Risk Assessment work plan (Tetra Tech, 2006b), CO_2 leakage from the FutureGen reservoirs was estimated using a combination of relevant industry experience, natural analog studies, modeling, and expert judgment. The first task for each site was to conduct a qualitative risk screening based upon a systems analysis of the site features and scenarios portrayed in the CSM. Risks were qualitatively weighted and prioritized using procedures identified in a HSE risk screening and ranking framework (SRF) recently developed by LBNL for geologic CO_2 storage site selection (Oldenburg, 2005). This approach, which falls loosely under the category of multi-attribute utility theory, is based on the assumption that HSE risk due to CO_2 leakage is dependent upon three basic characteristics of a geologic CO_2 storage site:

1. The potential for primary containment by the target formation;
2. The potential for secondary containment if the primary formation leaks; and
3. The potential for attenuation and dispersion of leaking CO_2 if the primary formation leaks and secondary containment fails.

The risk screening evaluates the sites on the basis of their potential for HSE risks due to CO_2 leakage and seepage, and identifies the key strengths and weaknesses of each site for safely sequestering CO_2. The results are discussed for each site separately in Section 5.5.

Release Scenarios

The second task for each site is to define the key release scenarios. As discussed in the workplan (Tetra Tech, 2006b), the potential release mechanisms listed in Section 5.1 were used to determine the potential release scenarios for each site. Sections 5.3.1 through 5.3.4 give an overview of the most important release scenarios (IPCC, 2005) considered at the FutureGen sites, and a brief discussion of the methodology employed for estimating the magnitude, duration, and probability of CO_2 release for each release scenario. The estimated magnitudes, durations, and probability of release for each particular FutureGen site are given in Section 5.5 and the consequences from those releases are evaluated in Section 5.6. The release estimates are derived based upon both the releases reported for natural analog sites, and the site-specific quantitative reservoir leakage model results presented for the various failure scenarios outlined in the EIVs. It is important to note that leakage from the target reservoir, if it occurs, may take many years, decades, and even centuries to reach the surface, and that CO_2 often may not begin leaking (if ever) for long time periods after the start of CO_2 injection at a site. Details regarding the time periods required for releases to occur are addressed individually for each release scenario since the time-scale for each release scenario will vary depending on the release mechanism and pathway.

5.3.1 UPWARD LEAKAGE THROUGH CAPROCK AND SEALS

These release scenarios assume that CO_2 could be released by upward migration through the caprock from the unaltered native state reservoir, disregarding induced fracturing, fault re-activation, and well bores (i.e., these release scenarios will be addressed separately below). Thus, these release scenarios assume the flow and transport of CO_2 through the caprock and integrate the influence of the following system properties and processes:

- The barrier to CO_2 flow provided by both the low permeability and the capillary entry pressure of the primary and secondary seals;
- Leakage through the seals due to flow through pre-existing fracture zones. This considers both the possible juxtaposition of permeable zones above and below the seals due to the fault throw, as well as the potential fracturing and fracture enhanced permeability of the seals in the fault zone (this is the mechanism for upward migration through seals at Crystal Geyser as proposed by Shipton et al., 2005);

- Leakage through the seals due to a facies change from impermeable to permeable strata within the seal lithologic group;
- The driving force applied by both the pressure and buoyancy of CO_2 in the reservoir. Note that while natural CO_2 reservoirs are often filled slowly without the large pressure increases expected during CO_2 sequestration, there are natural CO_2 reservoirs that are overpressured to levels expected during CO_2 sequestration. For example, the Jackson Dome CO_2 reservoir is overpressured at levels of 0.70 psi per foot and studies of this reservoir indicate that there is no evidence of CO_2 leakage; and
- Slow diffusion through the seals.

As such, this release scenario is analogous to CO_2 leakage from natural CO_2 reservoirs in the absence of anthropogenic influences.

5.3.1.1 Catastrophic Failure And Quick Release

This release scenario evaluates the possibility that an eruptive release occurs from the CO_2 reservoir, where releases occur at very high rates almost instantaneously in an explosive eruption similar in nature to release events in volcanic areas. However, as noted in prior natural analog studies for CO_2 sequestration, and as confirmed by the information presented in the analog database, these types of releases have only occurred in VHM settings. No eruptive events have ever been recorded in sedimentary basins (IEA Greenhouse Gas R&D Program, 2006a) nor have any been recorded for underground natural gas sites (IEA Greenhouse Gas R&D Program, 2006b). Theoretical studies of the potential for eruptive releases due to pneumatic eruptions have also recently been studied by LBNL, who concluded that "...currently there is no evidence that eruptive release can be powered solely by mechanical energy of compression" (Pruess, 2006). Given these results from both analog and theoretical studies, it appears highly improbable that an eruptive release could occur in a stable sedimentary basin, especially sedimentary basins with properties like those estimated for the FutureGen sites. If such an event were to be considered in this risk assessment, the frequency of such an event would be vanishingly remote (e.g., probability of less than 10^{-6} per 5,000 years).

5.3.1.2 Gradual And Slow Release

The release rates for this scenario depend on the dominant mechanisms at each site and were estimated using the analog database based upon CO_2 emission rates from analog sites with similar geologic conditions. Thus, for sedimentary basins, releases are constrained to either no leakage, or leakage rates at values between 0.000144 and 169 μmol/m^2-s, as shown in Figure 5-2. Note that releases for most analog sites are often below the range of normal soil respiration rates for CO_2 (i.e., 0.05 to 20 μmol/m^2-s), and typically only exceed the range of normal soil respiration rates for CO_2 when faults are the dominant release pathway. To accommodate uncertainty in the CO_2 emissions estimate, a range of values were given covering the reasonable low and high values, as determined using expert judgment. The probability of this release rate is high, since it is based upon the best estimate of each site's geologic conditions, and no failure mechanisms are necessary that may have a low probability of occurring. Frequencies were assigned for each site based upon expert judgment.

The area over which CO_2 is assumed to be released to the atmosphere includes the entire footprint of the CO_2 plume. Although the plume size will vary, given the 5,000 year timeframe considered in the risk assessment, the maximum plume area, which is typically reached within a few hundred years, is used to estimate emissions. This is a reasonable but conservative assumption. The most likely release duration for this scenario may be on the order of the entire duration of the CO_2 sequestration time period (i.e., 5,000 years), however, this depends on the dominant release mechanism. For example, if leakage is mainly via diffusion through the seal, it will take thousands of years for any released CO_2 to reach the ground surface (Cawley et al., 2005). However, if leakage is mainly through faults in the seals, the time it will take for any released CO_2 to reach the ground surface is likely to be on the order of a single decade (Birkholzer et al., 2006). To accommodate uncertainty in the CO_2 emissions, a range of release durations are given covering the reasonable low and high values as determined using expert judgment.

Hydrogen Sulfide Behavior during Upward Diffuse Migration - H_2S migrating upward from the injection zone will encounter formation water and dissolve. Although the solubility of H_2S is greater at higher pH values, even at very low pH the solubility is enough to significantly limit the upward H_2S flux. Preliminary calculations indicate that the formation water can hold over 1,400 times the total amount of H_2S that will be injected. Furthermore, some of the H_2S will be captured by the formation of metallic sulfides (e.g., iron sulfide [FeS]), elemental sulfur, and in the upper oxic portion of the permeable media, as sulfate.

5.3.2 RELEASE THROUGH FAULTS

These release scenarios evaluate possible releases that could occur by migration through fault zones due to induced fracturing and re-activation of existing faults. Thus, these releases consider the flow and transport of CO_2 through the primary and secondary seals and integrate the influence of the following system properties and processes:

- Breach of the flow barrier provided by both the low permeability and the capillary entry pressure of the primary and secondary seals;

- Leakage through the seals can then occur due to either the possible juxtaposition of permeable zones above and below the seals due to the fault throw, or the potential fracturing and fracture enhanced permeability of the seals in the fault zone (this is the mechanism for upward migration through seals at Crystal Geyser as proposed by Shipton et al., 2005); and

- The driving force applied by both the pressure and buoyancy of CO_2 in the reservoir provides the energy for creating and/or activating the faults.

As such, this leakage mechanism is analogous to CO_2 leakage from a natural CO_2 reservoir where natural processes have created fractures/faults that allow CO_2 to leak through the overlying seals and discharge at either the ground surface or into shallow groundwater. Key factors in estimating the potential for and impact of this scenario are the stress-conditions induced in the subsurface by CO_2 injection and reservoir pressurization, and the geomechanical properties of the rocks at the site. The final estimated leakage rates also integrate the impact of monitoring, mitigation, and verification (MMV) measures that would be employed to detect micro-seismissivity associated with such events and alter the injection strategy to eliminate or minimize the continued creation and movement of fractures/faults. The EIVs also present quantitative leakage models for releases from the target formations via faults, which have been identified as one of the most important release scenarios for CO_2 release (Lewicki et al., 2006). The EIV model results were used to determine the timing of fault releases and provide another tool for estimating the range of possible fault release rates.

5.3.2.1 Releases through Existing Faults Due To Increased Pressure

The potential for release through existing faults due to increased pressure was estimated based upon the presence or absence of faults within the plume footprint, and whether CO_2 injection increases reservoir pressure until it exceeds the dynamic fault-slip limit. The most likely release rate for this scenario depends on the extent of slip occurring on the fault and was estimated from the analog database using known CO_2 emissions from analog sites where faults breach the primary and secondary seals. Thus, sedimentary basin releases are constrained to leakage rates at between about 5 and 169 µmol/m^2-s (Figure 5-2). To accommodate uncertainty in the CO_2 emissions estimate, a range of values were given covering the reasonable low and high values, as determined using expert judgment. The probability of this release scenario is considered highly sensitive to site conditions, since it is dependent upon pre-existing stress conditions, the pressure requirements for injection, and the nature of the overlying seals. For example,

- At some sites the minimum horizontal stress may be a very large compressive stress due to regional compressive stress, while at others, the minimum horizontal stress may be a very small compressive stress due to regional extensional stresses;
- At some sites the injection pressure may be very large due to low formation injection capacity, while at others, the injection pressure may be very low due to high injection capacity; and
- At some sites the sealing formations may be thick and self-healing (such as salts), while at others, the sealing formation may be thin and brittle.

The area over which CO_2 is assumed to be released to the atmosphere includes the fault prone area of the CO_2 plume. The most likely release duration for this scenario may be on the order of the entire duration of the CO_2 sequestration time period (i.e., 5,000 years). However, this depends on the magnitude of the leak, as high release rates are more likely to be detected and mitigated. Since the time period for emissions to reach the ground surface via faults through the seals is likely to be on the order of a single decade (Birkholzer et al., 2006), release durations could range from a few decades if mitigated to 5,000 years, if not mitigated. To accommodate uncertainty in the CO_2 emissions, a range of release durations are given covering the reasonable low and high values, as determined using expert judgment.

5.3.2.2 Induced Faults Due To Increased Pressure

The potential for release through fracturing/induced faults due to increased pressure was estimated based upon the differential between the reservoir/well injection pressure and the minimum hydraulic fracture pressure, and whether CO_2 injection potentially alters the formation conditions in a way that lowers the minimum hydraulic fracture pressure. The most likely release rate for this scenario depends on the extension of fractures through the caprock(s), the extent of slip occurring on the fault, and was estimated using the analog database, based upon known CO_2 emissions from analog sites where faults breach the seals in a similar manner. Thus, sedimentary basin releases are constrained to leakage rates at between about 5 and 169 µmol/m^2-s (Figure 5-2), however, these releases are unlikely to be at the surface since fracturing is extremely unlikely to extend to the surface. These releases may then be further attenuated during transport to the surface such that only a fraction is released there, while the remaining fraction may impact geochemical conditions in intermediate depth formations. To accommodate uncertainty in the CO_2 emissions and impact estimate, a range of values was given covering the reasonable low and high values, as determined using expert judgment. The probability of this release scenario is highly sensitive to site conditions since it is dependent upon site fracture and stress conditions, the pressure requirements for injection, and the nature of the overlying seals. For example,

- At some sites, the minimum fracture pressure may be low relative to operating conditions, while at others, the minimum fracture pressure may be high relative to operating conditions;
- At some sites, the injection pressure may be very high due to low formation injection capacity, while at others the injection pressure may be very small due to high injection capacity; and
- At some sites, the sealing formations may be thick and self-healing (such as salts), while at others, the sealing formation may be thin and brittle.

The area over which CO_2 is assumed to be released to the atmosphere includes the areal extent of a created fault. The most likely release duration for this scenario may be on the order of the entire duration of the CO_2 sequestration time period (i.e., 5,000 years), however, this depends on the magnitude of the leak, as high release rates are more likely to be detected and mitigated. Since the time period for emissions to reach the ground surface via faults through the seals are likely to be only on the order of a single decade (Birkholzer et al., 2006), release periods could range from a few decades if mitigated to 5,000 years if not mitigated. To accommodate uncertainty in the CO_2 emissions, a range of release durations were given covering the reasonable low and high values, as determined using expert judgment.

5.3.3 MIGRATION INTO NON-TARGET AQUIFERS

These release scenarios evaluate possible releases that could occur due to migration into non-target aquifers. This includes either upward migration through the caprock (e.g., due to an unanticipated facies change from impermeable to permeable strata within the seals), or lateral migration out of the target zone (e.g., due to an unanticipated dip or stratigraphic connection within the injection horizon). Thus, these releases evaluate the flow and transport of CO_2 and integrate the influence of the following system properties and processes:

- The flow barrier provided by both the primary and secondary seals;
- The limitations on lateral flow imposed by the permeability, dip, and regional gradient in the injection horizon;
- Any leakage through the seals due to a facies change from impermeable to permeable strata within the seal lithologic group;
- The driving force applied by both the pressure and buoyancy of CO_2 in the reservoir; and
- Slow diffusion through the seals and into deep regional aquifers.

This leakage mechanism is analogous to CO_2 leakage from natural CO_2 reservoirs in the absence of anthropogenic influence.

5.3.3.1 Due To Unknown Structural Or Stratigraphic Connections

The potential for release due to unknown structural or stratigraphic connections was estimated based upon the stratigraphic and structural setting of the site (e.g., the formation depositional environment), and the amount of uncertainty in the site characteristics due to data gaps that may be present at the site. The most likely release rate for this scenario depends on the types of facies changes that may occur and the flow and transport characteristics of the units, and was estimated using the analog database, based upon known CO_2 emissions from analog sites where facies changes provide pathways through the seals and/or laterally into deep regional aquifers. Thus, sedimentary basin releases are constrained to leakage rates between about 2.5 and 5 $\mu mol/m^2$-s (Figure 5-2). These releases may then be further attenuated during transport to the surface such that only a fraction is released there, while the remaining fraction may impact geochemical conditions at intermediate depths. To accommodate uncertainty in the CO_2 emissions and impact estimate, a range of values were given covering the reasonable low and high values, as determined using expert judgment. The probability of these releases is considered highly sensitive to site conditions and data availability, for example:

- At some sites, the depositional environment may suggest excellent lateral and vertical continuity of seals, while at others, the depositional environment may suggest a fair chance of a lateral facies change in the seal or a vertical thinning of the seal formation; and

- At some sites, there may be a wealth of data on geologic conditions, while at others, there may be very little data on the geologic conditions.

The area over which CO_2 is assumed to be released into non-target aquifers covers the areal extent of the possible structural or stratigraphic connections (e.g., the areal extent of the "window" in the seal). The most likely release duration for this scenario may be on the order of the entire duration of the CO_2 sequestration time period (i.e., 5,000 years). To accommodate uncertainty in the CO_2 emissions, a range of release durations are given covering the reasonable low and high values, as determined using expert judgment.

5.3.3.2 Due to Lateral Migration from the Target Zone

The potential for release due to lateral migration from the target zone was estimated based upon the stratigraphic and structural setting of the site (e.g., the regional hydraulic gradient and/or dip), and the amount of uncertainty in the site characteristics due to data gaps that may be present at the site. The most likely release rate for this scenario depends on the types of lateral rate of escape from the target zone as well as the upward migration to shallow exposure points, and was estimated using the analog database, based upon known CO_2 emissions from analog sites where high lateral flow rates provide pathways into deep regional aquifers. Thus, sedimentary basin releases are constrained to leakage rates between about 2.5 and 5 $\mu mol/m^2$-s (Figure 5-2). These releases may then be further attenuated during transport to the surface such that only a fraction is released there, while the remaining fraction may impact geochemical conditions at intermediate depths. To accommodate uncertainty in the CO_2 emissions and impact estimate, a range of values were given covering the reasonable low and high values, as determined using expert judgment. The probability of this release rate is considered highly sensitive to site conditions and data availability, for example:

- At some sites, the formation dip may be flat and there may be a very low regional hydraulic gradient (i.e., suggesting limited lateral migration), while at others, the formation dip may be high and there may be a very high regional hydraulic gradient in the updip direction (i.e., suggesting the potential for lateral migration); and

- At some sites, there may be wealth of data on the geologic conditions, while at others, there may be very little data on the geologic conditions.

The area over which CO_2 is assumed to be released into non-target aquifers covers the areal extent of the estimated outward release points. The most likely release duration for this scenario may be on the order of the entire duration of the CO_2 sequestration time period (i.e., 5,000 years), but it also may take a very long time for these releases to reach any potential receptors. To accommodate uncertainty in the CO_2 emissions, a range of release duration values were given covering the reasonable low and high values, as determined using expert judgment.

5.3.4 UPWARD MIGRATION THROUGH WELLS

These release scenarios evaluate possible releases that could occur by upward migration through wellbores. Thus, these release scenarios evaluate the flow and transport of CO_2 through well conduits and integrate the influence of the following system properties and processes:

- Leakage via poorly constructed wells, improperly abandoned wells, and undocumented wells;

- The potential for leakage directly at the surface as well as flow behind the casing into intermediate and shallow depth formations which may also eventually release gas to the surface; and

- Leakage is evaluated for releases directly from deep wells in the target sequestration reservoir. Leakage may also occur through intermediate and shallow depth wells via releases from the target sequestration reservoir that have migrated into intermediate and shallow depth horizons. However, releases from intermediate and shallow depth wells would be at lower frequencies and rates per well than leakage from deep wells.

This release mechanism is analogous to the leakage reported from natural gas industry experience, oil and gas industry experience, and experiences in natural CO_2 reservoirs. Thus, the data presented in the analog site and well failure databases (Sections 5.2 and 5.3) were used to define the relative frequency, duration, and magnitude of well releases at each FutureGen Site. Site specific leakage was then estimated using these generic well release frequencies, durations, and rates by considering the number of wells in each category.

5.3.4.1 Poorly Constructed and Abandoned Deep Wells

The potential for release due to poorly constructed wells was estimated based upon the number of wells present at the site and the probability of release due to well failure, as given in Table 5-3 and Table 5-4. This category is meant to cover all of the wells drilled through the primary seal and within the plume footprint. Two types of releases are possible, high rate releases that are assumed to be detected and mitigated (thus, active for only short time periods), and low rate releases that are not assumed to be detected and remain unmitigated (thus, potentially active for long time periods). The most likely release rate for poorly completed wells is based upon the number of wells present and the failure frequencies in Table 5-3 and Table 5-4. Thus, well releases are constrained to leakage rates at between about 220 tons (200 metric tons) per year for slow rate leaks and 12,125 tons (11,000 metric tons) per year for high rate leaks. To accommodate uncertainty in the CO_2 emission rates, a range of values were given covering the reasonable low and high values as determined using expert judgment. The estimated frequencies for this release rate are based upon historical experience at natural and industrial analog sites.

The area over which CO_2 is assumed to be released to the atmosphere in this scenario is very small (i.e., the immediate area of the leaking wells) and is considered as a point source in the risk assessment. The most likely release duration for this scenario may be on the order of the entire duration of the CO_2 sequestration time period (i.e., 5,000 years) for slow leaks, but is likely to be limited to between 0.5 and 5 days for high rate releases based upon industry experience with well failures and mitigation.

5.3.4.2 Poorly Constructed And Abandoned Shallow Wells

The potential for release due to poorly abandoned wells is treated in the same manner as poorly constructed and abandoned deep wells. This category is meant to cover all the other wells whose maximum depth is above the base of the primary seal and within the plume footprint.

5.3.4.3 Undocumented Wells

The potential for release due to ***undocumented*** wells is treated in the same manner as poorly constructed and abandoned deep wells. The number of undocumented wells per site was estimated based expert judgment using information on the degree of historical mineral exploration activity in the area.

5.3.4.4 Leakage Scenarios Analyzed in EIVs

Table 5-5 summarizes the leakage scenarios analyzed and presented in the four final EIVs. For these analyses, it was concluded that four of the scenarios had such a low probability of occurrence that quantitative analysis was not warranted. The final two scenarios were simulated using the STOMP numerical model, as described in the EIVs. The quantitative estimates of release rates are provided in Section 5.5.1, along with those estimated using the analog database approach. In contrast to the approach in the EIVs, all potential release scenarios are quantitatively examined in this report, and release probabilities are then associated with those scenarios. It is emphasized (see footnote "d" to Table 5-5), that the quantitative release estimates made by STOMP are for releases that migrate to the base of the secondary seal and not to the biosphere. Thus, the releases predicted by STOMP are higher than those predicted using the analog database. Also, the emissions predicted by STOMP are comparable to emissions from volcanic sites in the analog database (see Figure 5-2).

Table 5-5. Summary of Subsurface Leakage Scenarios Analyzed in Final EIVs

	Were Scenarios Quantitatively Analyzed?			
Scenario	**Jewett**	**Odessa**	**Mattoon**	**Tuscola**
Well bore leakage	No[a]	No[a]	No[a]	No[a]
Seal permeation	No[b]	No[b]	No[b]	No[b]
Stratigraphic leakage	No[c]	No[c]	No[c]	No[c]
Overpressure induced crack seepage	No[b]	No[b]	No[b]	No[b]
Buoyant migration along faults	Yes[d]	Yes[d]	Yes[d]	Yes[d]
Leakage associated with seismicity	Yes[d]	Yes[d]	Yes[d]	Yes[d]

[a] Scenario assumed to have a low probability, and result in risks equivalent to a wellhead failure, due to proposed monitoring and early leak detection and prevention for all wells.

[b] Low probability of occurrence.

[c] Scenario assumed to have a low probability due to monitoring and mitigation.

[d] Releases are predicted from the primary storage reservoir to the base of the secondary seal and to the biosphere.

5.4 Exposure Analysis

5.4.1 HUMAN RECEPTORS

As stated in Section 4.2.1, the FutureGen plant will occupy a 62-acre (25-hectare) or 75-acre (30-hectare) footprint (Quest, 2006). There is expected to be a buffer of about 600 feet (183 meters) around the plant footprint out to the property boundary, which encompasses at least 200 acres (81 hectares). Workers will be present at the site; the estimated number of full-time workers at the plant under operating conditions is 200 people (DOE EIS, 2007).

The Jewett plant site is located close to the town of Jewett, TX. The two injection sites and plant are not co-located. The 50-year sequestration plume footprint for the northern injection site (Figure 2-11 of the EIS) is partially located within the Coffield State Prison Farm. Although there are no towns, schools, nursing homes, or hospitals within the 50-year sequestration plume footprints of this injection site, the plume does come within approximately 1 mile (1.6 kilometers) of the town of Sand Hill and close to a prison yard. Otherwise, the land over the sequestration plumes is a combination of agricultural, range, and forested lands. Census data indicate that the population density within the northern sequestration plume is fairly high (i.e., 100 to 500 people per square mile; see maps in Section 2). However, it should be noted that this estimated population density is due to the prisons, which are actually just outside the sequestration plume footprints. Groundwater in the vicinity of the proposed sequestration reservoir extends from near the surface to 500 feet (152 meters) below ground surface (bgs) and is suitable for potable water supply (see Table 2-1).

The Odessa plant site is located 15 miles (24 kilometers) west of the city of Odessa, TX. The injection site is located about 58 miles (93 kilometers) south of the plant site. Fort Stockton is about 8 miles (13 kilometers) from the injection site, although there may be a shorter distance between the nearest of the 10 injection wells and the town, depending on the exact location of the wells. There are no towns, schools, nursing homes, or hospitals on the land above the 50-year sequestration plume, which is underneath land that is largely open and has a relatively low population density (i.e., 0 to 50 people per square mile; see maps in Section 2). However, there may be isolated farm houses within the estimated 50-year sequestration plume footprint. Groundwater is not produced in the sequestration area, although local aquifers exist. The water table is at approximately 200 feet (61 meters) bgs (see Section 2.5.2.2).

The Mattoon plant site is about one mile northwest from the town of Mattoon, IL. The injection site is planned to be located in the center of the 444-acre (180-hectare) plant site property. There are no towns, schools, nursing homes, or hospitals on the land above the 50-year sequestration plume footprint, although the edge of the estimated 50-year sequestration plume extends to within 0.3 miles (0.5 kilometers) of populated areas and there is a school within 1 mile (1.6 kilometers) of the edge of the plume. The land surrounding the plant site and overlying the sequestration plume is farmland, so there are some isolated farm houses within the estimated 50-year sequestration plume footprint. Otherwise, the land above the 50-year sequestration plume has a relatively low population density (i.e., 0 to 50 people per square mile (see maps in Section 2). Sporadic groundwater exists in shallow sand and gravel deposits 20 to 125 feet (6 to 38 meters) below surface and there are several private wells in the area (see Table 2-1).

The Tuscola plant site is about 2 miles (3.2 kilometers) west from the town of Tuscola, IL. The injection site is located 11 miles (18 kilometers) south of the plant site. The estimated 50-year sequestration plume footprint is about 1 mile (1.6 kilometers) from the town of Arcola. There are no schools, hospitals, or nursing homes within the sequestration plumes for the injection site. Although the US Census data indicate that the population density within the sequestration plume is 100 to 500 people per square mile (see maps in Section 2), this may not be accurate as the land above the sequestration plume is largely agricultural, with scattered farmhouses. Groundwater is present in sand and gravel aquifers 70 feet to 100 feet (21 to 30 meters) below surface and there are several private wells in the area (see Section 2.5.4).

Worker exposures to post-sequestration releases are considered to be the same as those for future residents, since worker exposures would not necessarily be work-related. To estimate exposures to the releases presented here, it has been assumed that receptors are located either directly above the release source or nearby. Thus, if subsurface releases occur during the first 50 years, workers at the Mattoon Site might be exposed, while workers at the other FutureGen plant sites might not be exposed. However, the more likely scenario is that releases would occur after the first 50 years of the FutureGen program (i.e., after the FutureGen plant has ceased operations). Therefore, the evaluations presented here assume that receptors may be near a well and/or above the plume footprint, even if they are not there now and that all potential future exposures can be evaluated using the health-protective residential exposure scenario.

5.4.2 ECOLOGICAL RECEPTORS

The potential ecological receptor groups near the injection sites are discussed separately for each site. A summary of the land use and environmental setting for each of the sites is presented in Section 2, along with maps of each site.

The land overlying the 50-year sequestration plume footprint at Jewett (TX) is characterized by open woodlands and savannah ecological habitats and is traversed by the Trinity River. The northern portion of the proposed sequestration area has perennial streams and ponds of a larger size than the southern portion, and contains the Trinity River and its floodplain system throughout its central portion. Many ephemeral streams occur in this region and fast-growing, opportunistic macrophytes should be expected when flow is present. Permanent creeks and riverine habitat are also found in the area. Because there are no federal listed species known to occur in the land area above the proposed sequestration reservoir, no critical habitat has been designated by the FWS (see Section 2.5.1).

The land overlying the 50-year sequestration plume footprint at Odessa (TX) is characterized by diverse habitats and vegetation, varying from desert valleys and plateaus to wooded mountain slopes. National Wetland Inventory maps indicate Sixshooter Draw, Monument Draw, Tunas Creek, and several on-channel impoundments as areas potentially subject to Section 404 jurisdiction within the land area above the proposed sequestration reservoir. No known federal or state-listed species are known to be present in the pipeline corridor or the injection site. The endangered pupfish in spring-fed habitats exists well to the north of the planned pipeline. Endangered birds such as bald eagles, peregrine falcons, and whooping cranes may visit the area on a transient basis (see Section 2.5.2).

The land overlying the 50-year sequestration plume footprint at Mattoon (IL) is mostly farmland where corn and soybeans are grown. About 18 small wetlands have been identified, and several small streams and lakes are present. Healthy aquatic macroinvertebrates and biotic communities are expected in these water bodies and wetlands. The threatened Eastern Sand Darter may be present, in addition to an endangered Indiana Bat, which lives in caves and mines in the winter in Coles County and in trees in the summer (see Section 2.5.3).

The land overlying the 50-year sequestration plume footprint at Tuscola (IL) is part industrial and part agricultural. Crops grown are mostly corn and soybeans. Above the sequestration site, no federal or state-listed species are known for those areas. Also, no areas of sensitive or critical habitat for any listed species is known for this area. Aquatic habitat above the sequestration reservoir is limited to a small section of the Kaskaskia River, the adjacent floodplain, and several intermittent drainage ways. The endangered Indiana bat *(Myotis sodalis)* may also be present within the wooded riparian habitat along the rivers or tributaries. This species occupies caves and abandoned mines during the winter. During the remainder of the year, Indiana bats utilize trees with rough or exfoliating bark and/or cavities for roosting (see Section 2.5.4)

In summary, ecological receptors are evaluated at all four sites.

5.4.3 RELEASE SCENARIOS EVALUATED

Not all release scenarios from Section 5.3 were evaluated. Releases from shallow wells are not evaluated quantitatively as the release rates and release probabilities are lower than for the deep wells. The scenarios that were selected for evaluation are provided in Table 5-6. This table indicates the duration of potential exposures, the primary exposure media, and the likely receptors.

Table 5-6. Release Scenarios

Release Scenario	Exposure Duration	Potential Volume	Initial Release to	Receptors
Upward leakage through the caprock due to catastrophic failure and quick release	Short-term	Variable, could be large	Air	Humans Ecological
Upward leakage through the caprock due to gradual failure and slow release	Long-term	Small	Air, groundwater	Humans Ecological
Upward leakage through the CO_2 injection well(s)	Short-term and long-term	Variable, could be large	Air, groundwater	Humans Ecological
Upward leakage through deep oil and gas wells	Short-term and long-term	Variable, could be large	Air, groundwater	Humans Ecological
Upward leakage through undocumented, abandoned, or poorly constructed wells	Short-term and long-term	Variable, could be large	Air, groundwater	Humans Ecological
Release through existing faults due to the effects of increased pressure	Long-term	Variable, could be large	Air, groundwater	Humans Ecological
Release through induced faults due to the effects of increased pressure	Long-term	Variable, could be large	Air, groundwater	Humans Ecological
Lateral or vertical leakage into non-target aquifers due to lack of geochemical trapping	Long-term	Variable	Groundwater	Humans Ecological
Lateral or vertical leakage into non-target aquifers due to inadequate retention time in the target zone	Long-term	Variable	Groundwater	Humans Ecological
Gas intrusion into groundwater (with potential release of radon)	Long-term	Low	Groundwater	Humans Ecological

5.4.3.1 Exposure Media

CO_2 and trace gas releases could potentially be released to either air or groundwater. Releases to groundwater could also result in secondary releases to either the atmosphere or surface water. Releases up through the soil column could also lead to changes in soil chemistry; therefore, soils are also considered to be a potential exposure medium. Potential exposures to each environmental medium are evaluated below.

5.4.3.2 Exposure Parameters

The toxicity information used to estimate the consequences from assumed exposures consisted of benchmark concentration effect levels (see Section 3). These concentration effect levels are given in terms of a concentration to which receptors may be exposed for a given duration. Therefore, the only exposure parameter used in this assessment is exposure duration. Two exposure durations were used for exposure scenario: 1) short-term (i.e., minutes to days) and 2) long-term (i.e., lifetime).

5.4.3.3 Chemicals of Potential Concern (COPCs)

The composition of the gas injected into the target reservoirs was provided by Battelle for use by the FutureGen team. Battelle determined that CO_2, H_2S, and nitrogen would be present in the injected gases (see Table 4-2). Nitrogen is a major component of earth's atmosphere (at approximately 78 percent) and is not considered to be toxic in this form. Therefore, CO_2 and H_2S are the COPCs.

It should be noted that other compounds may be present in the injected gas (e.g., CH_4, CO, mercury, cyanide, SO_X, and NO_X) (see Section 2.4). However, estimated concentrations of these chemicals are addressed in the EIS. These chemicals were not evaluated as COPCs. Assumed exposures to the two COPCs are evaluated below for each site.

Additionally, if CO_2 were to leak from a primary storage reservoir and seep into the biosphere, naturally occurring radon in soil gas could be swept along with the CO_2, and enter residences through subsurface intrusion. Depending on background radon concentrations, the additional radon that intrudes might increase human health risks through inhalation of the radon and its progeny.

To evaluate the potential importance of radon, the four candidate FutureGen sites were ranked from highest to lowest risk potential based on a nation-wide database developed by EPA that examines the issue of indoor radon at the county wide level. Each county is designated as zone 1, 2, or 3. As can be seen in the table below, both Mattoon IL and Tuscola IL have the highest potentials (zone 1), and the two Texas sites have the lowest potentials (both zone 3). The range of estimated indoor radon concentrations is also shown in Table 5-7. For both the Mattoon and Tuscola Sites, the upper limits of the range for radon concentrations in basements (18 and 41.6 pCi/L for Mattoon and Tuscola, respectively) far exceed the EPA action level of 4 pCi/L. However, concentrations in the bedrooms were below the action level. For the Texas sites, mean concentrations in residences were approximately 1 piC/L.

Table 5-7. Radon Ranking

Candidate FutureGen Site	Ranking based on EPA Nation-wide data base	Estimated indoor concentrations, pCi/L	Source of data
Mattoon, IL	Zone 1: highest potential (> 4 pCi/L)	Basement: 0.6-18.5 Bedroom: 0.8	Coles County Health Dept.
Tuscola, IL	Zone 1: highest potential (> 4 pCi/L)	Basement: 0.1-41.6 Bedroom: 0.6-3.0	Douglas County Health Dept.
Odessa, TX	Zone 3: lowest potential (< 2 pCi/L)	Mean in residences: 1.0 Percent > 4: 2.5	Texas statewide survey
Jewett, TX	Zone 3: lowest potential (< 2 pCi/L)	Mean in residences: 0.9 Percent > 4: 5.8	Texas statewide survey

Very little information is present in the analog database on radon. One exception is Weyburn, where radon concentrations were estimated at 11 locations, including background. The concentrations at all the locations, including the background location, were very similar, indicating that near-surface soil gas associated with carbon sequestration activities did not contain elevated levels of radon. This provides some evidence that elevated concentrations of radon would not be expected at the four candidate sites. To continue the analysis, assume that the indoor radon concentration were to increase by 1 pCi/L. This is likely to be a conservatively high estimate. In that case, the indoor air concentrations in the bedrooms of the Illinois sites or mean concentrations in the residences of the Texas sites would all still be below 4 pCi/L, the action level. The upper ends of the ranges in Illinois basements and Texas residents were already above this action level. Therefore, the situation with respect to radon would remain unchanged as to whether action levels are exceeded. This indicates that there would be no incremental risks above background from radon for any of the four sites. Based upon this determination, radon was not selected as a COPC and was not evaluated.

5.5 Exposure Models

This section describes the procedures used to estimate the concentrations of COPCs in environmental media to which receptors may be exposed. First, a leakage analysis was performed for each site to determine site-specific release rates (Section 5.5.1), then dispersion models were used to estimate COPC concentrations in outdoor air to which receptors may be exposed (Section 5.5.2).

5.5.1 LEAKAGE ANALYSIS

5.5.1.1 Jewett, TX

The first step in the sequestered gas leakage analyses was to conduct a HSE risk screening and ranking using the SRF recently developed by LBNL for geologic CO_2 storage site selection (Oldenburg, 2005). The results for the Jewett Site are given in Appendix D-1. The SRF summary analysis indicates that the Jewett Site has good primary and secondary sealing potential and fair to good attenuation potential, with a high degree of certainty in these characteristics based upon reasonably well known data. The most significant areas of uncertainty include:

- The possibility of re-activation of the existing normal faults within the plume area, as discussed in the Jewett Site EIV Section 4 (Geologic Description). This may be most significant for injection into Travis Peak, as its’ low permeability may require high injection and reservoir pressures (i.e., the Woodbine formation has a high permeability that would not require as high injection and reservoir pressures). However, with appropriate monitoring, fault re-activation would most likely be detected and mitigated by reducing injection pressures or moving injection to a new well;

- Travis Peak has a low permeability that will require four pressure relief water extraction wells, complicating reservoir operations that could increase leakage potential by increasing the number of wells and causing differential reservoir stresses both above and below native conditions; and

- There are deep wells that penetrate the primary seal, and many shallow wells above the primary seal that could provide a conduit for leakage, if the primary seal also leaks.

The Eagle Ford Shale and roughly 2,300 feet of shallower low permeability carbonates and shales provide good primary and secondary seals.

Release Scenarios

The second task in the sequestered gas leakage analyses was to define the key release scenarios relevant to the long-term safety and performance of the CO_2 storage system, and to estimate the magnitude, probability, and duration of CO_2 leakage associated with each release scenario. Given the Jewett SCM, EIV database, and the SRF results presented above, the list of release scenarios presented in Section 5.3 covers all key release scenarios that may give rise to CO_2 leakage from the Jewett sequestration reservoir. The magnitude, probability, and duration of CO_2 leakage rates from the sequestration reservoir are summarized in Table 5-8 and discussed in detail below. Table 5-8 also presents this information for the other three sites as well.

Table 5-8. Predicted CO_2 Leakage Rates

Site	Mechanism	Frequency	Frequency Units	Flux Rate (μmol/m^2-s)	Flux Area, acres (hectares)	Number of Items	Duration (Years)
Jewett, TX	Leakage via Upward Migration through Caprock due to Gradual and slow release	0.2	1/5,000 year-item	0 to 0.17	5,147.03 (2,082.92)	1	5,000
Jewett, TX	Leakage via Upward Migration through Caprock due to catastrophic failure and quick release	less than 10^{-6}	1/5,000 year-item	NA	NA	NA	NA
Jewett, TX	Leakage through existing faults due to increased pressure (regional overpressure)	1.E-04	1/5,000 year-item	1 to 30	20.909 (8.462)	1	10
Jewett, TX	Release through induced faults due to increased pressure (local overpressure)	1.E-04	1/5,000 year-item	1 to 30	4.1818 (1.6923)	1	1
Jewett, TX	Leakage into non-target aquifers due to unknown structural or stratigraphic connections	1.E-05	1/5,000 year-item	5 to 170	83.636 (33.846)	1	100
Jewett, TX	Leakage into non-target aquifers due to lateral migration from the target zone	1.E-06	1/5,000 year-item	1 to 30	5,147.03 (2082.93)	1	100
Jewett, TX	Leaks due to deep CO_2 wells, high rate	1.E-05	1/year-well	NA	NA	3	0.01

Table 5-8 (continued). Predicted CO_2 Leakage Rates

Site	Mechanism	Frequency	Frequency Units	Flux Rate (µmol/m^2-s)	Flux Area, acres (hectares)	Number of Items	Duration (Years)
Jewett, TX	Leaks due to deep CO_2 wells, low rate	1.E-05	1/year-well	NA	NA	3	5,000
Jewett, TX	Leaks due to deep O&G wells, high rate	1.E-03	1/year-well	NA	NA	57	0.01
Jewett, TX	Leaks due to deep O&G wells, low rate	1.E-03	1/year-well	NA	NA	57	5,000
Jewett, TX	Leaks due to undocumented deep wells, high rate	1.E-03	1/year-well	NA	NA	13	0.01
Jewett, TX	Leaks due to undocumented deep wells, low rate	1.E-03	1/year-well	NA	NA	13	5,000
Odessa, TX	Leakage via Upward Migration through Caprock due to Gradual and slow release	0.2	1/5,000 year-item	0 to 1	10,635.9 (4,304.2)	1	5,000
Odessa, TX	Leakage via Upward Migration through Caprock due to catastrophic failure and quick release	less than 10^{-6}	1/5,000 year-item	NA	NA	NA	NA
Odessa, TX	Leakage through existing faults due to increased pressure (regional overpressure)	1.E-04	1/5,000 year-item	1 to 30	20.909 (8.462)	1	10

Table 5-8 (continued). Predicted CO_2 Leakage Rates

Site	Mechanism	Frequency	Frequency Units	Flux Rate (µmol/m^2-s)	Flux Area, acres (hectares)	Number of Items	Duration (Years)
Odessa, TX	Release through induced faults due to increased pressure (local overpressure)	1.E-04	1/5,000 year-item	1 to 30	4.1818 (1.6923)	1	1
Odessa, TX	Leakage into non-target aquifers due to unknown structural or stratigraphic connections	1.E-05	1/5,000 year-item	2.4 to 5	83.636 (33.846)	1	100
Odessa, TX	Leakage into non-target aquifers due to lateral migration from the target zone	1.E-06	1/5,000 year-item	1 to 30	10,635.9 (4,304.2)	1	100
Odessa, TX	Leaks due to deep CO_2 wells, high rate	1.E-05	1/year-well	NA	NA	10	0.01
Odessa, TX	Leaks due to deep CO_2 wells, low rate	1.E-05	1/year-well	NA	NA	10	5,000
Odessa, TX	Leaks due to deep O&G wells, high rate	1.E-03	1/year-well	NA	NA	0 (16 nearby)	0.01
Odessa, TX	Leaks due to deep O&G wells, low rate	1.E-03	1/year-well	NA	NA	0 (16 nearby)	5,000
Odessa, TX	Leaks due to undocumented deep wells, high rate	1.E-03	1/year-well	NA	NA	2	0.01

Table 5-8 (continued). Predicted CO_2 Leakage Rates

Site	Mechanism	Frequency	Frequency Units	Flux Rate ($\mu mol/m^2$-s)	Flux Area, acres (hectares)	Number of Items	Duration (Years)
Odessa, TX	Leaks due to undocumented deep wells, low rate	1.E-03	1/year-well	NA	NA	2	5,000
Mattoon, IL	Leakage via Upward Migration through Caprock due to Gradual and slow release	0.2	1/5,000 year-item	0.0048 to 0.17	5,473.75 (2,215.12)	1	5,000
Mattoon, IL	Leakage via Upward Migration through Caprock due to catastrophic failure and quick release	less than 10^{-6}	1/5,000 year-item	NA	NA	NA	NA
Mattoon, IL	Leakage through existing faults due to increased pressure (regional overpressure)	1.E-04	1/5,000 year-item	1 to 30	15	1	10
Mattoon, IL	Release through induced faults due to increased pressure (local overpressure)	1.E-04	1/5,000 year-item	1 to 30	3	1	1
Mattoon, IL	Leakage into non-target aquifers due to unknown structural or stratigraphic connections	1.E-05	1/5,000 year-item	1 to 30	5,473.75 (2,215.12)	1	100

Table 5-8 (continued). Predicted CO_2 Leakage Rates

Site	Mechanism	Frequency	Frequency Units	Flux Rate (µmol/m^2-s)	Flux Area, acres (hectares)	Number of Items	Duration (Years)
Mattoon, IL	Leakage into non-target aquifers due to lateral migration from the target zone	1.E-06	1/5,000 year-item	1 to 30	5,473.75 (2,215.12)	1	100
Mattoon, IL	Leaks due to deep CO_2 wells, high rate	1.E-05	1/year-well	NA	NA	1	0.01
Mattoon, IL	Leaks due to deep CO_2 wells, low rate	1.E-05	1/year-well	NA	NA	1	5,000
Mattoon, IL	Leaks due to deep O&G wells, high rate	1.E-03	1/year-well	NA	NA	0	0.01
Mattoon, IL	Leaks due to deep O&G wells, low rate	1.E-03	1/year-well	NA	NA	0	5,000
Mattoon, IL	Leaks due to undocumented deep wells, high rate	1.E-03	1/year-well	NA	NA	2	0.01
Mattoon, IL	Leaks due to undocumented deep wells, low rate	1.E-03	1/year-well	NA	NA	2	5,000
Tuscola, IL	Leakage via Upward Migration through Caprock due to Gradual and slow release	0.2	1/5,000 year-item	0 to 0.17	5,147.03 (2,082.93)	1	5,000

Table 5-8 (continued). Predicted CO_2 Leakage Rates

Site	Mechanism	Frequency	Frequency Units	Flux Rate (µmol/m^2-s)	Flux Area, acres (hectares)	Number of Items	Duration (Years)
Tuscola, IL	Leakage via Upward Migration through Caprock due to catastrophic failure and quick release	less than 10^{-6}	1/5,000 year-item	NA	NA	NA	NA
Tuscola, IL	Leakage through existing faults due to increased pressure (regional overpressure)	1.E-04	1/5,000 year-item	1 to 30	14.545 (5.886)	1	10
Tuscola, IL	Release through induced faults due to increased pressure (local overpressure)	1.E-04	1/5,000 year-item	1 to 30	2.9091 (1.1773)	1	1
Tuscola, IL	Leakage into non-target aquifers due to unknown structural or stratigraphic connections	1.E-05	1/5,000 year-item	1 to 30	5,147.03 (2082.93)	1	100
Tuscola, IL	Leakage into non-target aquifers due to lateral migration from the target zone	1.E-06	1/5,000 year-item	1 to 30	5,147.03 (2082.93)	1	100
Tuscola, IL	Leaks due to deep CO_2 wells, high rate	1.E-05	1/year-well	NA	NA	1	0.01
Tuscola, IL	Leaks due to deep CO_2 wells, low rate	1.E-05	1/year-well	NA	NA	1	5,000
Tuscola, IL	Leaks due to deep O&G wells, high rate	1.E-03	1/year-well	NA	NA	0	0.01

Table 5-8 (continued). Predicted CO_2 Leakage Rates

Site	Mechanism	Frequency	Frequency Units	Flux Rate ($\mu mol/m^2$-s)	Flux Area (acres)	Number of Items	Duration (Years)
Tuscola, IL	Leaks due to deep O&G wells, low rate	1.E-03	1/year-well	NA	NA	0	5,000
Tuscola, IL	Leaks due to undocumented deep wells, high rate	1.E-03	1/year-well	NA	NA	3	0.01
Tuscola, IL	Leaks due to undocumented deep wells, low rate	1.E-03	1/year-well	NA	NA	3	5,000

Upward Migration through Caprock due to gradual and slow release - This release scenario evaluates possible releases via upward migration through the caprock from the unaltered native state reservoir. This release scenario does not include releases due to induced fracturing, fault re-activation, and wellbores; these are each addressed in separate release scenarios below. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar release mechanisms and geologic conditions. Based upon a qualitative comparison of the Jewett Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog sites that are the closest match to the Jewett Site are the Teapot Dome and Farnham Dome sites. For example,

- The reservoir is sandstone, the seal is shale, and the depth is about 4,921 feet (1,500 meters) at both the Jewett and Teapot Dome sites; and
- The reservoir is sandstone and the seal is shale at both the Jewett and Farnham Dome sites, and the depth (4,757 feet) 1,450 meters at Jewett and (2,953 feet) 900 meters at Farnham Dome.

Based upon this analogy, CO_2 emissions were estimated to be either zero or at 0 to 0.17 μmol/m^2-s. To be conservative, the upper end of the emission range was used in the risk analyses. The frequency of a release at this rate is assumed to be 0.2 per 5,000 years, since it is based upon the best estimate of each site's geologic condition, and no failure mechanisms are necessary that may have a low probability of occurring. The area over which the CO_2 emissions are released covers the entire area of the CO_2 plume, and a 5,000 year timeframe was used as the emission duration (a reasonable but conservative assumption).

Upward migration through caprock due to catastrophic failure and quick release - This release scenario evaluates an eruptive/explosive release at very high rates, similar in nature to release events in volcanic areas. As noted in Section 5.4, no natural CO_2 eruptive events have ever been recorded in sedimentary basins (IEA Greenhouse Gas R&D Program, 2006a), no eruptive events have been recorded at underground natural gas storage sites (IEA Greenhouse Gas R&D Program, 2006b), and there is no evidence that CO_2 eruptive release can be powered solely by mechanical energy of compression (Pruess, 2006). Thus, it appears reasonable to assume that an eruptive release in stable sedimentary formations, such as those found at the Jewett Site, are extremely improbable. Based upon a qualitative comparison of the Jewett Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, this release scenario is considered vanishingly remote and was assigned a frequency of less than 10^{-6} per 5,000 years. The only event that hypothetically could cause a large scale release in this geologic setting would be an earthquake of magnitude 6 or greater, however, the frequency of such an event is also less than 10^{-6} per 5,000 years. For these reasons, emissions from catastrophic caprock failure were not estimated nor were assumed exposure to emissions from catastrophic caprock failure.

Release through existing faults due to increased pressure - Four main factors are key for release via this mechanism: (1) the presence of faults, (2) magnitude of pressure increase due to injection operations, (3) the stress regime at the site, and (4) the magnitude of stress at the site. At the Jewett Site, (1) faults are present, (2) the likelihood of pressure increase is low due to the high injectivity of Woodbine Sandstone, (3) the stress regime is normal-fault type extensional stress regime, and (4) there is a differential between the minimum and maximum horizontal stress. Thus, three of these four factors are favorable for this release scenario at the Jewett Site. The potential for release at the Jewett Site through existing faults due to increased pressure was estimated based upon the known normal faults within the plume footprint, and the probability that CO_2 injection increases pressure until it exceeds the dynamic fault-slip limit. For example,

- There are small normal faults (i.e., throw of 200 feet [61 meters]) that cut the Woodbine within the sequestration site, but that do not off-set the Eagle Ford caprock seal (thickness of 400 feet); and

- Pore pressure associated with the injection of CO_2 (85 percent of 0.7 psi/feet) can decrease friction on pre-existing faults, and may cause them to become transmissive or to slip given that the current stress differentials between the vertical overburden (S_V) and the minimum horizontal principal stress (S_{hmin}) may already be large enough to generate the critical shear stress necessary for opening/movement. Pore pressure increases caused by fluid injection can decrease the effective normal stress on certain fault orientations for pre-existing faults such that it induces fault slip, most typically in regions with frictional equilibrium stress states.

This release scenario is analogous to the CO_2 leakage from a natural CO_2 reservoir where natural processes have created regional scale fractures/faults that allow CO_2 to leak through the overlying seals and discharge at either the ground surface or into shallow groundwater. The most likely release rate for this scenario depends upon the extent of slip occurring on the fault, and was estimated using the analog database, based upon known CO_2 emissions from analog sites where faults breach the primary and secondary seals. Based upon a qualitative comparison of the Jewett Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Jewett Site after fault-reactivation has occurred is the Pine Lodge fault discharge area. Based upon this analogy, CO_2 emissions were estimated based upon the analog database at 1 to 30 μmol/m^2-s. Leakage from faults also was modeled in the Jewett Site EIV using leakage simulation models for leakage through the Eagle Ford Shale primary seal. The EIV leakage simulation models predicted that leakage rates from the Woodbine Reservoir to the base of the Pecan Gap secondary seal are on the order of 5×10^{-6} kilogram/m^2-s (or 104 μmol/m^2-s) and take roughly 2 to 16 years to reach the Pecan Gap seal. Considering both the analog database and modeling results, CO_2 emissions were estimated to be 1 to 30 μmol/m^2-s. While these leakage rates are less than those predicted by STOMP, they are not directly comparable since the STOMP predictions are for releases to the base of the secondary seal, while the analog database predictions are for releases to the atmosphere. The frequency of releases at this rate is assumed to be 10^{-4} per 5,000 years. Although releases from oil and gas reservoirs have occurred elsewhere, monitoring nearly always detects these types of leaks, and the leaks are subsequently mitigated. The area over which the CO_2 emissions are released was assumed to cover 25 percent of the area of the fault trace over the CO_2 plume; this assumes (based upon expert judgment) that only this fraction of the fault zone will be sufficiently overpressured to re-activate the fault. A 10-year (decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release, and that flow along a fracture zone can reach the surface at timescales of only a decade, as shown by the modeling work in the EIV.

Release through induced faults due to increased pressure - The potential for release at the Jewett Site through induced faults due to increased pressure was estimated based upon the maximum expected injection pressures at the site and the probability that CO_2 injection increases pressure until it exceeds the fracture gradient. For example, pore pressure associated with the injection of CO_2 (85 percent of 0.7 psi/feet) can increase stress until the stress overcomes the fracture pressure, which was estimated at approximately 0.78-0.83 psi/feet. This release scenario is analogous to CO_2 leakage from a natural CO_2 reservoir where natural processes have created local scale fractures/faults that allow CO_2 to leak through the overlying seals and discharge at either the ground surface or into shallow groundwater. The most likely release rate for this scenario depends upon the extent and permeability of the fracture and was estimated using the analog database, based upon known CO_2 emissions from analog sites where faults breach the primary seals. Based upon a qualitative comparison of the Jewett Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Jewett Site after fault-reactivation has occurred is the Pine Lodge fault discharge area. Based upon this analogy, CO_2 emissions were estimated using the analog database at 1 to 30 µmol/m^2-s. Leakage from faults also was modeled in the Jewett Site EIV using leakage simulation models for leakage through the Eagle Ford Shale primary seal. The EIV leakage simulation models predicted that leakage rates from the Woodbine Reservoir to the base of the Pecan Gap secondary seal are on the order of $5x10^{-6}$ kilogram/m^2-s (or 104 µmol/m^2-s) and take roughly 2 to 16 years to reach the Pecan Gap seal. Considering both the analog database and modeling results, CO_2 emissions were estimated to be 1 to 30 µmol/m^2-s. While these leakage rates are less than those predicted by STOMP, they are not directly comparable since the STOMP predictions are for releases to the base of the secondary seal, while the analog database predictions are for releases to the atmosphere. The frequency of a release at this rate is assumed to be 10^{-4} per 5,000 years. Although releases from oil and gas reservoirs have occurred elsewhere, monitoring nearly always detects these types of leaks and the leaks are subsequently mitigated. The area over which the CO_2 emissions are released was assumed to cover 5 percent of the area of the CO_2 plume; this assumes (based upon expert judgment) that only this fraction of the plume will be sufficiently overpressured to create fractures. A 10-year (decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release, and that flow along a fracture zone can reach the surface at timescales of only a decade, as shown by the modeling work in the EIV.

Leakage into non-target aquifers due to unknown structural or stratigraphic connections- The potential for release at the Jewett Site that could occur by leakage from the target sequestration zone into non-target aquifers due to unknown structural or stratigraphic connections (e.g., due to an unanticipated facies change from impermeable to permeable strata within the seals) was estimated based upon the stratigraphic and structural setting of the site and the amount of uncertainty in the site characteristics due to data gaps that may be present at the site. For the Jewett Site, the stratigraphic and structural setting suggests that there is a very low probability of a facies change in the seal. However, there is faulting at the site that could naturally breach the seal if either:

- the fault throw is larger than expected;
- the seal thickness is smaller than expected; or
- the seal permeability is altered due to fracturing of the seal along the fault.

This leakage mechanism is analogous to CO_2 leakage from a natural CO_2 reservoir with features such as a fault that breaches the seals. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar geologic conditions to those proposed for the Jewett Site with a leaky fault through the seal. Based upon a qualitative comparison of the Jewett Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Jewett Site is the Crystal Geyser site. Based upon this analogy, CO_2 emissions were estimated at 5 to 170 µmol/m^2-s. The frequency of a release at this rate is assumed to be 10^{-5} per 5,000 years. The area over which the CO_2 emissions are released covers the area of the fault trace over the CO_2 plume. A 100-year (multi-decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release by stopping injection, but that flow will continue.

Leakage into non-target aquifers due to lateral migration from the target zone- The potential for release at the Jewett Site that could occur by leakage from the target sequestration zone into non-target aquifers due to lateral migration from the target zone (e.g., the regional hydraulic gradient and/or dip may provide high lateral flow rates into deep regional aquifers). For the Jewett Site, the stratigraphic and structural setting suggests that there is only a small probability that lateral flow could escape the target zone because the formation dip and hydraulic gradient are so small. In addition, due to the great depth and small dip, a very large migration distance and time would be required before CO_2 would reach areas where receptors could be exposed, and CO_2 trapping mechanisms may even deplete the CO_2 prior to that. However, it was assumed that CO_2 may eventually find a conduit for surface exposure, but at greatly diminished rates due to the torturous and long flow path involved.

This leakage mechanism is analogous to CO_2 leakage from a natural CO_2 reservoir where lateral flow allows CO_2 to leak into shallower zones. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar geologic conditions. Based upon a qualitative comparison of the Jewett Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Jewett Site is the Pine Lodge permeable zone area. Based upon this analogy, CO_2 emissions were estimated at 1 to 30 $\mu mol/m^2$-s. The frequency of a release at this rate is assumed to be 10^{-6} per 5,000 years. The area over which the CO_2 emissions are released covers the area of the CO_2 plume. A 100-year (multi-decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release by stopping injection, but that flow will continue.

Upward migration through poorly constructed and abandoned deep wells - The potential for release at the Jewett Site that could occur by leakage from the target sequestration zone through poorly constructed and abandoned deep wells was estimated based upon the number of deep wells at the Jewett Site and the relative probability, duration, and magnitude of well releases experienced at industrial analog sites. The Jewett Site leakage was then estimated using these generic well release probabilities, durations, and rates based upon the actual number of deep wells at the site. There are two categories of deep wells, those constructed for the site (two wells at one location plus one at another location), and other oil and gas wells (57 total). Deep wells constructed for this project were assigned a frequency of failure of 10^{-5} per year, based upon failure rates reported for production class industrial wells because these wells are constructed to the highest quality standards. Other deep wells were assigned a failure frequency of 10^{-3} per year, based upon failure rates reported for exploration class industrial wells because these wells are not constructed to the same quality standards as production wells.

Two types of releases are possible: 1) high rate leaks and 2) low rate leaks. It was assumed that high rate leaks would be readily detected and mitigated (therefore, releases were assumed to be short (i.e., 0.5 to 5 days), whereas low rate leaks were assumed to go undetected and remain unmitigated (therefore, releases were assumed to last for 5,000 years). The well release rates are constrained to leakage rates at approximately 220 tons (200 metric tons) per year for slow rate leaks and 12,125 tons (11,000 metric tons) per year for high rate leaks, based upon the data in Table 5-3 and Table 5-4. The low rate is based on the well leakage rate used for the two Latrobe Valley sites in Australia (see Table 5-4). A high leakage rate of 5,511 tons (5,000 metric tons) per year was used for the highly permeable and transmissive target reservoir at Jewett, the Woodbine Formation.

Upward migration through undocumented deep wells - The potential for release at the Jewett Site that could occur by leakage from the target sequestration zone through undocumented deep wells was estimated using the same general methodology applied for documented wells. The Jewett Site leakage was then estimated using these generic well release probabilities, durations, and rates based upon the actual number of undocumented deep wells at the site. Based upon the site characteristics and the depth of the target reservoir, 13 undocumented deep wells were assumed for the site, based upon expert judgment. Because these deep wells were not drilled for this project, they were assigned a frequency of failure of 10^{-3} per year, based upon failure rates reported for exploration class industrial wells. The well releases used in the modeling were the same as used for abandoned deep wells.

5.5.1.2 Odessa, TX

The first step in the sequestered gas leakage analyses was to conduct a HSE risk screening and ranking using the SRF recently developed by LBNL for geologic CO_2 storage site selection (Oldenburg, 2005). The results for the Odessa Site are given in Appendix D-2. The SRF summary analysis indicates that the Odessa Site has good primary sealing potential, good to fair secondary sealing potential, and fair to good attenuation potential, with a high degree of certainty in these characteristics based upon reasonably well known data. The most significant areas of uncertainty are the following:

- The possibility of leakage from deep wells that penetrate the primary seal, since there are 16 wells that penetrate all primary and secondary seals that could provide a conduit for leakage, and the injection well pattern had to be judiciously chosen to avoid impacting any of these well locations;
- The possibility for low injectivity and high injection pressures due to the low permeability of the Queen and Delaware Mountain Sandstones increases the number of wells required, and also increase the chance for well failures, which may cause an increased probability of leakage from the target formation;
- The shallow depth of the target zone (2,700 feet [823 meters]) results in formation temperatures and pressures just above the CO_2 critical point, such that any significant decrease in pressures (e.g., due to leakage into shallower zones) allow CO_2 to drop below the critical point, greatly expanding its volume and potentially accelerating its leakage; and
- The lack of hydrocarbons may be due to the lack of a seal, either laterally between the basin slope sandstones and the carbonate platform deposits or vertically through the Upper Queen and Seven Rivers seals.

The secondary seal provided by the Salado anhydrites and halite is particularly robust due its low permeability and high capillary entry pressure, as well as the fact that the salts have not been and are unlikely to be compromised by fracturing. The site also has no mapped faults or fractures above the basement, but the low differential stress suggests that if even if there are faults they are not likely to be transmissive (especially east-west orientations). The low differential stress also suggests undetected fault seals will not fail during normal sequestration operations.

Release Scenarios

The second task in the sequestered gas leakage analyses was to define the key release scenarios relevant to the long-term safety and performance of the CO_2 storage system, and the estimate the magnitude, probability, and duration of CO_2 leakage associated with each release scenario. Given the Odessa SCM, EIV database, and the SRF results given above, the list of release scenarios presented in Section 5.3 covers all key release scenarios that may give rise to CO_2 leakage from the Odessa sequestration reservoir. The magnitude, probability, and duration of CO_2 leakage rates from the sequestration reservoir are summarized in Table 5-8 and discussed in detail below:

Upward migration through caprock due to gradual and slow release - This release scenario evaluates possible releases via upward migration through the caprock from the unaltered native state reservoir. This release scenario does not include releases due to induced fracturing, fault re-activation, and wellbores; these are each addressed in separate release scenarios below. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar release mechanisms and geologic conditions. Based upon a qualitative comparison of the Odessa Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog sites that are the closest match to the Odessa Site are the St. Johns Dome and Vorderrhon, Germany sites. For example,

- At both the Odessa and St. Johns Dome sites, the reservoir is sandstone, the seal is anhydrite, and the depth is moderate (i.e., 2,690 feet [820 meters] at Odessa and up to 2,461 feet [750 meters] at St. Johns Dome); and

- At Odessa, the reservoir is sandstone, the upper seal is salt, and the depth is 2,690 feet (820 meters), while at Vorderrhon, Germany the reservoir is siltstone, the upper seal is salt, and the depth is 3,281 feet (1,000 meters).

CO_2 emissions are estimated to be zero at Vorderrhon, Germany and from 0 to 1 $\mu mol/m^2$-s at St. Johns Dome. Based upon this analogy, CO_2 emissions were estimated to be from 0 to 1 $\mu mol/m^2$-s at the Odessa Site. To be conservative, the upper end of the emission range was used in the risk analyses. The frequency of a release at this rate is assumed to be 0.2 per 5,000 years, since it is based upon the best estimate of each site's geologic condition, and no failure mechanisms are necessary that may have a low probability of occurring. The area over which the CO_2 emissions are released covers the entire area of the CO_2 plume, and a 5,000 year timeframe was used as the emission duration (a reasonable but conservative assumption).

Upward migration through caprock due to catastrophic failure and quick release - This release scenario evaluates an eruptive/explosive release at very high rates, similar in nature to release events in volcanic areas. As noted in Section 5.4, no natural CO_2 eruptive events have ever been recorded in sedimentary basins (IEA Greenhouse Gas R&D Program, 2006a), no eruptive events have been recorded at underground natural gas storage sites (IEA Greenhouse Gas R&D Program, 2006b), and there is no evidence that a CO_2 eruptive release can be powered solely by mechanical energy of compression (Pruess, 2006). Based upon a qualitative comparison of the Odessa Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, this release scenario is considered vanishingly remote at the Odessa sequestration site and was assigned a frequency of less than 10^{-6} per 5,000 years. The only event that hypothetically could cause a large scale release in this geologic setting would be an earthquake of magnitude 6 or greater, however, the frequency of such an event is also less than 10^{-6} per 5,000 years. For these reasons, emissions from catastrophic caprock failure were not estimated nor were assumed exposure to emissions from catastrophic caprock failure.

Release through existing faults due to increased pressure – Four main factors are key for release via this mechanism: (1) the presence of faults, (2) magnitude of pressure increase due to injection operations, (3) the stress regime at the site, and (4) the magnitude of stress at the site. At the Odessa Site, (1) there are no faults, (2) pressure increase could be high due to the low injectivity of the Queen and Delaware Mountain Sandstones, (3) the stress regime is mixed normal (tensional) and strike-slip, and (4) there is a low differential between the minimum and maximum horizontal stress. Thus, three of these four factors are unfavorable for this release scenario at the Odessa Site; for release to occur, the observation that faults are not present must be in error, the injection pressure would need to be much higher than expected, and the minimum horizontal stress would need to be lower than expected. In addition, the fault would need to breach the shallow Salado anhydrites and halite, which is highly unexpected given the seal properties.

This release scenario is analogous to CO_2 leakage from a natural CO_2 reservoir where natural processes have created regional scale fractures/faults that allow CO_2 to leak through the overlying seals and discharge at either the ground surface or into shallow groundwater. The most likely release rate for this scenario depends upon the extent of slip occurring on the fault, and was estimated using the analog database, based upon known CO_2 emissions from analog sites where faults breach the primary and secondary seals. Based upon a qualitative comparison of the Odessa Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Odessa Site after fault-reactivation has occurred is the Pine Lodge fault zone area. Based upon this analogy, CO_2 emissions were estimated based upon the analog database at 1 to 30 µmol/m^2-s. Leakage from faults also was modeled in the Odessa Site EIV using leakage simulation models for leakage through the Goat Seep seal. The EIV leakage simulation models predicted that leakage rates from the Delaware Reservoir to the base of the Upper Queen/Seven Rivers seal are on the order of 7 x 10^{-4} kilogram/m^2-s (or 14,600 µmol/m^2-s) and take roughly 0.2 to 20 years to reach the Upper Queen/Seven Rivers seal. Considering both the analog database and modeling results, CO_2 emissions were estimated to be 1 to 30 µmol/m^2-s. While these leakage rates are less than those predicted by STOMP, they are not directly comparable since the STOMP predictions are for releases to the base of the secondary seal, while the analog database predictions are for releases to the atmosphere. The frequency of a release at this rate is assumed to be 10^{-4} per 5,000 years; monitoring nearly always detects these types of leaks, and the leaks are subsequently mitigated. The area over which the CO_2 emissions are released covers the area of a hypothetical fault trace over the CO_2 plume, assumed to be 25 percent of the plume diameter. A 10-year (decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release, and that flow along a fracture zone can reach the surface at timescales of only a decade, as indicated by the modeling results in the EIV.

Release through induced faults due to increased pressure - The potential for release at the Odessa Site through induced faults due to increased pressure was estimated based upon the maximum expected injection pressures at the site, and the probability that CO_2 injection increases pressure until it exceeds the fracture gradient. For example, pore pressure associated with the injection of CO_2 (85 percent of 0.7 psi/feet) can increase stress until the stress overcomes the fracture pressure, which was estimated at approximately 0.7 psi/feet. This release scenario is analogous to CO_2 leakage from a natural CO_2 reservoir where natural processes have created local scale fractures/faults that allow CO_2 to leak through the overlying seals and discharge at either the ground surface or into shallow groundwater. The most likely release rate for this scenario depends upon the extent and permeability of the fracture, and was estimated using the analog database, based upon known CO_2 emissions from analog sites where faults breach the primary seals. Based upon a qualitative comparison of the Odessa Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog sites that is the closest match to the Odessa Site after fracturing has occurred is the Pine Lodge fault zone area. Based upon this analogy, CO_2 emissions were estimated using the analog database at 1 to 30 µmol/m^2-s. Leakage from faults also was modeled in the Odessa Site EIV using leakage simulation models for leakage through the Goat Seep seal. The EIV leakage simulation models predicted that leakage rates from the Delaware Reservoir to the base of the Upper Queen/Seven Rivers seal are on the order of 7 x 10^{-4} kilogram/m^2-s (or 14,600 µmol/m^2-s) and take roughly 0.2 to 20 years to reach the Upper Queen/Seven Rivers seal. Considering both the analog database and modeling results, CO_2 emissions were estimated to be 1 to 30 µmol/m^2-s. While these leakage rates are less than those predicted by STOMP, they are not directly comparable since the STOMP predictions are for releases to the base of the secondary seal, while the analog database predictions are for releases to the atmosphere. The frequency of a release at this rate is considered assumed to be 10^{-4} per 5,000 years. The area over which the CO_2 emissions are released covers the area of the fracture trace over the CO_2 plume, with is assumed to be 5 percent of the plume diameter. A 10-year (decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release, and that flow along a fracture zone can reach the surface at timescales of only a decade, as indicated by the modeling results in the EIV.

Leakage into non-target aquifers due to unknown structural or stratigraphic connections- The potential for release at the Odessa Site that could occur by leakage from the target sequestration zone into non-target aquifers due to unknown structural or stratigraphic connections (e.g., due to an unanticipated facies change from impermeable to permeable strata within the seals) was estimated based upon the stratigraphic and structural setting of the site and the amount of uncertainty in the site characteristics due to data gaps that may be present at the site. For the Odessa Site, the stratigraphic and structural setting suggests that there is no faulting at the site that could naturally breach the seal since no faults are thought to be present; therefore, the probability of this scenario is remote. There is also only a low probability of a facies change in the seals given the areal extent over which the seal is well documented, but this scenario appears more likely than leakage through faults in the seal. Though leakage through the seal via a facies change is thought to be a low probability, it is a viable leakage mechanism.

This leakage mechanism is analogous to the CO_2 leakage rate from a natural CO_2 reservoir with a facies change in the seals. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar geologic conditions to those proposed for the Odessa Site with a seal leak. Based upon a qualitative comparison of the Odessa Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Odessa Site is the Pine Lodge permeable zone area. Based upon this analogy, CO_2 emissions were estimated at 2.4 to 5 μmol/m^2-s. The frequency of a release at this rate is assumed to be 10^{-5} per 5,000 years. The area over which the CO_2 emissions are released covers the area of CO_2 plume, a conservative but reasonable assumption. A 100-year (multi-decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release by stopping injection, but that flow will continue.

Leakage into non-target aquifers due to lateral migration from the target zone- The potential for release at the Odessa Site that could occur by leakage from the target sequestration zone into non-target aquifers due to lateral migration from the target zone (e.g., the regional hydraulic gradient and/or dip may provide high lateral flow rates into deep regional aquifers). For the Odessa Site, the stratigraphic and structural setting suggests that there is only a small probability that lateral flow could escape the target zone because the formation dip and hydraulic gradient are so small. In addition, due to the great depth and small dip, a very large migration distance and time would be required before CO_2 would reach areas where receptors could be exposed, and CO_2 trapping mechanisms may even deplete the CO_2 prior to reaching exposure points. However, it was assumed that CO_2 may eventually find a conduit for surface exposure, but at greatly diminished rates due to the torturous and long flow path involved.

This leakage mechanism is analogous to the CO_2 leakage rate from a natural CO_2 reservoir where lateral flow allows CO_2 to leak into shallower zones. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar geologic conditions. Based upon a qualitative comparison of the Odessa Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Odessa Site is the Pine Lodge permeable zone area. Based upon this analogy, CO_2 emissions were estimated at 1 to 30 μmol/m^2-s. The frequency of a release at this rate is assumed to be 10^{-6} per 5,000 years. The area over which the CO_2 emissions are released covers the area of the CO_2 plume. A 100-year (multi-decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release by stopping injection, but that flow will continue.

Upward migration through poorly constructed and abandoned deep wells - The potential for release at the Odessa Site that could occur by leakage from the target sequestration zone through poorly constructed and abandoned deep wells was estimated based upon the number of deep wells at the Odessa Site and the relative probability, duration, and magnitude of well releases experienced at industrial analog sites. The Odessa Site leakage was then estimated using these generic well release probabilities, durations, and rates based upon the actual number of deep wells at the site. There are two categories of deep wells, those constructed for the site (10 total), and other oil and gas wells (zero with the 50-year sequestration plume footprint but there are16 wells just outside of the footprint). Deep wells constructed for this project were assigned a frequency of failure of 10^{-5} per year based upon failure rates reported for production class industrial wells because these wells are constructed to the highest quality standards. Other deep wells were assigned a failure frequency of 10^{-3} per year based upon failure rates reported for exploration class industrial wells because these wells are not constructed to the same quality standards as production wells.

Two types of releases are possible: 1) high rate leaks and 2) low rate leaks. It was assumed that high rate leaks would be readily detected and mitigated (therefore, releases were assumed to be short, i.e., 0.5 to 5 days) whereas low rate leaks were assumed to go undetected and remain unmitigated (therefore, releases were assumed last for 5,000 years). The well releases are constrained to leakage rates at approximately 220 tons (200metric tons) per year for slow rate leaks and 12,125 tons (11,000 metric tons) per year for high rate leaks, based upon the data in Table 5-3 and Table 5-4. The low rate is based on the well leakage rate used for the two Latrobe Valley sites in Australia (see Table 5-4). A high leakage rate of 551 tons (500 metic tons) per year was used for the target reservoir at Odessa, since the target reservoir is shallow and has a low permeability.

Upward migration through undocumented deep wells - The potential for release at the Odessa Site that could occur by leakage from the target sequestration zone through undocumented deep wells was estimated using the same general methodology applied for documented wells. The Odessa Site leakage was then estimated using these generic well release probabilities, durations, and rates based upon the actual number of undocumented deep wells at the site. Based upon the site characteristics and the depth of the target reservoir, two undocumented deep wells were assumed for the site, based upon expert judgment. Because these deep wells were not drilled for this project, they were assigned a frequency of failure of 10^{-3} per year based upon failure rates reported for exploration class industrial wells. The well releases used in the modeling were the same as used for abandoned deep wells.

5.5.1.3 Mattoon, IL

The first step in the sequestered gas leakage analyses was to conduct a HSE risk screening and ranking using the SRF recently developed by LBNL for geologic CO_2 storage site selection (Oldenburg, 2005). The results for the Mattoon Site are given in Appendix D-3. The SRF summary analysis indicates that the Mattoon Site has good primary and secondary sealing potential and good attenuation potential. There is a high degree of certainty in the attenuation potential based upon reasonably well known data, but only a fair degree of certainty in the primary sealing and secondary sealing potential. The most significant areas of uncertainty are the following:

- The formation properties for both the primary and secondary seals and the target sequestration reservoir must be extrapolated from a considerable distance to the site (36 miles [58 kilometers]). While the facies may be reasonably well extrapolated to the site since the depositional environment of the Mt. Simon Sandstone does not appear to vary much across Illinois, hydraulic and storage properties such as porosity and permeability values may only be extrapolated to the site with considerable uncertainty;
- Because the Mt Simon thins to zero thickness in some areas, there is a small risk of the Mt. Simon not being present at the Mattoon Site; and
- Lateral changes in mineralogy of the Eau Claire could result in increased permeability of the caprock and make it susceptible to slow permeation.

The compressive nature of the regional stress regime suggests that faults should not easily rupture or become transmissive in the event of natural or induced seismic events and that fractures and faults will not tend to open due to normal field operations. Since no wells penetrate the Eau Claire seal, leakage through wellbores is not a significant concern at the site.

Release Scenarios

The second task in the sequestered gas leakage analyses was to define the key release scenarios relevant to the long-term safety and performance of the CO_2 storage system, and to estimate the magnitude, probability, and duration of CO_2 leakage associated with each release scenario. Given the Mattoon SCM, EIV database, and the SRF results given above, the list of release scenarios presented in Section 5.3 covers all key release scenarios that may give rise to CO_2 leakage from the Mattoon sequestration reservoir. The magnitude, probability, and duration of CO_2 leakage rates from the sequestration reservoir are summarized in Table 5-8 and discussed in detail below:

Upward migration through caprock due to gradual and slow release - This release scenario evaluates possible releases via upward migration through the caprock from the unaltered native state reservoir. This release scenario does not include releases due to induced fracturing, fault re-activation, and wellbores; these are each addressed in separate release scenarios below. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar release mechanisms and geologic conditions. Based upon a qualitative comparison of the Mattoon Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog sites that are the closest match to the Mattoon Site are the Rangely, CO and Teapot Dome sites. For example,

- The reservoir is sandstone, the seal is shale, and the depth is about 6,562 feet (2,000 meters) at both the Mattoon and Rangely sites; and
- The reservoir is sandstone, the seal is shale, and the depth is moderate at both the Mattoon (6,398 feet [1,950 meters]) and Teapot Dome (5,512 feet [1,680 meters]) sites.

CO_2 emissions are estimated to range from 0.0016 to 0.034 $\mu mol/m^2$-s at Rangely, and 0.0048 to 0.17 $\mu mol/m^2$-s at Teapot Dome. Based upon this analogy, CO_2 emissions were estimated to range from 0.0016 to 0.17 $\mu mol/m^2$-s at the Mattoon Site. To be conservative, the upper end of the emission range was used in the risk analyses. The probability of a release at this rate is considered high (0.2) since it is based upon the best estimate of each site's geologic condition, and no failure mechanisms are necessary that may have a low probability of occurring. The area over which the CO_2 emissions are released covers the entire area of the CO_2 plume, and the 5,000 year timeframe was used as the emission duration (a reasonable but conservative assumption).

Upward migration through caprock due to catastrophic failure and quick release - This release scenario evaluates an eruptive/explosive release at very high rates, similar in nature to release events in volcanic areas. As noted in Section 5.4, no natural CO_2 eruptive events have ever been recorded in sedimentary basins (IEA Greenhouse Gas R&D Program, 2006a), no eruptive events have been recorded at underground natural gas storage sites (IEA Greenhouse Gas R&D Program, 2006b), and there is no evidence that CO_2 eruptive release can be powered solely by mechanical energy of compression (Pruess, 2006). Based upon a qualitative comparison of the Mattoon Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, this release scenario is considered vanishingly remote and was assigned a frequency of less than 10^{-6} per 5,000 years. Thus, it appears reasonable to assume that an eruptive release from stable sedimentary formations, such as those found at the Mattoon Site, are extremely unlikely. The only event that hypothetically could cause a large scale release in this geologic setting would be an earthquake of magnitude 6 or greater, however, the frequency of such an event is also less than 10^{-6} per 5,000 years. For these reasons, emissions from catastrophic caprock failure were not estimated nor were assumed exposure to emissions from catastrophic caprock failure.

Release through existing faults due to increased pressure - Four main factors are key for release via this mechanism: (1) the presence of faults, (2) magnitude of pressure increase due to injection operations, (3) the stress regime at the site, and (4) the magnitude of stress at the site. At the Mattoon Site, (1) there are no faults present, (2) pressure increase is only moderate due to fair injectivity of the Mt Simon Sandstone, (3) the stress regime is compressional (mixed thrust and strike-slip faults), and (4) the maximum horizontal stress (S_{HMax}) and intermediate horizontal stress (S_{hmin}) are both higher than the vertical stress (S_V). Thus, all four factors are unfavorable for this release scenario at the Mattoon Site; for release to occur, the observation that faults are not present must be in error, and the injection pressure would need to overcome the high horizontal compressive stresses at the site.

This release scenario is analogous to CO_2 leakage from a natural CO_2 reservoir where natural processes have created regional scale fractures/faults that allow CO_2 to leak through the overlying seals and discharge at either the ground surface or into shallow groundwater. The most likely release rate for this scenario depends upon the extent of slip occurring on the fault, and was estimated using the analog database, based upon known CO_2 emissions from analog sites where faults breach the primary and secondary seals. Based upon a qualitative comparison of the Mattoon Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Mattoon Site after fault-reactivation has occurred is the Pine Lodge fault zone area. Based upon this analogy, CO_2 emissions were estimated using the analog database at 1 to 30 μmol/m^2-s. Leakage from faults also was modeled in the Mattoon Site EIV using leakage simulation models for leakage through the Eau Clare seal. The EIV leakage simulation models predicted that leakage rates from the Mt. Simon Reservoir to the base of the Maquoketa seal are on the order of 7×10^{-4} kilogram/m^2-s (or 14,600 μmol/m^2-s) and take roughly 5 to 8 years to reach the Maquoketa seal. Considering both the analog database and modeling results, CO_2 emissions were estimated to be 1 to 30 μmol/m^2-s. While these leakage rates are less than those predicted by STOMP, they are not directly comparable since the STOMP predictions are for releases to the base of the secondary seal, while the analog database predictions are for releases to the atmosphere. The frequency of a release at this rate is assumed to be 10^{-4} per 5,000 years; monitoring nearly always detects these types of leaks, and the leaks are subsequently mitigated. The area over which the CO_2 emissions are released covers the area of a hypothetical fault trace over the CO_2 plume, assumed to be 25 percent of the plume diameter. A 10-year (decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release, and that flow along a fracture zone can reach the surface at timescales of only a decade, as shown by the modeling results in the EIV.

Release through induced faults due to increased pressure - The potential for release at the Mattoon Site through induced faults due to increased pressure was estimated based upon the maximum expected injection pressures at the site, and the probability that CO_2 injection increases pressure until it exceeds the fracture gradient. For example, pore pressure associated with the injection of CO_2 (85 percent of 0.8 psi/feet) can increase stress until the stress overcomes the fracture pressure, which was estimated at approximately 0.8 psi/feet. This release scenario is analogous to CO_2 leakage from a natural CO_2 reservoir where natural processes have created local scale fractures/faults that allow CO_2 to leak through the overlying seals and discharge at either the ground surface or into shallow groundwater. The most likely release rate for this scenario depends upon the extent and permeability of the fracture, and was estimated using the analog database, based upon known CO_2 emissions from analog sites where faults breach the primary seals. Based upon a qualitative comparison of the Mattoon Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Mattoon Site after fracturing has occurred is the Pine Lodge fault zone area. Based upon this analogy, CO_2 emissions were estimated using the analog database at 1 to 30 μmol/m^2-s. Leakage from faults also was modeled in the Mattoon Site EIV using leakage simulation models for leakage through the Eau Clare seal. The EIV leakage simulation models predicted that leakage rates from the Mt. Simon Reservoir to the base of the Maquoketa seal are on the order of 7×10^{-4}

kilogram/m^2-s (or 14,600 µmol/m^2-s) and take roughly 5 to 8 years to reach the Maquoketa seal. Considering both the analog database and modeling results, CO_2 emissions were estimated to be 1 to 30 µmol/m^2-s. While these leakage rates are smaller than those predicted by STOMP, they are not directly comparable since the STOMP predictions are for releases to the base of the secondary seal, while the analog database predictions are for releases to the atmosphere. The frequency of a release at this rate is assumed to be 10^{-4} per 5,000 years. The area over which the CO_2 emissions are released covers the area of the fracture trace over the CO_2 plume, which is assumed to be 5 percent of the plume diameter. A 10-year (decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release, and that flow along a fracture zone can reach the surface at timescales of only a decade, as shown by the modeling results in the EIV.

Leakage into non-target aquifers due to unknown structural or stratigraphic connections- The potential for release at the Mattoon Site that could occur by leakage from the target sequestration zone into non-target aquifers due to unknown structural or stratigraphic connections (e.g., due to an unanticipated facies change from impermeable to permeable strata within the seals) was estimated based upon the stratigraphic and structural setting of the site and the amount of uncertainty in the site characteristics due to data gaps that may be present at the site. For the Mattoon Site, the stratigraphic and structural setting suggests that there is no faulting at the site that could naturally breach the seal since no faults are thought to be present; therefore, the probability of this scenario is remote. There is also only a low probability of a facies change in the seals given the areal extent over which the seal is well documented, but this scenario appears more likely than leakage through faults in the seal. Though leakage through the seal via a facies change is thought to be a low probability, it is a viable leakage mechanism. This leakage mechanism is analogous to CO_2 leakage from a natural CO_2 reservoir with a facies change in the seals. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar geologic conditions to those proposed for the Mattoon Site with a seal leak. Based upon a qualitative comparison of the Mattoon Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Mattoon Site is the Pine Lodge permeable zone area. Based upon this analogy, CO_2 emissions were estimated at 2.4 to 5 µmol/m^2-s. The frequency of a release at this rate is assumed to be 10^{-5} per 5,000 years. The area over which the CO_2 emissions are released covers the area of CO_2 plume, a conservative but reasonable assumption. A 100-year (multi-decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release by stopping injection, but that flow will continue.

Leakage into non-target aquifers due to lateral migration from the target zone- The potential for release at the Mattoon Site that could occur by leakage from the target sequestration zone into non-target aquifers due to lateral migration from the target zone (e.g., the regional hydraulic gradient and/or dip may provide high lateral flow rates into deep regional aquifers). For the Mattoon Site, the stratigraphic and structural setting suggests that there is only a small probability that lateral flow could escape the target zone because the formation dip and hydraulic gradient are so small. In addition, due to the great depth and small dip, a very large migration distance and time would be required before CO_2 would reach areas where receptors could be exposed, and CO_2 trapping mechanisms may even deplete the CO_2 prior to reaching exposure points. However, it was assumed that CO_2 may eventually find a conduit for release to the surface, but at greatly diminished rates due to the torturous and long flow path involved.

This leakage mechanism is analogous to CO_2 leakage from a natural CO_2 reservoir where lateral flow allows CO_2 to leak into a shallower zone. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar geologic conditions. Based upon a qualitative comparison of the Mattoon Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Mattoon Site is the Pine Lodge permeable zone area. Based upon this analogy, CO_2

emissions were estimated at 1 to 30 µmol/m^2-s. The frequency of a release at this rate is assumed to be 10^{-6} per 5,000 years. The area over which the CO_2 emissions are released covers the area of the CO_2 plume. A 100-year (multi-decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release by stopping injection, but that flow will continue.

Upward migration through poorly constructed and abandoned deep wells - The potential for release at the Mattoon Site that could occur by leakage from the target sequestration zone through poorly constructed and abandoned deep wells was estimated based upon the number of deep wells at the Mattoon Site and the relative probability, duration, and magnitude of well releases experienced at industrial analog sites. The Mattoon Site leakage was then estimated using these generic well release probabilities, durations, and rates based upon the actual number of deep wells at the site. Since there are no deep wells, except those constructed for the site, there is only one category of deep wells (i.e., those constructed for the site, two total). Deep wells constructed for this project were assigned a frequency of failure of 10^{-5} per year, based upon failure rates reported for production class industrial wells because these wells are constructed to the highest quality standards. Two types of releases are possible: 1) high rate leaks; and 2) low rate leaks. It was assumed that high rate leaks would be readily detected and mitigated (therefore, releases were assumed to be short, i.e., 0.5 to 5 days) whereas low rate leaks were assumed to go undetected and remain unmitigated (therefore, releases were assumed last for 5,000 years). The well releases are constrained to leakage rates at approximately 220 tons (200 metric tons) per year for slow rate leaks and 12,125 tons (11,000 metric tons) per year for high rate leaks, based upon the data in Table 5-3 and Table 5-4. The low rate is based on the well leakage rate used for the two Latrobe Valley sites in Australia (see Table 5-4). A high leakage rate of 1,102 tons (1,000 metric tons) per year was used for the target reservoir at Mattoon, since the target reservoir has moderate permeability.

Upward migration through undocumented deep wells - The potential for release at the Mattoon Site that could occur by leakage from the target sequestration zone through undocumented deep wells was estimated using the same general methodology applied for documented wells. The Mattoon Site leakage was then estimated using these generic well release probabilities, durations, and rates based upon the actual number of undocumented deep wells at the site. Based upon the site characteristics and the depth of the target reservoir, 2 undocumented deep wells were assumed for the site, based upon expert judgment. Because these deep wells were not drilled for this project, they were assigned a frequency of failure of 10^{-3} per year based upon failure rates reported for exploration class industrial wells. The well releases were the same as used for abandoned deep wells.

5.5.1.4 Tuscola, IL

The first step in the sequestered gas leakage analyses was to conduct a HSE risk screening and ranking using the SRF recently developed by LBNL for geologic CO_2 storage site selection (Oldenburg, 2005). The results for the Tuscola Site are given in Appendix D-4. The SRF summary analysis indicates that the Tuscola Site has good primary and secondary sealing potential and good attenuation potential. There is a high degree of certainty in the attenuation potential based upon reasonably well known data, but only a fair degree of certainty in the primary sealing and secondary sealing potential. The most significant areas of uncertainty are the following:

- The formation properties for both the primary and secondary seals and the target sequestration reservoir must be extrapolated from a considerable distance to the site (56 miles). While the facies may be reasonably well extrapolated to the site since the depositional environment of the Mt. Simon Sandstone does not appear to vary much across Illinois, hydraulic and storage properties such as porosity and permeability values may only be extrapolated to the site with considerable uncertainty;

- Because the Mt Simon thins to zero thickness in some areas, there is a small risk of the Mt. Simon not being present at the Tuscola Site; and
- Lateral changes in mineralogy of the Eau Claire could result in increased permeability of the caprock and make it susceptible to slow permeation.

The compressive nature of the regional stress regime suggests that faults should not easily rupture or become transmissive in the event of natural or induced seismic events, and that fractures and faults will not tend to open due to normal field operations. Since no wells penetrate the Eau Claire seal, leakage through wellbores is not a significant concern at the site.

Release Scenarios

The second task in the sequestered gas leakage analyses was to define the key release scenarios relevant to the long-term safety and performance of the CO_2 storage system, and then estimate the magnitude, probability, and duration of CO_2 leakage associated with each release scenario. Given the Tuscola SCM, EIV database, and the SRF results given above, the list of release scenarios presented in Section 5.3 covers all key release scenarios that may give rise to CO_2 leakage from the Tuscola sequestration reservoir. The magnitude, probability, and duration of CO_2 leakage rates from the sequestration reservoir are summarized in Table 5-8 and discussed in detail below:

Upward migration through caprock due to gradual and slow release - This release scenario evaluates possible releases via upward migration through the caprock from the unaltered native state reservoir. This release scenario does not include releases due to induced fracturing, fault re-activation, and wellbores; these are each addressed in separate release scenarios below. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar release mechanisms and geologic conditions. Based upon a qualitative comparison of the Tuscola Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog sites that are the closest match to the Tuscola Site are the Rangely, CO and Teapot Dome sites. For example,

- The reservoir is sandstone, the seal is shale, and the depth is about 6,562 feet (2,000 meters) at both the Tuscola and Rangely sites; and
- The reservoir is sandstone, the seal is shale, and the depth is moderate at both the Tuscola (6,152 feet [1,875 meters]) and Teapot Dome (5,512 feet [1,680 meters]) sites.

CO_2 emissions are estimated to range from 0.0016 to 0.034 $\mu mol/m^2$-s at Rangely, and 0.0048 to 0.17 $\mu mol/m^2$-s at Teapot Dome. Based upon this analogy, CO_2 emissions were estimated to range from 0.0016 to 0.17 $\mu mol/m^2$-s at the Tuscola Site. To be conservative, the upper end of the emission range was used in the risk analyses. The frequency of a release at this rate is assumed to be 0.2 per 5,000 years since it is based upon the best estimate of each site's geologic condition, and no failure mechanisms are necessary that may have a low probability of occurring. The area over which the CO_2 emissions are released covers the entire area of the CO_2 plume, and the 5,000 year timeframe was used as the emission duration (a reasonable but conservative assumption).

Upward migration through caprock due to catastrophic failure and quick release - This release scenario evaluates an eruptive/explosive release at very high rates, similar in nature to release events in volcanic areas. As noted in Section 5.4, no natural CO_2 eruptive events have ever been recorded in sedimentary basins (IEA Greenhouse Gas R&D Program, 2006a), no eruptive events have been recorded at underground natural gas storage sites (IEA Greenhouse Gas R&D Program, 2006b), and there is no evidence that CO_2 eruptive release can be powered solely by mechanical energy of compression (Pruess, 2006). Based upon a qualitative comparison of the Tuscola Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, this release scenario is considered vanishingly remote and was assigned a frequency of less than 10^{-6} per 5,000 years. The only event that hypothetically could cause a large scale release in this geologic setting would be an earthquake of magnitude 6 or greater, however, the frequency of such an event is also less than 10^{-6} per 5,000 years. For these reasons, emissions from catastrophic caprock failure were not estimated nor were assumed exposure to emissions from catastrophic caprock failure.

Release through existing faults due to increased pressure - Four main factors are key for release via this mechanism: (1) the presence of faults, (2) magnitude of pressure increase due to injection operations, (3) the stress regime at the site, and (4) the magnitude of stress at the site. At the Tuscola Site, (1) there are no faults present, (2) pressure increase is only moderate due to fair injectivity of the Mt Simon Sandstone, (3) the stress regime is compressional (mixed thrust and strike-slip faults), and (4) the maximum horizontal stress (S_{HMax}) and intermediate horizontal stress (S_{hmin}) are both higher than the vertical stress (S_V). Thus, all four factors are unfavorable for this release scenario at the Tuscola Site; for release to occur, the observation that faults are not present must be in error, and the injection pressure would need to overcome the high horizontal compressive stresses at the site.

This release scenario is analogous to CO_2 leakage from a natural CO_2 reservoir where natural processes have created regional scale fractures/faults that allow CO_2 to leak through the overlying seals and discharge at either the ground surface or into shallow groundwater. The most likely release rate for this scenario depends upon the extent of slip occurring on the fault, and was estimated using the analog database, based upon known CO_2 emissions from analog sites where faults breach the primary and secondary seals. Based upon a qualitative comparison of the Tuscola Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Tuscola Site after fault-reactivation has occurred is the Pine Lodge fault zone area. Based upon this analogy, CO_2 emissions were estimated using the analog database at 1 to 30 μmol/m^2-s. Leakage from faults also was modeled in the Tuscola Site EIV using leakage simulation models for leakage through the Eau Clare seal. The EIV leakage simulation models predicted that leakage rates from the Mt. Simon Reservoir to the base of the Maquoketa seal are on the order of 7×10^{-4} kilogram/m^2-s (or 14,600 μmol/m^2-s) and take roughly 4 to 7 years to reach the Maquoketa seal. Considering both the analog database and modeling results, CO_2 emissions were estimated to be 1 to 30 μmol/m^2-s. While these leakage rates are smaller than those predicted by STOMP, they are not directly comparable since the STOMP predictions are for releases to the base of the secondary seal, while the analog database predictions are for releases to the atmosphere. The frequency of a release at this rate is assumed to be 10^{-4} per 5,000 years; monitoring nearly always detects these types of leaks, and the leaks are subsequently mitigated. The area over which the CO_2 emissions are released covers the area of a hypothetical fault trace over the CO_2 plume, assumed based upon expert opinion to be 25 percent of the plume diameter. A 10-year (decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release, and that flow along a fracture zone can reach the surface at timescales of only a decade, as shown by the modeling results in the EIV.

Release through induced faults due to increased pressure - The potential for release at the Tuscola Site through induced faults due to increased pressure was estimated based upon the maximum expected injection pressures at the site, and the probability that CO_2 injection increases pressure until it exceeds the fracture gradient. For example, pore pressure associated with the injection of CO_2 (85 percent of 0.8 psi/feet) can increase stress until the stress overcomes the fracture pressure, which was estimated at approximately 0.8 psi/feet. This release scenario is analogous to CO_2 leakage from a natural CO_2 reservoir where natural processes have created local scale fractures/faults that allow CO_2 to leak through the overlying seals and discharge at either the ground surface or into shallow groundwater. The most likely release rate for this scenario depends upon the extent and permeability of the fracture, and was estimated using the analog database, based upon known CO_2 emissions from analog sites where faults breach the primary seals. Based upon a qualitative comparison of the Tuscola Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Tuscola Site after fracturing has occurred is the Pine Lodge fault zone area. Based upon this analogy, CO_2 emissions were estimated using the analog database at 1 to 30 μmol/m^2-s. Leakage from faults also was modeled in the Tuscola Site EIV using leakage simulation models for leakage through the Eau Clare seal. The EIV leakage simulation models predicted that leakage rates from the Mt. Simon Reservoir to the base of the Maquoketa seal are on the order of 7 x 10^{-4} kilogram/m^2-s (or 14,600 μmol/m^2-s) and take roughly 4 to 7 years to reach the Maquoketa seal. Considering both the analog database and modeling results, CO_2 emissions were estimated to be 1 to 30 μmol/m^2-s. While these leakage rates are smaller than those predicted by STOMP, they are not directly comparable since the STOMP predictions are for releases to the base of the secondary seal, while the analog database predictions are for releases to the atmosphere. The frequency of a release at this rate is assumed to be 10^{-4} per 5,000 years. The area over which the CO_2 emissions are released covers the area of the fracture trace over the CO_2 plume, which is assumed based upon expert judgment to be 5 percent of the plume diameter. A 10-year (decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release, and that flow along a fracture zone can reach the surface at timescales of only a decade, as shown by the modeling results in the EIV.

Leakage into non-target aquifers due to unknown structural or stratigraphic connections- The potential for release at the Tuscola Site that could occur by leakage from the target sequestration zone into non-target aquifers due to unknown structural or stratigraphic connections (e.g., due to an unanticipated facies change from impermeable to permeable strata within the seals) was estimated based upon the stratigraphic and structural setting of the site and the amount of uncertainty in the site characteristics due to data gaps that may be present at the site. For the Tuscola Site, the stratigraphic and structural setting suggests that there is no faulting at the site that could naturally breach the seal since no faults are thought to be present; therefore, the probability of this scenario is remote. There is also only a low probability of a facies change in the seals given the areal extent over which the seal is well documented, but this scenario appears more likely than leakage through faults in the seal. Though leakage through the seal via a facies change is thought to be a low probability, it is a viable leakage mechanism.

This leakage mechanism is analogous to the CO_2 leakage rate from a natural CO_2 reservoir with a facies change in the seals. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar geologic conditions to those proposed for the Tuscola Site with a seal leak. Based upon a qualitative comparison of the Tuscola Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Tuscola Site is the Pine Lodge permeable zone area. Based upon this analogy, CO_2 emissions were estimated at 2.4 to 5 μmol/m^2-s. The frequency of a release at this rate is assumed to be 10^{-5} per 5,000 years. The area over which the CO_2 emissions are released covers the area of CO_2 plume, a conservative but reasonable assumption. A 100-year (multi-decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release by stopping injection, but that flow will continue.

Leakage into non-target aquifers due to lateral migration from the target zone- The potential for release at the Tuscola Site that could occur by leakage from the target sequestration zone into non-target aquifers due to lateral migration from the target zone (e.g., the regional hydraulic gradient and/or dip may provide high lateral flow rates into deep regional aquifers). For the Tuscola Site, the stratigraphic and structural setting suggests that there is only a small probability that lateral flow could escape the target zone because the formation dip and hydraulic gradient are so small. In addition, due to the great depth and small dip, a very large migration distance and time would be required before CO_2 would reach areas where receptors could be exposed, and CO_2 trapping mechanisms may even deplete the CO_2 prior to reaching exposure points. However, it was assumed that CO_2 may eventually find a conduit for surface exposure, but at greatly diminished rates due to the torturous and long flow path involved.

This leakage mechanism is analogous to the CO_2 leakage rate from a natural CO_2 reservoir where lateral flow allows CO_2 to leak into shallower zone. The most likely release rate was estimated using the analog database based upon known CO_2 emissions from analog sites with similar geologic conditions. Based upon a qualitative comparison of the Tuscola Site structural and stratigraphic characteristics with the analog sites, and a quantitative comparison of the analog site database, the analog site that is the closest match to the Tuscola Site is the Pine Lodge permeable zone area. Based upon this analogy, CO_2 emissions were estimated at 2.4 to 5 $\mu mol/m^2$-s. The frequency of a release at this rate is assumed to be 10^{-6} per 5,000 years. The area over which the CO_2 emissions are released covers the area of the CO_2 plume. A 100-year (multi-decade) timeframe was used as the emission duration, assuming that the operator will detect and successfully mitigate this release by stopping injection, but that flow will continue.

Upward migration through poorly constructed and abandoned deep wells - The potential for release at the Tuscola Site that could occur by leakage from the target sequestration zone through poorly constructed and abandoned deep wells was estimated based upon the number of deep wells at the Tuscola Site and the relative probability, duration, and magnitude of well releases experienced at industrial analog sites. The Tuscola Site leakage was then estimated using these generic well release probabilities, durations, and rates based upon the actual number of deep wells at the site. Since there are no deep wells except those constructed for the site, there is only one category of deep wells, those constructed for the site (two total). Deep wells constructed for this project were assigned a frequency of failure of 10^{-5} per year, based upon failure rates reported for production class industrial wells because these wells are constructed to the highest quality standards. Two types of releases are possible: 1) high rate leaks and 2) low rate leaks. It was assumed that high rate leaks would be readily detected and mitigated (therefore, releases were assumed to be short, i.e., 0.5 to 5 days) whereas low rate leaks were assumed to go undetected and remain unmitigated (therefore, releases were assumed last for 5,000 years). The well releases are constrained to leakage rates at approximately 220 tons (200 metric tons) per year for slow rate leaks and 12,125 tons (11,000 metric tons) per year for high rate leaks, based upon the data in Table 5-3 and Table 5-4. The low rate is based on the well leakage rate used for the two Latrobe Valley sites in Australia (see Table 5-4). A high leakage rate of 1,102 tons (1,000 metric tons) per year was used for the target reservoir at Tuscola, since the target reservoir has moderate permeability.

Upward migration through undocumented deep wells - The potential for release at the Tuscola Site that could occur by leakage from the target sequestration zone through undocumented deep wells was estimated using the same general methodology applied for documented wells. The Tuscola Site leakage was then estimated using these generic well release probabilities, durations, and rates based upon the actual number of undocumented deep wells at the site. Based upon the site characteristics and the depth of the target reservoir, three undocumented deep wells were assumed for the site based upon expert judgment. Because these deep wells were not drilled for this project, they were assigned a frequency of failure of 10^{-3} per year based upon failure rates reported for exploration class industrial wells. The well releases used in the modeling are the same as for the abandoned wells.

5.5.1.5 Release from Non-target Aquifers to the Atmosphere

Leakage of CO_2 into non-target aquifers, as discussed separately above for each site, can potentially occur if upward migration of CO_2 occurs from the target reservoir and sufficient migration occurs to reach the overlying non-target aquifers. Potential non-target aquifers are shown in Table 5-9 below for each site.

The table shows the major relevant features of non-target aquifers and locations of injection. If injection occurs at multiple depths into different formations, only the top most formation is given.

The non-target aquifers are relatively shallow (i.e., bottom depth of 400-500 feet [122-152 meters]) for the Illinois sites, and deeper for the Texas sites. For all sites, there are thick seals (ranging between 300 feet to 1,200 feet [91 to 366 meters]) between the injection sites and the non-target aquifers. This indicates that the likelihood of release into non-target aquifers for any of the sites is small. Based on the analog database, as described above, it was determined that the probability (note that since it was assumed that there was only one release into a non-target aquifer over the 5,000 year lifespan of the project, the frequency and probability of release are the same) of release into a non-target aquifer over 5,000 years is 10^{-5} (see Table 5-10).

Table 5-9. Characteristics of Locations of Major Potable Aquifers Relative to Injection Depths and Seal Thicknesses

Candidate Site	Approximate depth to top of potable non-target aquifer, feet (meters)	Approximate depth to bottom of potable non-target aquifer, feet (meters)	Depth to top of injection reservoir, feet (meters)	Thickness of seals above injection reservoir, feet (meters)	Percent of injection rate into upper most target reservoir
Jewett, TX	400 (122)	1,400 (427)	4,800 (1,463)	800 (244)	12
Odessa, TX	100 (30)	1,200 (366)	2,900 (884)	1,200 (366)	2
Mattoon, IL	20-70 (6-21)	400 (122)	4,800 (1,463)	500 (152)	6
Tuscola, IL	20-70 (6-21)	500 (152)	4,000 (1,219)	300 (91)	5

Table 5-10. Probabilities of Leakage into Non-target Aquifers and Surface Waters over 5,000 Years

Candidate Site	Leakage into non-target aquifers due to unknown structural or stratigraphic connections	Leakage into non-target aquifers due to lateral migration from the target zone	Leakage into non-target aquifer and subsequent surface discharge
Jewett, TX	1.0E-05	1.0E-06	1.0E-07
Odessa, TX	1.0E-05	1.0E-06	1.0E-07
Mattoon, IL	1.0E-05	1.0E-06	1.0E-06
Tuscola, IL	1.0E-05	1.0E-06	1.0E-06

After leaking into a non-target aquifer, subsequent migration and discharge (either to the atmosphere or surface water) are required for surface exposures to occur. The probability of subsequent leakage from the non-target aquifer into surface waters was assumed to be 0.01 to 0.1 times the probability of leakage into non-target aquifers for the Texas sites, and 0.1 times the probability of leakage into non-target aquifers for the Illinois sites. A slightly higher probability was used for the Illinois sites as the aquifers are closer to the surface in Illinois than Texas. In all cases, the probabilities are vanishingly small. With the additional dilution and time for geochemical trapping permitted by the tortuous route of this potential release scenario, it was assumed that any potential releases via this scenario would not be significant. Therefore, the release scenarios for lateral migration into non-target aquifers are not evaluated further in this report.

5.5.2 DISPERSION MODELING

Following the determination of release rates, SCREEN3 was used to perform dispersion modeling to estimate concentrations in air for releases from the ground surface (i.e., for migration upwards through the caprock formation, releases from wells, and releases from fractures) at various distances from the source. The modeling is described in detail in Section 4.4. The predicted concentrations in air are provided in the tables in Section 5.6 and are used to estimate the potential for adverse effects due to assumed exposures to the released COPCs.

5.6 Consequence Analysis

Human health and ecological effects were evaluated by examining the routes by which receptors may be exposed to captured gases released into the atmosphere, surface water, groundwater, or in surface soils. The key exposure route that was evaluated in this risk assessment is the inhalation of gaseous COPCs released to the atmosphere. Potentially, receptors may also be exposed to COPCs released to: 1) surface water via swimming and subsequent releases from surface water; 2) groundwater via potable water use and subsequent releases from groundwater that is used to irrigate crops; and 3) soils via direct contact. As the inhalation of COPCs from the atmosphere was assumed to result in the highest levels of exposure, these secondary exposure pathways were not evaluated. Exposures via these secondary exposure pathways are assumed to be relatively minor compared to exposures via the inhalation of airborne COPCs and, therefore, the omission of these exposure pathways is assumed to have resulted in only a relatively minor degree of underestimation in the risks.

Determining the potential for adverse effects from assumed exposures to gaseous COPCs released to the atmosphere, is a two step process, as follows:

1. Identify appropriate toxicity criteria for each COPC and each exposure duration (see Section 3); and
2. Estimate the potential for adverse effects to occur using the following equation:

$$\text{Risk Ratio} = \frac{\text{Predicted airborne concentration}}{\text{Toxicity criterion}}$$

Risk ratios less than 1 indicate that health effects are not likely to occur, while risk ratios greater than 1 indicate that health effects may occur. Higher risk ratios generally represent the potential for higher levels of health concern, although many of the toxicity criteria used here include safety factors to ensure the protection of sensitive individuals.

5.6.1 JEWETT, TX

For both the short-term and long-term release scenarios at the Jewett (TX) site, assumed exposures to CO_2 did not exceed either the acute or chronic toxicity criteria, respectively (Table 5-11 and Table 5-12). This indicates that assumed exposures to potentially released CO_2 is unlikely to pose a risk to residential receptors post-sequestration. Assumed exposures to H_2S did not exceed toxicity criteria for the short-term release scenarios. Further, H_2S was not assumed to be released through the caprock, and did not exceed toxicity criteria for long-term releases through both existing and induced faults. However, assumed long-term releases of H_2S from all three types of wells resulted in assumed exposures to concentrations that exceeded the toxicity criteria within (745 feet) 227 meters of the release (Table 5-12). The locations of existing deep wells near the Jewett injection sites are shown in Figure 2-8. The 50-year sequestration plume footprint of the injection sites are located in an area of agricultural, range, and forested lands with a low population density, indicating that relatively few people would be exposed to any potential releases from wells there. However, the no effect boundary for potential H_2S releases via wells comes to within 1 mile of the town of Sand Hill and 0.1 miles (0.16 kilometers) of a prison yard. No other sensitive receptors were located within the sequestration plume footprints. The results for a well release are illustrated in Figure 5-3.

Table 5-13 shows that the only likely ecological effects from assumed releases of CO_2 and H_2S are olfactory effects in moths and butterflies. These effects are not expected to significantly affect ecological communities. However, it should be noted that there are no ecological toxicity criteria available for H_2S.

Table 5-11. Acute Human Health Effects (Jewett, TX) Within 328 feet (100 meters) of Wells

Release Scenario	Gas	Effects			Exposures	Risk Ratio
		Level (ppmv)	Type		Concentration (ppmv)	
Upward leakage through the CO_2 injection well(s) (days)	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	1,490	0.07
		60,000	Tremors	USEPA 2000	1,490	0.02
		70,000	Unconsciousness	USEPA 2000	1,490	0.02
	H_2S	0.20	MRL - inh. Acute	No effects	0.15	0.8
		0.33	AEGL 1 (8 hours)	No transient effects	0.15	0.5
		17	AEGL 2(8 hours)	No serious or irreversible effects	0.15	0.009
		31	AEGL 3(8 hours)	No life-threatening effects	0.15	0.005
Upward leakage through deep oil and gas wells (days)	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	1,490	0.07
		60,000	Tremors	USEPA 2000	1,490	0.02
		70,000	Unconsciousness	USEPA 2000	1,490	0.02
	H_2S	0.20	MRL - inh. Acute	No effects	0.15	0.8
		0.33	AEGL 1 (8 hours)	No transient effects	0.15	0.5
		17	AEGL 2(8 hours)	No serious or irreversible effects	0.15	0.009
		31	AEGL 3(8 hours)	No life-threatening effects	0.15	0.005
Upward leakage through undocumented, abandoned, or poorly constructed wells (days)	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	1,490	0.07
		60,000	Tremors	USEPA 2000	1,490	0.02
		70,000	Unconsciousness	USEPA 2000	1,490	0.02
	H_2S	0.20	MRL - inh. Acute	No effects	0.15	0.8
		0.33	AEGL 1 (8 hours)	No transient effects	0.15	0.5
		17	AEGL 2 (8 hours)	No serious or irreversible effects	0.15	0.009
		31	AEGL 3 (8 hours)	No life-threatening effects	0.15	0.005

Table 5-12. Chronic Human Health Effects (Jewett, TX)

		Effects			Exposures		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Radius (from source area or well), feet (meter)**	**Concentration (ppmv)**	**Risk Ratio**
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.076	0.000008
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.076	0.000002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.076	0.000002
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.076	0.000001
	H_2S	0.0014	RfC	USEPA IRIS	Not released		Not released
Release through existing faults due to effects of increased pressure	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	4	0.0004
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	4	0.0001
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	4	0.00008
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	4	0.00006
	H_2S	0.0014	RfC	USEPA IRIS	< 3.3 (1)	0.0004	0.3
		0.02	MRL-Int	ATSDR	< 3.3 (1)	0.0004	0.02

Table 5-12 (continued). Chronic Human Health Effects (Jewett, TX)

		Effects			Exposures		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Radius (from source area or well, feet (meter)**	**Concentration (ppmv)**	**Risk Ratio**
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	2.2	0.0002
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	2.2	0.00006
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	2.2	0.00004
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	2.2	0.00003
	H_2S	0.0014	RfC	USEPA IRIS	< 3.3 (1)	0.00022	0.2
Upward leakage through the CO_2 injection well(s)	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.006
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.001
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.0009
	H_2S	0.0014	RfC	USEPA IRIS	745 (227)	0.006	4

Table 5-12 (continued). Chronic Human Health Effects (Jewett, TX)

		Effects			Exposures		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Radius (from source area or well feet (meter))**	**Concentration (ppmv)**	**Risk Ratio**
Upward leakage through deep oil and gas wells	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.006
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.001
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.0009
	H_2S	0.0014	RfC	USEPA IRIS	745 (227)	0.006	4
Upward leakage through undocumented, abandoned, or poorly constructed wells	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.006
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.001
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.0009
	H_2S	0.0014	RfC	USEPA IRIS	745 (227)	0.006	4.3

Table 5-13. Chronic Effects on Biota (Jewett, TX)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
		Effects			Effects			Effects					
Release Scenario	Gas	Level (ppmv)	Type	Exposure Concentration (ppmv)	Level (ppmv)	Type	Exposure Concentration (ppmv)	Level (ppmv)	Type	Exposure Concentration (ppmv)	Animals	Plants	Insect/ Behavioral Effects
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	1,000	respiratory stimulation	0.076	380	increased growth, biomass	0.076	0.5	moth, butterfly olfactory sensation	0.076	0.00008	0.0002	0.2
		10,000	insect, spiracle aperture regulation	0.076	700	increases/decreases in plant respiration	0.076	10	mosquitoes, ticks, fire bugs olfactory activation	0.076	0.000008	0.0001	0.008
		50,000	respiratory poisoning	0.076	10,000	fungi, abnormal growth	0.076	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	0.076	0.000002	0.000008	0.00008
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	0.076	-	-	0.00002
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-13 (continued). Chronic Effects on Biota (Jewett, TX)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
Release Scenario	**Gas**	**Effects**		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**			
		Level (ppmv)	**Type**		**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Animals**	**Plants**	**Insect/ Behavioral Effects**
Release through existing faults due to effects of increased pressure	CO_2	1,000	respiratory stimulation	4	380	increased growth, biomass	4	0.5	moth, butterfly olfactory sensation	4 (6,562 feet [2,000 meters])	0.004	0.01	**8**
		10,000	insect, spiracle aperture regulation	4	700	increases/decreases in plant respiration	4	10	mosquitoes, ticks, fire bugs olfactory activation	4	0.0004	0.006	0.4
		50,000	respiratory poisoning	4	10,000	fungi, abnormal growth	4	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	4	0.00008	0.0004	0.004
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	4	**-**	**-**	0.0008
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-13 (continued). Chronic Effects on Biota (Jewett, TX)

		Animals			**Plants**			**Insect/Behavioral Effects**			**Risk Ratios**		
		Effects		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**			
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Animals**	**Plants**	**Insect/ Behavioral Effects**
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	1,000	respiratory stimulation	2.2	380	increased growth, biomass	2.2	0.5	moth, butterfly olfactory sensation	2.2 (3,609 feet [1,100 meters])	0.002	0.006	**4**
		10,000	insect, spiracle aperture regulation	2.2	700	increases/decreases in plant respiration	2.2	10	mosquitoes, ticks, fire bugs olfactory activation	2.2	0.0002	0.003	0.2
		50,000	respiratory poisoning	2.2	10,000	fungi, abnormal growth	2.2	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	2.2	0.00004	0.0002	0.002
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	2.2	**-**	**-**	0.0004
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-13 (continued). Chronic Effects on Biota (Jewett, TX)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
		Effects			Effects			Effects					
Release Scenario	**Gas**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Animals**	**Plants**	**Insect/ Behavioral Effects**
Upward leakage through the CO_2 injection well(s)	CO_2	1,000	respiratory stimulation	60	380	increased growth, biomass	60	0.5	moth, butterfly olfactory sensation	60 (5,751 feet [1,753 meters])	0.06	0.2	**120**
		10,000	insect, spiracle aperture regulation	60	700	increases/decreases in plant respiration	60	10	mosquitoes, ticks, fire bugs olfactory activation	60 (909 feet [277 meters])	0.006	0.09	**6**
		50,000	respiratory poisoning	60	10,000	fungi, abnormal growth	60	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	60	0.001	0.006	0.06
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	60	-	-	0.01
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-13 (continued). Chronic Effects on Biota (Jewett, TX)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
Release Scenario		Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)			
	Gas	Level (ppmv)	Type		Level (ppmv)	Type		Level (ppmv)	Type		Animals	Plants	Insect/ Behavioral Effects
Upward leakage through deep oil and gas wells	CO_2	1,000	respiratory stimulation	60	380	increased growth, biomass	60	0.5	moth, butterfly olfactory sensation	60 (5,751 feet [1,753 meters])	0.06	0.2	**120**
		10,000	insect, spiracle aperture regulation	60	700	increases/decreases in plant respiration	60	10	mosquitoes, ticks, fire bugs olfactory activation	60 (909 feet [277 meters])	0.006	0.09	**6**
		50,000	respiratory poisoning	60	10,000	fungi, abnormal growth	60	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	60	0.001	0.006	0.06
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	60	-	-	0.01
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-13 (continued). Chronic Effects on Biota (Jewett, TX)

		Animals			**Plants**			**Insect/Behavioral Effects**					
		Effects		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**	**Risk Ratios**		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Animals**	**Plants**	**Insect/ Behavioral Effects**
Upward leakage through undocumented, abandoned, or poorly constructed wells	CO_2	1,000	respiratory stimulation	60	380	increased growth, biomass	60	0.5	moth, butterfly olfactory sensation	60 (5,751 feet [1,753 meters])	0.06	0.2	**120**
		10,000	insect, spiracle aperture regulation	60	700	increases/decreases in plant respiration	60	10	mosquitoes, ticks, fire bugs olfactory activation	60 (909 feet [277 meters])	0.006	0.09	**6**
		50,000	respiratory poisoning	60	10,000	fungi, abnormal growth	60	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	60	0.001	0.006	0.06
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	60	-	-	0.01
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

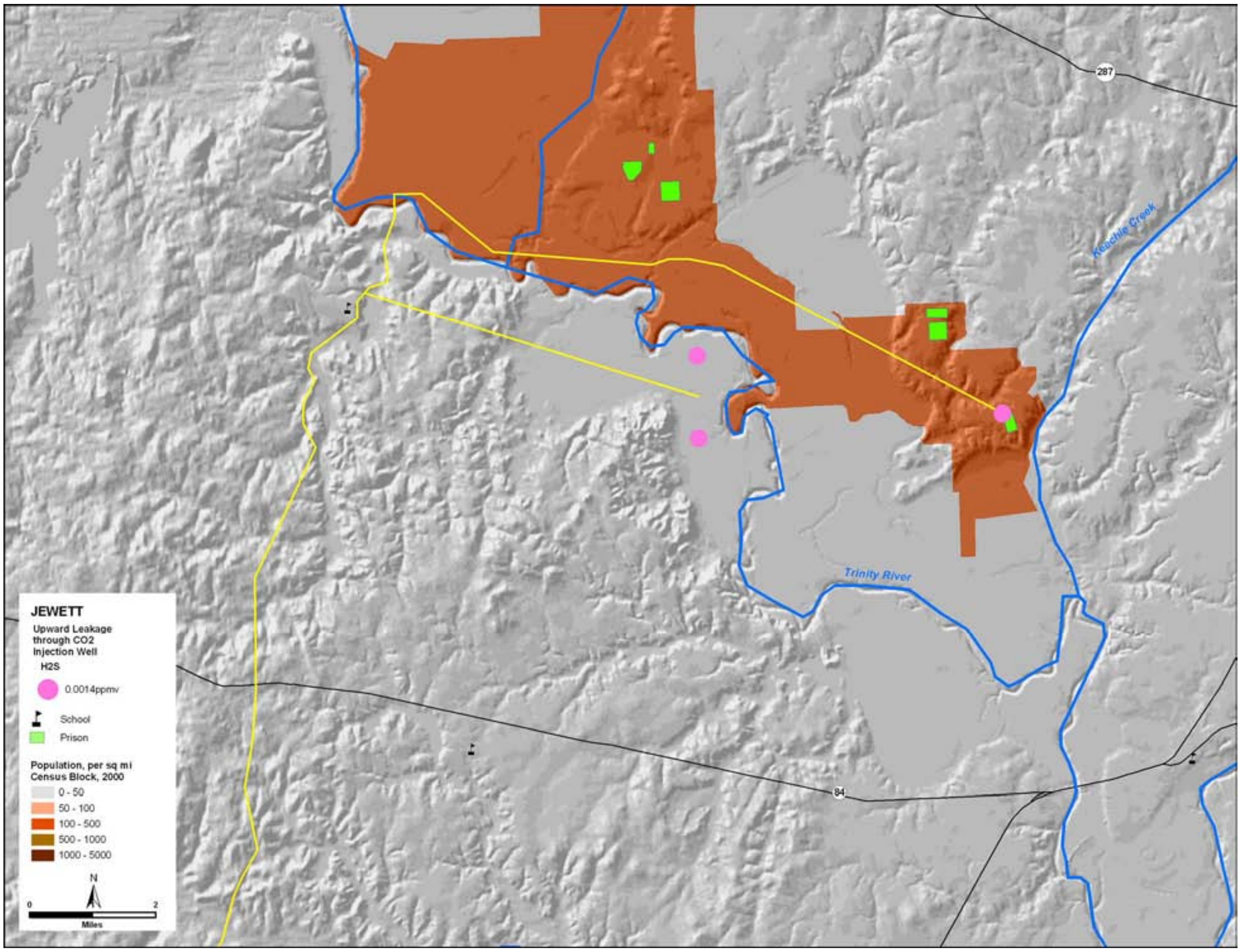

Figure 5-3. Area Within Which H_2S Released from CO_2 Injection Wells Exceeds Chronic Toxicity Criteria (i.e., 0.0014 ppmv H_2S) at the Jewett (TX) Site

5.6.2 ODESSA, TX

For both the short-term and long-term release scenarios at the Odessa (TX) site, assumed exposures to CO_2 did not exceed either the acute or chronic toxicity criteria, respectively (Table 5-14 and Table 5-15). This indicates that assumed exposures to potentially released CO_2 is unlikely to pose a risk to residential receptors post-sequestration. Assumed exposures to H_2S did not exceed toxicity criteria for the short-term release scenarios. Further, H_2S was not assumed to be released through the caprock and did not exceed toxicity criteria for long-term releases through both existing and induced faults. However, assumed long-term releases of H_2S from all three types of wells resulted in assumed exposures to concentrations that exceeded the toxicity criteria within 909 feet (227 meters) of the release (Table 5-14). The locations of existing deep wells near the Odessa injection site are shown in Figure 2-8. The 50 year sequestration plume footprint is located in an area that is largely open and has a relatively low population density, indicating that relatively few people would be exposed to any potential releases from wells there. Further, there are no sensitive receptors within the sequestration plume footprint and the nearest town is 8 miles (13 kilometers) from the injection site. The results for a well release are illustrated in Figure 5-4.

Table 5-16 shows that the only likely ecological effects from assumed releases of CO_2 and H_2S are olfactory effects in several insects. These effects are not expected to significantly affect ecological communities. However, it should be noted that no ecological toxicity criteria were available for H_2S.

Table 5-14. Acute Human Health Effects (Odessa, TX) within 328 feet (100 meters) of wells

Release Scenario	**Gas**	**Effects**			**Exposures**	**Risk Ratio**
		Level (ppmv)	**Type**		**Concentration (ppmv)**	
Upward leakage through the CO_2 injection well(s) (days)	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	149	0.007
		60,000	Tremors	USEPA 2000	149	0.002
		70,000	Unconsciousness	USEPA 2000	149	0.002
	H_2S	0.20	MRL - inh. Acute	No effects	0.015	0.08
		0.33	AEGL 1 (8 hours)	No transient effects	0.015	0.05
		17	AEGL 2 (8 hours)	No serious or irreversible effects	0.015	0.0009
		31	AEGL 3 (8 hours)	No life-threatening effects	0.015	0.0005
Upward leakage through deep oil and gas wells (days)	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	149	0.01
		60,000	Tremors	USEPA 2000	149	0.002
		70,000	Unconsciousness	USEPA 2000	149	0.002
	H_2S	0.20	MRL - inh. Acute	No effects	0.015	0.08
		0.33	AEGL 1 (8 hours)	No transient effects	0.015	0.05
		17	AEGL 2 (8 hours)	No serious or irreversible effects	0.015	0.0009
		31	AEGL 3 (8 hours)	No life-threatening effects	0.015	0.0005
Upward leakage through undocumented, abandoned, or poorly constructed wells (days)	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	149	0.007
		60,000	Tremors	USEPA 2000	149	0.002
		70,000	Unconsciousness	USEPA 2000	149	0.002
	H_2S	0.20	MRL - inh. Acute	No effects	0.015	0.08
		0.33	AEGL 1 (8 hours)	No transient effects	0.015	0.05
		17	AEGL 2 (8 hours)	No serious or irreversible effects	0.015	0.0009
		31	AEGL 3 (8 hours)	No life-threatening effects	0.015	0.0005

Table 5-15. Chronic Human Health Effects (Odessa, TX)

		Effects			Exposures		
Release Scenario	Gas	Level (ppmv)	Type		Radius (from source area or well), feet (meter)	Concentration (ppmv)	Risk Ratio
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.6	0.0002
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.6	0.00004
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.6	0.00003
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.6	0.00002
	H_2S	0.0014	RfC	USEPA IRIS	Not released		Not released
Release through existing faults due to effects of increased pressure	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	4.1	0.0004
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	4.1	0.0001
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	4.1	0.00008
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	4.1	0.00006
	H_2S	0.0014	RfC	USEPA IRIS	< 3.3 (1)	0.0004	0.3
		0.02	MRL-Int	ATSDR	< 3.3 (1)	0.0004	0.02

Table 5-15 (continued). Chronic Human Health Effects (Odessa, TX)

Release Scenario		Effects			Exposures		Risk Ratio
	Gas	Level (ppmv)	Type		Radius (from source area or well feet (meter))	Concentration (ppmv)	
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	2.2	0.0002
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	2.2	0.00006
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	2.2	0.00004
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	2.2	0.00003
	H_2S	0.0014	RfC	USEPA IRIS	< 3.3 (1)	0.00022	0.2
Upward leakage through the CO_2 injection well(s)	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.006
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.001
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.0009
	H_2S	0.0014	RfC	USEPA IRIS	745 (227)	0.006	4.3

Table 5-15 (continued). Chronic Human Health Effects (Odessa, TX)

		Effects			**Exposures**		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Radius (from source area or well feet (meter)**	**Concentration (ppmv)**	**Risk Ratio**
Upward leakage through deep oil and gas wells	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.006
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.001
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.0009
	H_2S	0.0014	RfC	USEPA IRIS	745 (227)	0.006	4.3
Upward leakage through undocumented, abandoned, or poorly constructed wells	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.006
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.001
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.0009
	H_2S	0.0014	RfC	USEPA IRIS	328 (100)	0.006	**4.3**

Table 5-16. Chronic Effects on Biota (Odessa, TX)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
		Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)			
Release Scenario	Gas	Level (ppmv)	Type		Level (ppmv)	Type		Level (ppmv)	Type		Animals	Plants	Insect/ Behavioral Effects
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	1,000	respiratory stimulation	1.6	380	increased growth, biomass	1.6	0.5	moth, butterfly olfactory sensation	1.6	0.002	0.004	**3**
		10,000	insect, spiracle aperture regulation	1.6	700	increases/decreases in plant respiration	1.6	10	mosquitoes, ticks, fire bugs olfactory activation	1.6	0.0002	0.002	0.2
		50,000	respiratory poisoning	1.6	10,000	fungi, abnormal growth	1.6	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	1.6	0.00003	0.0002	0.002
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	1.6	-	-	0.0003
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-16 (continued). Chronic Effects on Biota (Odessa, TX)

		Animals			Plants			Insect/Behavioral Effects					
		Effects			Effects			Effects			Risk Ratio		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Animals**	**Plants**	**Insect/ Behavioral Effects**
Release through existing faults due to effects of increased pressure	CO_2	1,000	respiratory stimulation	4.1	380	increased growth, biomass	4.1	0.5	moth, butterfly olfactory sensation	4.1	0.004	0.01	**8**
		10,000	insect, spiracle aperture regulation	4.1	700	increases/decreases in plant respiration	4.1	10	mosquitoes, ticks, fire bugs olfactory activation	4.1	0.0004	0.006	0.4
		50,000	respiratory poisoning	4.1	10,000	fungi, abnormal growth	4.1	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	4.1	0.00008	0.0004	0.004
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	4.1	-	-	0.0008
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-16 (continued). Chronic Effects on Biota (Odessa, TX)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
Release Scenario		Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)			
	Gas	Level (ppmv)	Type		Level (ppmv)	Type		Level (ppmv)	Type		Animals	Plants	Insect/ Behavioral Effects
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	1,000	respiratory stimulation	2.2	380	increased growth, biomass	2.2	0.5	moth, butterfly olfactory sensation	2.2	0.002	0.006	**4**
		10,000	insect, spiracle aperture regulation	2.2	700	increases/decreases in plant respiration	2.2	10	mosquitoes, ticks, fire bugs olfactory activation	2.2	0.0002	0.003	0.2
		50,000	respiratory poisoning	2.2	10,000	fungi, abnormal growth	2.2	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	2.2	0.00004	0.0002	0.002
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	2.2	-	-	0.0004
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-16 (continued). Chronic Effects on Biota (Odessa, TX)

		Animals			Plants			Insect/Behavioral Effects					
		Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)	Risk Ratios		
Release Scenario	Gas	Level (ppmv)	Type		Level (ppmv)	Type		Level (ppmv)	Type		Animals	Plants	Insect/ Behavioral Effects
Upward leakage through the CO_2 injection well(s)	CO_2	1,000	respiratory stimulation	60	380	increased growth, biomass	60	0.5	moth, butterfly olfactory sensation	60 (5,751 feet [1,753 meters])	0.06	0.2	**120**
		10,000	insect, spiracle aperture regulation	60	700	increases/decreases in plant respiration	60	10	mosquitoes, ticks, fire bugs olfactory activation	60 (909 feet [277 meters])	0.006	0.09	**6**
		50,000	respiratory poisoning	60	10,000	fungi, abnormal growth	60	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	60	0.001	0.006	0.06
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	60	-	-	0.01
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-16 (continued). Chronic Effects on Biota (Odessa, TX)

		Animals			Plants			Insect/Behavioral Effects					
		Effects			Effects			Effects			Risk Ratios		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Animals**	**Plants**	**Insect/ Behavioral Effects**
Upward leakage through deep oil and gas wells	CO_2	1,000	respiratory stimulation	60	380	increased growth, biomass	60	0.5	moth, butterfly olfactory sensation	60 (5,751 feet [1,753 meters])	0.06	0.2	**120**
		10,000	insect, spiracle aperture regulation	60	700	increases/decreases in plant respiration	60	10	mosquitoes, ticks, fire bugs olfactory activation	60 (909 feet [277 meters])	0.006	0.09	**6**
		50,000	respiratory poisoning	60	10,000	fungi, abnormal growth	60	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	60	0.001	0.006	0.06
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	60	-	-	0.01
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-16 (continued). Chronic Effects on Biota (Odessa, TX)

		Animals			**Plants**			**Insect/Behavioral Effects**			**Risk Ratios**		
		Effects		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**			
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Animals**	**Plants**	**Insect/ Behavioral Effects**
Upward leakage through undocumented, abandoned, or poorly constructed wells	CO_2	1,000	respiratory stimulation	60	380	increased growth, biomass	60	0.5	moth, butterfly olfactory sensation	60 (5,751 feet [1,753 meters])	0.06	0.2	**120**
		10,000	insect, spiracle aperture regulation	60	700	increases/decreases in plant respiration	60	10	mosquitoes, ticks, fire bugs olfactory activation	60 (909 feet [277 meters])	0.006	0.09	**6**
		50,000	respiratory poisoning	60	10,000	fungi, abnormal growth	60	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	60	0.001	0.006	0.06
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	60	-	-	0.01
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

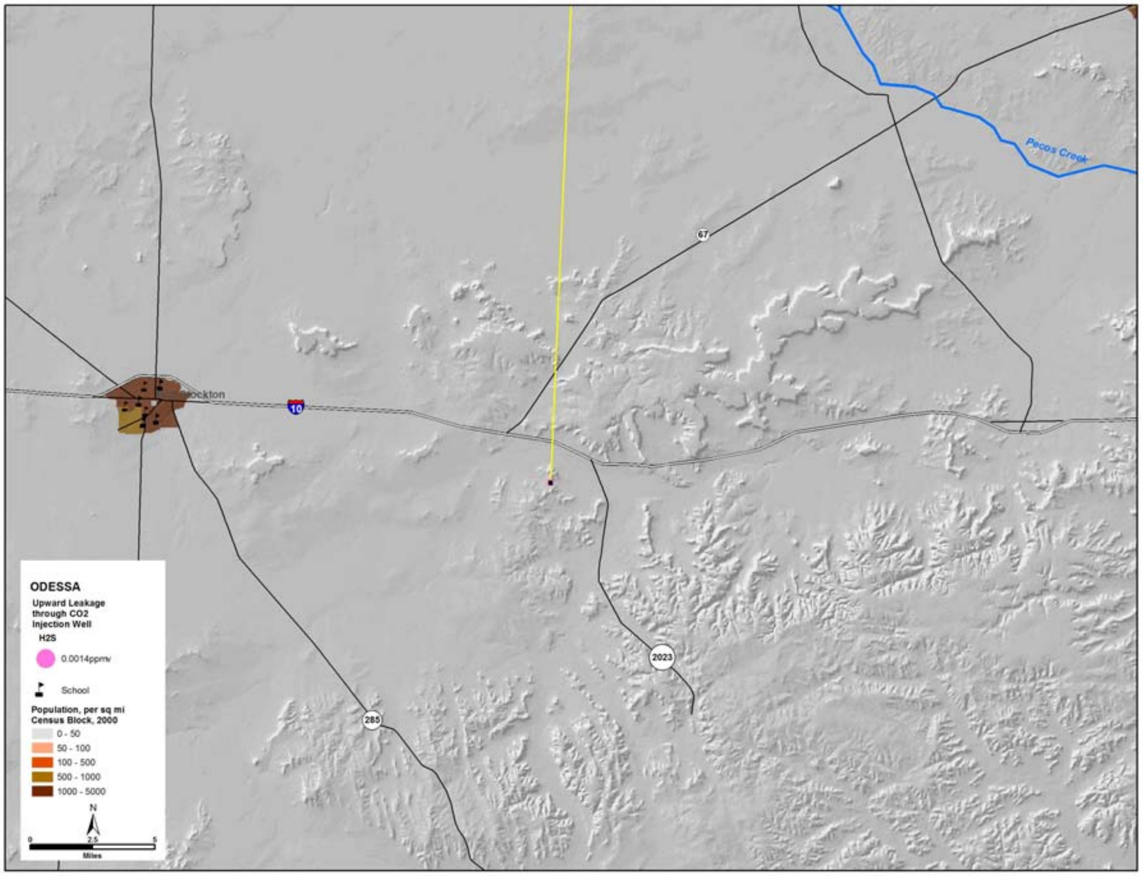

Figure 5-4. Area Within Which H_2S Released from CO_2 Injection Wells Exceeds Chronic Toxicity Criteria (i.e., 0.0014 ppmv H_2S) at the Odessa (TX) Site.
(Area shown is based on a release from a single well within the injection area. See Figure 2-11 for all wells at the injection site.)

5.6.3 MATTOON, IL

For the Mattoon (IL) site, there are no oil and gas wells within the 50-year sequestration footprint. Therefore, emissions from oil and gas wells was assumed to be an incomplete release scenario at this site and exposures were not estimated. For the release scenarios that were quantified, both the short-term and long-term CO_2 release scenarios did not exceed either the acute or chronic toxicity criteria, respectively (Table 5-17 and Table 5-18). This indicates that assumed exposures to potentially released CO_2 is unlikely to pose a risk to residential receptors post-sequestration. Assumed exposures to H_2S did not exceed toxicity criteria for the short-term release scenarios. Further, H_2S was not assumed to be released through the caprock and did not exceed toxicity criteria for long-term releases through both existing and induced faults. However, assumed long-term releases of H_2S from both well types resulted in assumed exposures to concentrations that exceeded the toxicity criteria within 745 feet (227 meters) of the release (Table 5-17). The 50-year sequestration plume footprint is located in an area that is largely farmland and has a relatively low population density, indicating that relatively few people would be exposed to any potential releases from wells there. However, the no effect boundary for potential H_2S releases via wells comes to within 0.25 miles (0.4 kilometers) of the town of Mattoon and 1.4 miles of the nearest school. The results for a well release are illustrated in Figure 5-5.

Table 5-19 shows that the only likely ecological effects from assumed releases of CO_2 and H_2S are olfactory effects in several insects. These effects are not expected to significantly affect ecological communities. However, it should be noted that there are no ecological toxicity criteria were available for H_2S.

Table 5-17. Acute Human Health Effects (Mattoon, IL) Within 328 feet (100 meters) of Wells

Release Scenario	Gas	Effects			Exposures	Risk Ratio
		Level (ppmv)	Type		Concentration (ppmv)	
Upward leakage through the CO2 injection well(s) (days)	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	298	0.01
		60,000	Tremors	USEPA 2000	298	0.005
		70,000	Unconsciousness	USEPA 2000	298	0.004
	H_2S	0.20	MRL - inh. Acute	No effects	0.029	0.1
		0.33	AEGL 1 (8 hours)	No transient effects	0.029	0.09
		17	AEGL 2 (8 hours)	No serious or irreversible effects	0.029	0.002
		31	AEGL 3 (8 hours)	No life-threatening effects	0.029	0.0009
Upward leakage through deep oil and gas wells (days) [No wells]	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	NA	NA
		60,000	Tremors	USEPA 2000	NA	NA
		70,000	Unconsciousness	USEPA 2000	NA	NA
	H_2S	0.20	MRL - inh. Acute	No effects	NA	NA
		0.33	AEGL 1 (8 hours)	No transient effects	NA	NA
		17	AEGL 2 (8 hours)	No serious or irreversible effects	NA	NA
		31	AEGL 3 (8 hours)	No life-threatening effects	NA	NA
Upward leakage through undocumented, abandoned, or poorly constructed wells (days)	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	298	0.01
		60,000	Tremors	USEPA 2000	298	0.005
		70,000	Unconsciousness	USEPA 2000	298	0.004
	H_2S	0.20	MRL - inh. Acute	No effects	0.029	0.1
		0.33	AEGL 1 (8 hours)	No transient effects	0.029	0.09
		17	AEGL 2 (8 hours)	No serious or irreversible effects	0.029	0.002
		31	AEGL 3 (8 hours)	No life-threatening effects	0.029	0.0009

Table 5-18. Chronic Human Health Effects (Mattoon, IL)

		Effects			Exposures		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Radius (from source area or well), feet (meters)**	**Concentration (ppmv)**	**Risk Ratio**
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.077	0.000008
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.077	0.000002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.077	0.000002
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.077	0.000001
	H_2S	0.0014	RfC	USEPA IRIS	Not released		Not released
Release through existing faults due to effects of increased pressure	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	3.7	0.0004
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	3.7	0.00009
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	3.7	0.00007
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	3.7	0.00005
	H_2S	0.0014	RfC	USEPA IRIS	< 3.3 (1)	0.0004	0.3
		0.02	MRL-Int	ATSDR	< 3.3 (1)	0.0004	0.02
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.9	0.0002
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.9	0.00005
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.9	0.00004
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.9	0.00003
	H_2S	0.0014	RfC	USEPA IRIS	< 3.3 (1)	0.00019	0.1

Table 5-18 (continued). Chronic Human Health Effects (Mattoon, IL)

		Effects			Exposures		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Radius (from source area or well feet (meter))**	**Concentration (ppmv)**	**Risk Ratio**
Upward leakage through the CO2 injection well(s)	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.006
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.001
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.0009
	H_2S	0.0014	RfC	USEPA IRIS	745 (227)	0.006	4.3
Upward leakage through deep oil and gas wells [No wells at this site]	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	NA	NA	NA
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	NA	NA	NA
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	NA	NA	NA
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	NA	NA	NA
	H_2S	0.0014	RfC	USEPA IRIS	NA	NA	NA
Upward leakage through undocumented, abandoned, or poorly constructed wells	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.006
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.001
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.0009
	H_2S	0.0014	RfC	USEPA IRIS	745 (227)	0.006	4.3

Table 5-19. Chronic Effects on Biota (Mattoon, IL)

		Animals			Plants			Insect/Behavioral Effects					
		Effects			Effects			Effects			Risk Ratios		
Release Scenario	Gas	Level (ppmv)	Type	Exposure Concentration (ppmv)	Level (ppmv)	Type	Exposure Concentration (ppmv)	Level (ppmv)	Type	Exposure Concentration (ppmv)	Animals	Plants	Insect/ Behavioral Effects
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	1,000	respiratory stimulation	0.077	380	increased growth, biomass	0.077	0.5	moth, butterfly olfactory sensation	0.077	0.00008	0.0002	0.2
		10,000	insect, spiracle aperture regulation	0.077	700	increases/decreases in plant respiration	0.077	10	mosquitoes, ticks, fire bugs olfactory activation	0.077	0.000008	0.0001	0.008
		50,000	respiratory poisoning	0.077	10,000	fungi, abnormal growth	0.077	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	0.077	0.000002	0.000008	0.00008
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	0.077	-	-	0.00002
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-19 (continued). Chronic Effects on Biota (Mattoon, IL)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
		Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)			
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Animals**	**Plants**	**Insect/ Behavioral Effects**
Release through existing faults due to effects of increased pressure	CO_2	1,000	respiratory stimulation	3.7	380	increased growth, biomass	3.7	0.5	moth, butterfly olfactory sensation	3.7	0.004	0.01	**7**
		10,000	insect, spiracle aperture regulation	3.7	700	increases/decreases in plant respiration	3.7	10	mosquitoes, ticks, fire bugs olfactory activation	3.7	0.0004	0.005	0.4
		50,000	respiratory poisoning	3.7	10,000	fungi, abnormal growth	3.7	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	3.7	0.00007	0.0004	0.004
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	3.7	-	-	0.0007
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-19 (continued). Chronic Effects on Biota (Mattoon, IL)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
		Effects			Effects			Effects					
Release Scenario	**Gas**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Animals**	**Plants**	**Insect/ Behavioral Effects**
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	1,000	respiratory stimulation	1.9	380	increased growth, biomass	1.9	0.5	moth, butterfly olfactory sensation	1.9	0.002	0.005	**4**
		10,000	insect, spiracle aperture regulation	1.9	700	increases/decreases in plant respiration	1.9	10	mosquitoes, ticks, fire bugs olfactory activation	1.9	0.0002	0.003	0.2
		50,000	respiratory poisoning	1.9	10,000	fungi, abnormal growth	1.9	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	1.9	0.00004	0.0002	0.002
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	1.9	-	-	0.0004
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-19 (continued). Chronic Effects on Biota (Mattoon, IL)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
Release Scenario	Gas	Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)			
		Level (ppmv)	Type		Level (ppmv)	Type		Level (ppmv)	Type		Animals	Plants	Insect/ Behavioral Effects
Upward leakage through the CO_2 injection well(s)	CO_2	1,000	respiratory stimulation	60	380	increased growth, biomass	60	0.5	moth, butterfly olfactory sensation	60 (5,751 feet [1,753 meters])	0.06	0.2	**120**
		10,000	insect, spiracle aperture regulation	60	700	increases/decreases in plant respiration	60	10	mosquitoes, ticks, fire bugs olfactory activation	60 (909 feet [277 meters])	0.006	0.09	**6**
		50,000	respiratory poisoning	60	10,000	fungi, abnormal growth	60	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	60	0.001	0.006	0.06
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	60	-	-	0.01
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-19 (continued). Chronic Effects on Biota (Mattoon, IL)

		Animals			**Plants**			**Insect/Behavioral Effects**			**Risk Ratios**		
		Effects		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**			
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Animals**	**Plants**	**Insect/ Behavioral Effects**
Upward leakage through deep oil and gas wells [No wells at this site]	CO_2	1,000	respiratory stimulation	NA	380	increased growth, biomass	NA	0.5	moth, butterfly olfactory sensation	NA	NA	NA	NA
		10,000	insect, spiracle aperture regulation	NA	700	increases/decreases in plant respiration	NA	10	mosquitoes, ticks, fire bugs olfactory activation	NA	NA	NA	NA
		50,000	respiratory poisoning	NA	10,000	fungi, abnormal growth	NA	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	NA	NA	NA	NA
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	NA	NA	NA	NA
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-19 (continued). Chronic Effects on Biota (Mattoon, IL)

		Animals			**Plants**			**Insect/Behavioral Effects**			**Risk Ratios**		
		Effects			**Effects**			**Effects**					
Release Scenario	**Gas**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Animals**	**Plants**	**Insect/ Behavioral Effects**
Upward leakage through undocumented, abandoned, or poorly constructed wells	CO_2	1,000	respiratory stimulation	60	380	increased growth, biomass	60	0.5	moth, butterfly olfactory sensation	60 (5,751 feet [1,753 meters])	0.06	0.2	**120**
		10,000	insect, spiracle aperture regulation	60	700	increases/decreases in plant respiration	60	10	mosquitoes, ticks, fire bugs olfactory activation	60 (909 feet [277 meters])	0.006	0.09	**6**
		50,000	respiratory poisoning	60	10,000	fungi, abnormal growth	60	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	60	0.001	0.006	0.06
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	60	-	-	0.01
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

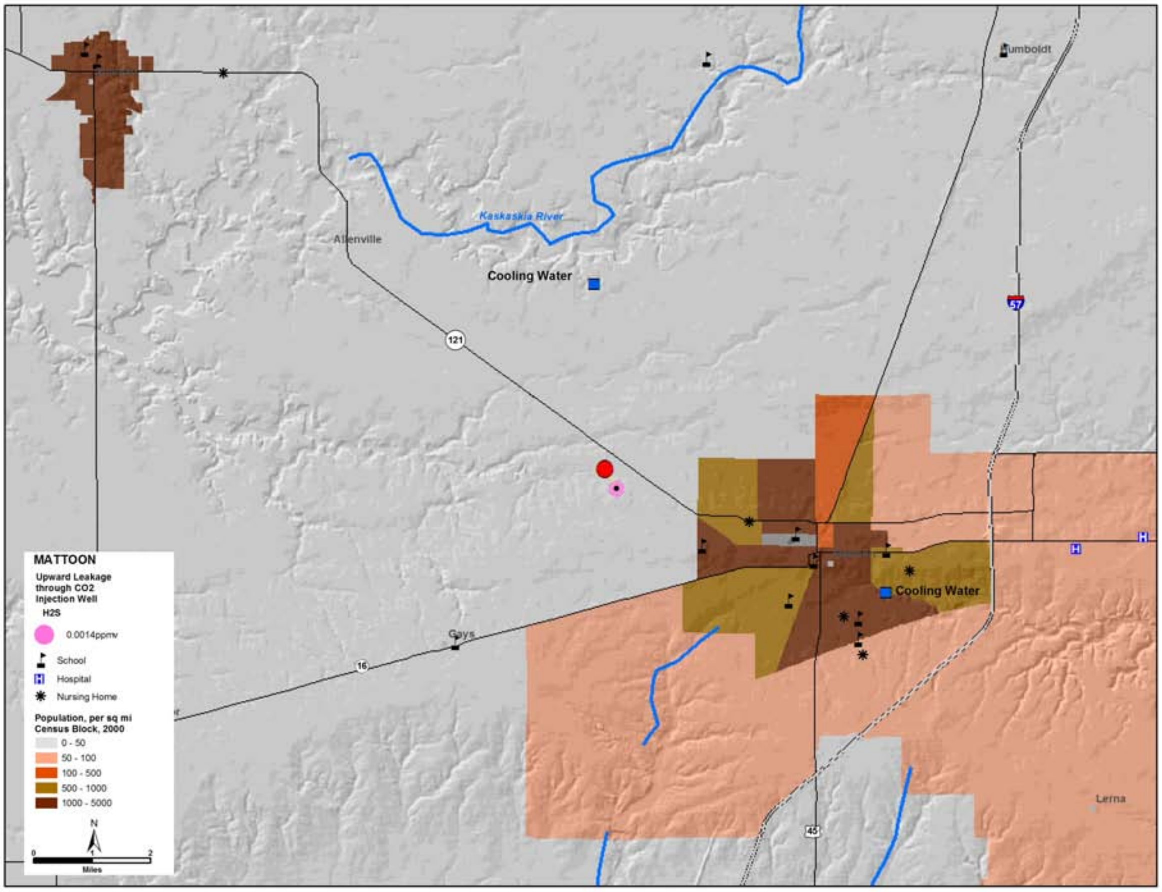

Figure 5-5. Area Within Which H_2S Released from CO_2 Injection Wells Exceeds Chronic Toxicity Criteria (i.e., 0.0014 ppmv H_2S) at the Mattoon (IL) Site

5.6.4 TUSCOLA, IL

For the Tuscola (IL) site, there are no oil and gas wells within the 50-year sequestration footprint. Therefore, emissions from oil and gas wells were assumed to be an incomplete release scenario at this site and exposures were not estimated. For the release scenarios that were quantified, both the short-term and long-term CO_2 release scenarios did not exceed either the acute or chronic toxicity criteria, respectively (Table 5-20 and Table 5-21). This indicates that assumed exposures to potentially released CO_2 is unlikely to pose a risk to residential receptors post-sequestration. Assumed exposures to H_2S did not exceed toxicity criteria for the short-term release scenarios. Further, H_2S was not assumed to be released through the caprock and did not exceed toxicity criteria for long-term releases through both existing and induced faults. However, assumed long-term releases of H_2S from both well types resulted in assumed exposures to concentrations that exceeded the toxicity criteria within 745 feet (227 meters) of the release (Table 5-20). The 50 year sequestration plume footprint is located near a town in an area that is largely agricultural. The results for a well release are illustrated in Figure 5-6.

Table 5-22 shows that the only likely ecological effects from assumed releases of CO_2 and H_2S are olfactory effects in several insects. These effects are not expected to significantly affect ecological communities. However, it should be noted that there are no ecological toxicity criteria were available for H_2S.

Table 5-20. Acute Human Health Effects (Tuscola, IL) Within 328 Feet (100 Meters) of Wells

Release Scenario	Gas	Effects			Exposures	Risk Ratio
		Level (ppmv)	Type		Concentration (ppmv)	
Upward leakage through the CO2 injection well(s) (days)	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	298	0.01
		60,000	Tremors	USEPA 2000	298	0.005
		70,000	Unconsciousness	USEPA 2000	298	0.004
	H_2S	0.20	MRL - inh. Acute	No effects	0.03	0.2
		0.33	AEGL 1 (8 hours)	No transient effects	0.03	0.09
		17	AEGL 2 (8 hours)	No serious or irreversible effects	0.03	0.002
		31	AEGL 3 (8 hours)	No life-threatening effects	0.03	0.001
Upward leakage through deep oil and gas wells (days) [No Wells]	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	NA	NA
		60,000	Tremors	USEPA 2000	NA	NA
		70,000	Unconsciousness	USEPA 2000	NA	NA
	H_2S	0.20	MRL - inh. Acute	No effects	NA	NA
		0.33	AEGL 1 (8 hours)	No transient effects	NA	NA
		17	AEGL 2 (8 hours)	No serious or irreversible effects	NA	NA
		31	AEGL 3 (8 hours)	No life-threatening effects	NA	NA
Upward leakage through undocumented, abandoned, or poorly constructed wells (days)	CO_2	20,000	Headache, etc.	Possible respiratory stimulant	298	0.01
		60,000	Tremors	USEPA 2000	298	0.005
		70,000	Unconsciousness	USEPA 2000	298	0.004
	H_2S	0.20	MRL - inh. Acute	No effects	0.03	0.2
		0.33	AEGL 1 (8 hours)	No transient effects	0.03	0.09
		17	AEGL 2 (8 hours)	No serious or irreversible effects	0.03	0.002
		31	AEGL 3 (8 hours)	No life-threatening effects	0.03	0.001

Table 5-21. Chronic Human Health Effects (Tuscola, IL)

		Effects			Exposures		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Radius (from source area or well), feet (meters)**	**Concentration (ppmv)**	**Risk Ratio**
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.076	0.000008
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.076	0.000002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	0.076	0.000002
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	-	0.076	0.000001
	H_2S	0.0014	RfC	USEPA IRIS	Not released		Not released
Release through existing faults due to effects of increased pressure	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	3.7	0.0004
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	3.7	0.00009
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	3.7	0.00007
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	3.7	0.00005
	H_2S	0.0014	RfC	USEPA IRIS	< 3.3 (1)	0.0004	0.3
		0.02	MRL-Int	ATSDR	< 3.3 (1)	0.0004	0.02
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.9	0.0002
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.9	0.00005
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.9	0.00004
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	< 3.3 (1)	1.9	0.00003
	H_2S	0.0014	RfC	USEPA IRIS	< 3.3 (1)	0.00019	0.1

Table 5-21 (continued). Chronic Human Health Effects (Tuscola, IL)

		Effects			Exposures		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**		**Radius (from source area or well feet (meter))**	**Concentration (ppmv)**	**Risk Ratio**
Upward leakage through the CO2 injection well(s)	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.006
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.001
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.0009
	H_2S	0.0014	RfC	USEPA IRIS	745 (227)	0.006	4.3
Upward leakage through deep oil and gas wells [No Wells]	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	NA	NA	NA
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	NA	NA	NA
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	NA	NA	NA
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	NA	NA	NA
	H_2S	0.0014	RfC	USEPA IRIS	NA	NA	NA
Upward leakage through undocumented, abandoned, or poorly constructed wells	CO_2	10,000	human discomfort	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.006
		40,000	Headache, etc.	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.002
		50,000	Injury, Tremors	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.001
		70,000	Unconsciousness	USEPA (2000); Saripalli (2003)	within 328 (100)	60	0.0009
	H_2S	0.0014	RfC	USEPA IRIS	745 (227)	0.006	4.3

Table 5-22. Chronic Effects on Biota (Tuscola, IL)

		Animals			Plants			Insect/Behavioral Effects					
		Effects			Effects			Effects			Risk Ratios		
Release Scenario	Gas	Level (ppmv)	Type	Exposure Concentration (ppmv)	Level (ppmv)	Type	Exposure Concentration (ppmv)	Level (ppmv)	Type	Exposure Concentration (ppmv)	Animals	Plants	Insect/ Behavioral Effects
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	1,000	respiratory stimulation	0.076	380	increased growth, biomass	0.076	0.5	moth, butterfly olfactory sensation	0.076	0.00008	0.0002	0.2
		10,000	insect, spiracle aperture regulation	0.076	700	increases/decreases in plant respiration	0.076	10	mosquitoes, ticks, fire bugs olfactory activation	0.076	0.000008	0.0001	0.008
		50,000	respiratory poisoning	0.076	10,000	fungi, abnormal growth	0.076	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	0.076	0.000002	0.000008	0.00008
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	0.076	-	-	0.00002
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-22 (continued). Chronic Effects on Biota (Tuscola, IL)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
		Effects			Effects			Effects					
Release Scenario	Gas	Level (ppmv)	Type	Exposure Concentration (ppmv)	Level (ppmv)	Type	Exposure Concentration (ppmv)	Level (ppmv)	Type	Exposure Concentration (ppmv)	Animals	Plants	Insect/ Behavioral Effects
Release through existing faults due to effects of increased pressure	CO_2	1,000	respiratory stimulation	3.7	380	increased growth, biomass	3.7	0.5	moth, butterfly olfactory sensation	3.7	0.004	0.01	7
		10,000	insect, spiracle aperture regulation	3.7	700	increases/decreases in plant respiration	3.7	10	mosquitoes, ticks, fire bugs olfactory activation	3.7	0.0004	0.005	0.4
		50,000	respiratory poisoning	3.7	10,000	fungi, abnormal growth	3.7	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	3.7	0.00007	0.0004	0.004
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	3.7	-	-	0.0007
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-22 (continued). Chronic Effects on Biota (Tuscola, IL)

		Animals			**Plants**			**Insect/Behavioral Effects**					
		Effects			**Effects**			**Effects**			**Risk Ratios**		
Release Scenario	**Gas**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Level (ppmv)**	**Type**	**Exposure Concentration (ppmv)**	**Animals**	**Plants**	**Insect/ Behavioral Effects**
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	1,000	respiratory stimulation	1.9	380	increased growth, biomass	1.9	0.5	moth, butterfly olfactory sensation	1.9	0.002	0.005	4
		10,000	insect, spiracle aperture regulation	1.9	700	increases/decreases in plant respiration	1.9	10	mosquitoes, ticks, fire bugs olfactory activation	1.9	0.0002	0.003	0.2
		50,000	respiratory poisoning	1.9	10,000	fungi, abnormal growth	1.9	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	1.9	0.00004	0.0002	0.002
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	1.9	-	-	0.0004
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-22 (continued). Chronic Effects on Biota (Tuscola, IL)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
Release Scenario		Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)			
	Gas	Level (ppmv)	Type		Level (ppmv)	Type		Level (ppmv)	Type		Animals	Plants	Insect/ Behavioral Effects
Upward leakage through the CO2 injection well(s)	CO_2	1,000	respiratory stimulation	60	380	increased growth, biomass	60	0.5	moth, butterfly olfactory sensation	60 (5,751 feet [1,753 meters])	0.06	0.2	120
		10,000	insect, spiracle aperture regulation	60	700	increases/decreases in plant respiration	60	10	mosquitoes, ticks, fire bugs olfactory activation	60 (909 feet [277 meters])	0.006	0.09	6
		50,000	respiratory poisoning	60	10,000	fungi, abnormal growth	60	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	60	0.001	0.006	0.06
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	60	-	-	0.01
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-22 (continued). Chronic Effects on Biota (Tuscola, IL)

		Animals			Plants			Insect/Behavioral Effects			Risk Ratios		
Release Scenario	Gas	Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)	Effects		Exposure Concentration (ppmv)			
		Level (ppmv)	Type		Level (ppmv)	Type		Level (ppmv)	Type		Animals	Plants	Insect/ Behavioral Effects
Upward leakage through deep oil and gas wells [No Wells]	CO_2	1,000	respiratory stimulation	NA	380	increased growth, biomass	NA	0.5	moth, butterfly olfactory sensation	NA	NA	NA	NA
		10,000	insect, spiracle aperture regulation	NA	700	increases/decreases in plant respiration	NA	10	mosquitoes, ticks, fire bugs olfactory activation	NA	NA	NA	NA
		50,000	respiratory poisoning	NA	10,000	fungi, abnormal growth	NA	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	NA	NA	NA	NA
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	NA	NA	NA	NA
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-22 (continued). Chronic Effects on Biota (Tuscola, IL)

		Animals			**Plants**			**Insect/Behavioral Effects**			**Risk Ratios**		
Release Scenario	**Gas**	**Effects**		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**	**Effects**		**Exposure Concentration (ppmv)**			
		Level (ppmv)	**Type**		**Level (ppmv)**	**Type**		**Level (ppmv)**	**Type**		**Animals**	**Plants**	**Insect/ Behavioral Effects**
Upward leakage through undocumented, abandoned, or poorly constructed wells	CO_2	1,000	respiratory stimulation	60	380	increased growth, biomass	60	0.5	moth, butterfly olfactory sensation	60 (5,751 feet [1,753 meters])	0.06	0.2	120
		10,000	insect, spiracle aperture regulation	60	700	increases/decreases in plant respiration	60	10	mosquitoes, ticks, fire bugs olfactory activation	60 (909 feet [277 meters])	0.006	0.09	6
		50,000	respiratory poisoning	60	10,000	fungi, abnormal growth	60	1,000	mosquitoes, ticks, fire bugs olfactory locomotion	60	0.001	0.006	0.06
		-	-	-	-	-	-	5,000	ants, bees, termites, beetles, nematodes olfactory sensation	60	-	-	0.01
	H_2S	-	-	-	-	-	-	-	-	-	-	-	-

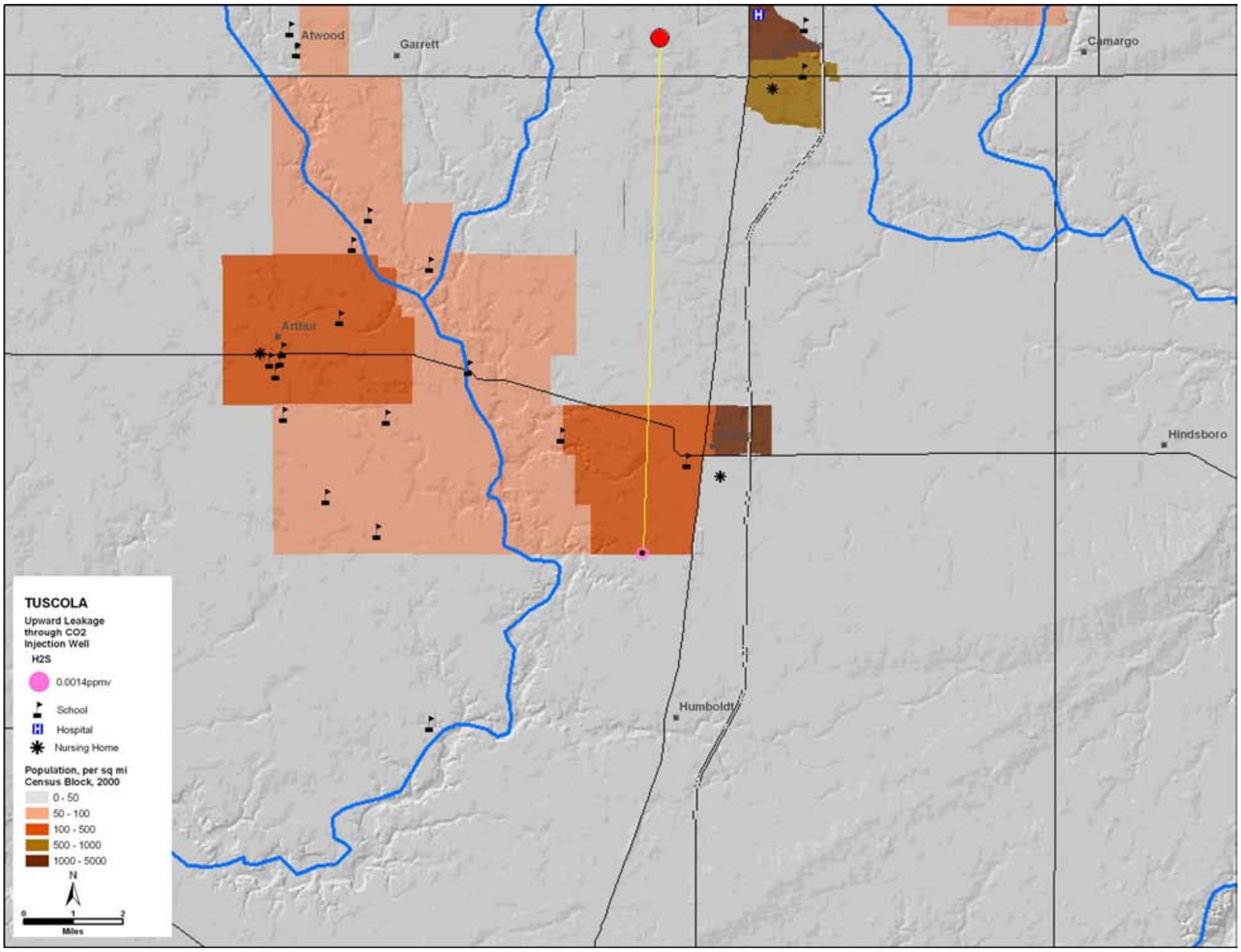

Figure 5-6. Area Within Which H_2S Released from CO_2 Injection Wells Exceeds Chronic Toxicity Criteria (i.e., 0.0014 ppmv H_2S) at the Tuscola (IL) Site

6.0 RISK SCREENING & PERFORMANCE ASSESSMENT

6.1 Risk Summary

The potential human-health and environmental effects identified for the four candidate FutureGen sites are summarized in Table 6-1 to Table 6-9. Separate sets of potential health effects are shown for workers and the general populace exposed to atmospherically dispersed gases from two main sources: (1) pre-sequestration releases from pipelines and wellheads and (2) post-sequestration releases through the caprock, faults, and well bores. Each set of potential health effects is described separately below. Potential health effects for plant workers are described only for short-term (minutes to hours) release scenarios that may occur during the planned 50-year duration of plant operations. The potential health effects for the workers as well as the general public for the short-term releases during plant operation are presented in Table 6-1 through Table 6-4. A summary of potential numbers of individuals from the public affected by pipeline releases is shown in Table 6-5. The potential health effects from both rapid and slow (days) releases that may occur from sequestered gas reservoirs are presented in Table 6-6 through Table 6-9. Color-coding is used to identify three levels of potential health effects: negligible (grey), moderate (yellow), and potentially significant (pink).

6.1.1 PRE-SEQUESTRATION RELEASES

For pipelines and wellheads, the health effects from released gases for plant workers are shown in terms of whether industrial hygiene criteria (e.g., the IDLH) would be exceeded at the plant boundary (i.e., 820 feet (250 meters) from the rupture point). Similarly, the health effects for the nearby general populace are shown in terms of the distance beyond which the release would cause no effect. For worker exposures, no health effect was predicted for CO_2 releases from either wellheads or pipelines at a distance of 820 feet (250 meters). However, there could be serious effects from the release of supercritical CO_2 at high velocity to workers in the immediate vicinity of a pipeline or wellhead. The release of H_2S from a pipeline or wellhead results in potential health effects for workers at all candidate sites except Mattoon. As the magnitude of health risk is influenced by pipeline size, the highest risk to workers is predicted for a pipeline rupture at the Jewett Site (Table 6-1 to Table 6-4), since this location has the largest diameter pipeline (19.3 inches [49 centimeters]). Potential risk to the public from wellhead releases also depends on the size of the wellbore, as well as the proximity of the injection well to populated areas. Even though populated areas are located near the plant site at both Jewett and Odessa, there are no predicted effects from pipeline or wellhead releases of CO_2 for the public at any of the candidate sites. However, H_2S releases from pipelines could impact the general populace at all of the candidate sites; H_2S releases from wellhead ruptures could affect the public at the Jewett and Tuscola Sites.

Pipeline ruptures and punctures and releases from the injection wellheads could result in elevated concentrations of H_2S for several hundred or thousand meters from the release point. However, the potential occurrence of health effects is dependent on the proximity of the release location to population centers. Populated areas occur within the potential impact zone from pipeline ruptures, punctures and wellhead ruptures at Jewett and Tuscola. At Jewett, pipeline ruptures or punctures could affect populated areas near Buffalo and north of the Trinity River. Of the three injection wells, the one located within the Coffield State Prison Farm could affect the greatest number of individuals. At Tuscola, there are two potentially affected populated areas: the town of Tuscola east of the plant site and the town of Arcola near the pipeline terminus. The potential impact zone for H_2S at Mattoon does not extend as far as the populated area east of the plant site. Only a few individual farmhouses are within the radial distance of the no effects boundary for H_2S. At Odessa, the populated areas near the plant site are outside the potential zone for H_2S effects from a pipeline rupture or puncture. The injection wells for Odessa are located in a sparsely populated area; the nearest town is Fort Stockton located about eight miles west of the wells.

To evaluate the potential effects of CO_2 and H_2S releases from pipeline ruptures and punctures in more detail, an automated “pipeline-walk” analysis was conducted. The methodology is described in Section 4.4.2 (Models for Releases to Outdoor Air From Rapid Releases – SLAB) and in Appendix C-IV. This analysis estimates the maximum expected number of individuals from the general public potentially affected by pipeline ruptures or punctures that occur at each site. The analysis takes into account the effects of variable meteorological conditions and the location of pipeline ruptures or punctures. The potential effects are evaluated in terms of toxicity criteria previously described in Section 3 (Tables 3-5 and 3-6):

- Adverse effect – Maximum CO_2 or H_2S concentrations without mild transient adverse health effects, or possible perception of an objectionable odor;
- Irreversible adverse effect – maximum concentration without irreversible or other serious health effects or symptoms impairing taking protective action; and
- Life threatening effect – maximum concentration without life-threatening health effects.

Table 6-1. Predicted Pre-Sequestration Human Health Risk Estimates Summary, Jewett, TX

		Population Exposed to Airborne Gas	
		Worker	**General Populace**
Release Scenario	**Gas**	**Effects**	**Distance (feet [meters]) to No Effects Level**
Pipeline			
Pipeline rupture (minutes)	CO_2	< IDLH at 820 feet (250 meters)	663 (202)
	H_2S	> Ceiling at 820 feet (250 meters)	22,589 (6,885)
Pipeline puncture (hours)	CO_2	< IDLH at 820 feet (250 meters)	551 (168)
	H_2S	< Ceiling at 820 feet (250 meters)	5,712 (1,741)
Sequestration Site			
Equipment rupture at Wellhead [Woodbine] (minutes)	CO_2	< IDLH at 66 feet (20 meters)	10 (3)
	H_2S	< Ceiling at 820 feet (250 meters)	1,752 (534)
Equipment rupture at Wellhead [Travis Peak] (minutes)	CO_2	< IDLH at 66 feet (20 meters)	26 (8)
	H_2S	< Ceiling at 820 feet (250 meters)	2,585 (788)

Legend:

	Workers	**General Populace**
🟥	> 10 X IDLH or Ceiling	Population center impacted by maximum release case
🟨	> IDLH < 10X IDLH or Ceiling	Population center immediately outside of no effects levels
⬜	< IDLH or Ceiling	Population center distant from no effects level

Definitions:
Ceiling – maximum concentration that should not be exceeded at any time
IDLH -immediately dangerous to life and health

Table 6-2. Predicted Pre-Sequestration Human Health Risk Estimates Summary, Odessa, TX

		Population Exposed to Airborne Gas	
		Worker	**General Populace**
Release Scenario	**Gas**	**Effects**	**Distance (feet [meters]) to No Effects Level**
Pipeline			
Pipeline rupture (minutes)	CO_2	< IDLH at 820 feet (250 meters)	397 (121)
	H_2S	> Ceiling at 820 feet (250 meters)	14,026 (4,275)
Pipeline puncture (hours)	CO_2	< IDLH at 820 feet (250 meters)	627 (191)
	H_2S	< Ceiling at 820 feet (250 meters)	5,692 (1,735)
Sequestration Site			
Equipment rupture at Wellhead (minutes)	CO_2	< IDLH at 66 feet (20 meters)	7 (2)
	H_2S	< Ceiling at 820 feet (250 meters)	951 (290)

Legend:

	Workers	**General Populace**
🟥	> 10 X IDLH or Ceiling	Population center impacted by maximum release case
🟨	> IDLH < 10X IDLH or Ceiling	Population center immediately outside of no effects levels
▨	< IDLH or Ceiling	Population center distant from no effects level

Definitions:
Ceiling – maximum concentration that should not be exceeded at any time
IDLH -immediately dangerous to life and health

Table 6-3. Predicted Pre-Sequestration Human Health Risk Estimates Summary, Mattoon, IL

		Population Exposed to Airborne Gas	
		Worker	General Populace
Release Scenario	Gas	Effects	Distance (feet [meters]) to No Effects Level
Pipeline			
Pipeline rupture (minutes)	CO_2	< IDLH at 66 feet (20 meters)	< 3.3 (1)
	H_2S	< Ceiling at 820 feet (250 meters)	4,170 (1,271)
Pipeline puncture (hours)	CO_2	< IDLH at 820 feet (250 meters)	646 (197)
	H_2S	< Ceiling at 820 feet (250 meters)	5,341 (1,628)
Sequestration Site			
Equipment rupture at Wellhead (minutes)	CO_2	< IDLH at 66 feet (20 meters)	16 (5)
	H_2S	< Ceiling at 820 feet (250 meters)	2,257 (688)

Legend:

	Workers	**General Populace**
🟥	> 10 X IDLH or Ceiling	Population center impacted by maximum release case
🟨	> IDLH < 10X IDLH or Ceiling	Population center immediately outside of no effects levels
▨	< IDLH or Ceiling	Population center distant from no effects level

Definitions:
Ceiling – maximum concentration that should not be exceeded at any time
IDLH -immediately dangerous to life and health

Table 6-4. Predicted Pre-Sequestration Human Health Risk Estimates Summary, Tuscola, IL

		Population Exposed to Airborne Gas	
		Worker	**General Populace**
Release Scenario	**Gas**	**Effects**	**Distance (feet [meters]) to No Effects Level**
Pipeline			
Pipeline rupture (minutes)	CO_2	< IDLH at 820 feet (250 meters)	459 (140)
	H_2S	> Ceiling at 820 feet (250 meters)	16,312 (4,972)
Pipeline puncture (hours)	CO_2	< IDLH at 820 feet (250 meters)	646 (197)
	H_2S	< Ceiling at 820 feet (250 meters)	9,416 (2,870)
Sequestration Site			
Equipment rupture at Wellhead (minutes)	CO_2	< IDLH at 66 feet (20 meters)	16 (5)
	H_2S	< Ceiling at 820 feet (250 meters)	2,034 (620)

Legend:

	Workers	**General Populace**
🟥	> 10 X IDLH or Ceiling	Population center impacted by maximum release case
🟨	> IDLH < 10X IDLH or Ceiling	Population center immediately outside of no effects levels
▨	< IDLH or Ceiling	Population center distant from no effects level

Definitions:
Ceiling – maximum concentration that should not be exceeded at any time
IDLH -immediately dangerous to life and health

Because the expected exposure durations are different for the two types of potential incidents, the concentrations associated with the definitions of levels below which effects may not occur for ruptures and punctures are also different. The levels below which H_2S and CO_2 exposures may not occur due to a short-term release (15 minutes or less) from a pipeline rupture are defined as:

- Adverse –

  H_2S: 0. 51 ppmv, this is the TEEL-1 (Temporary Emergency Exposure Limit) defined by the DOE

  CO_2: 30,000 ppmv, TEEL-1

- Irreversible adverse –

  H_2S: 27 ppmv, TEEL-2

  CO_2: 30,000 ppmv, TEEL-2

- Life threatening -

H_2S: 50 ppmv, TEEL-3

CO_2: 40,000 ppmv, TEEL-3

The levels for H_2S and CO_2 below which exposures to a longer term release (up to eight hours) may not occur due to a pipeline puncture are defined as:

- Adverse –

  H_2S: 0.33 ppmv, this is the AEGL-1 (Acute Exposure Guideline Level) defined by the National Research Council's Committee on Toxicology

  CO_2: 20,000 ppmv, U.S. EPA (2000)

- Irreversible adverse –

  H_2S: 17 ppmv, AEGL-2

- Life threatening -

  H_2S: 31 ppmv, AEGL-3

  CO_2: 40,000 ppmv, TEEL-3

The results of the “pipeline-walk” analyses are presented in Table 6-5. There are no predicted potential health effects from CO_2 releases due to pipeline ruptures or punctures at any of the four candidate sites. In all cases the expected number of individuals affected is less than one. The fractional values for the number of affected individuals predicted by the model simulations are preserved in the table to show the extent of the differences between sites. These differences are more clearly seen in the comparison of the effects of H_2S releases at the four sites. The largest number of people potentially affected by H_2S releases is associated with pipeline ruptures. The model simulations predict that up to 52 individuals from the general public would be expected to experience adverse effects from a pipeline rupture at the Jewett Site (H_2S, 0.51 ppmv). The potential for adverse effects from H_2S exposure are predicted for pipeline ruptures at the Tuscola Site for 7.4 individuals. Fewer numbers of individuals at both sites are predicted to be affected by a pipeline puncture. The maximum number of expected individuals experiencing adverse effects from the H_2S release from a puncture is six at the Jewett Site and one at the Tuscola Site. The maximum number of individuals expected to experience irreversible-adverse or life threatening effects in the unlikely event of a pipeline rupture for the Jewett pipeline is one. No adverse or life-threatening effects are predicted for H_2S releases from pipeline ruptures or punctures at the Odessa and Mattoon Sites.

These results indicate that the potential human-health effects due to pipeline ruptures or punctures at all sites are minimal. The primary predicted effect identified in the “pipeline-walk” analysis in the event of a release is mild transient health effects. It is anticipated that the predicted exposures can be avoided since the adverse-effects-level H_2S concentration (0.51 ppmv) is associated with the perception of an objectionable odor. Likewise, the life threatening effects of H_2S exposures are associated with long exposure levels that can be detected and avoided.

Table 6-5. Summary of Expected Numbers of Individuals from the Public Affected by Pipeline Releases

	Mattoon, IL	**Tuscola, IL**	**Jewett, TX**	**Odessa, TX**
(A) Ruptures				
CO_2 Health Effects				
Adverse	0	<0.1	<0.5	0
Irreversible Adverse	0	<0.1	<0.5	0
Life Threatening	0	<0.1	<0.5	0
H_2S Health Effects				
Adverse	0.12	7.4	52	0.19
Irreversible Adverse	0.001	<0.2	1	0.004
Life Threatening	<0.001	<0.2	1	<0.004
(B) Punctures				
CO_2 Health Effects[1]				
Adverse	0.01	<0.1	0.2	<0.01
Life Threatening	<0.01	<0.1	<0.2	<0.01
H_2S Health Effects				
Adverse	<0.2	1	6	<0.1
Irreversible Adverse	0.002	0.02	0.1	0.0005
Life Threatening	<0.002	<0.02	<0.1	<0.0001

[1] There are no applicable regulatory-derived CO_2 health-effect criteria for the irreversible adverse effect endpoint and long-term (up to 8 hours) exposures

6.1.2 POST-SEQUESTRATION RELEASES

The health effects from exposures to released gases for the general populace that may be above the plume footprint are shown as risk ratios (i.e., the ratio of the predicted atmospheric gas concentration to the threshold concentration at which no health effects occur). A risk ratio less than one indicates that no health effects are likely to occur, while risk ratios greater than one represent the potential for health effects to occur. Higher risk ratios generally represent higher levels of health concern, although regulatory-derived toxicity criteria include safety factors to ensure that sensitive individuals are protected.

None of the risk ratios exceed a value of one for predicted CO_2 exposures from post-sequestration conditions at any of the four candidate sites. Depending on the scenario, certain of the predicted H_2S releases result in risk ratios exceeding one (Table 6-6 to Table 6-9). Slow releases through the caprock and either existing or induced faults were not predicted to result in health effects for the general populace from exposures to either CO_2 or H_2S. Rapid releases of CO_2 and H_2S from the three types of wells evaluated (i.e., CO_2 injection wells, abandoned oil and gas wells, and undocumented, abandoned, or poorly constructed wells), as well as slow CO_2 releases from wells, were not predicted to result in health effects for the general populace. However, the occurrence of slow H_2S releases from all three well types was predicted to result in health effects for the general public (Table 6-6 to Table 6-9). H_2S release from injection wells at the Jewett Site has the greatest potential to impact the general populace; the Jewett Site has multiple injection wells, and one is near a populated area. While the predicted risk ratios from H_2S due to well leakage are the same for all candidate sites, the injection wells at the Odessa Site are not located in currently populated areas. Tuscola’s injection well is near a less densely populated area on the outskirts of Arcola. The Mattoon injection well is located on the plant site and the potentially affected area does not extend to the town of Mattoon. Future population levels, however, could change in the vicinity of the injection wells.

Table 6-6. Predicted Post-Sequestration Human Health Risk Estimates Summary, Jewett, TX

Release Scenario	**Gas**	**General Populace Risk Ratios**			
Plume Footprint		**Rapid Release**		**Slow Release**	
		Risk Ratio	**Distance (feet [meters]) to No Effects Level**	**Risk Ratio**	**Distance (feet [meters]) to No Effects Level**
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	NA	NA	0.000008	above reservoir
	H_2S	NA	NA	Not released	
Release through existing faults due to effects of increased pressure	CO_2	NA	NA	0.0004	above reservoir
	H_2S	NA	NA	0.3	above reservoir
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	NA	NA	0.0002	above reservoir
	H_2S	NA	NA	0.2	above reservoir
Upward leakage through the CO_2 injection well(s)	CO_2	0.07	near well	0.006	above reservoir
	H_2S	0.8	near well	**4**	**745 (227)**
Upward leakage through deep oil and gas wells	CO_2	0.07	near well	0.006	above reservoir
	H_2S	0.8	near well	**4**	**745 (227)**
Upward leakage through undocumented, abandoned, or poorly constructed wells (days)	CO_2	0.07	near well	0.006	above reservoir
	H_2S	0.8	near well	**4**	**745 (227)**

Legend:

	General Populace	**Risk Ratios**
🟥	Population center impacted by maximum release case	Risk ratio ≥10
🟨	Population center immediately outside of no effects levels	Risk ratio > 1 to 10
▒	Population center distant from no effects level	Risk ratio < 1

Definitions:
NA -not applicable

Table 6-7. Predicted Post-Sequestration Human Health Risk Estimates Summary, Odessa, TX

Release Scenario	**Gas**	**General Populace Risk Ratios**			
		Rapid Release		**Slow Release**	
Plume Footprint		**Risk Ratio**	**Distance (feet [meters]) to No Effects Level**	**Risk Ratio**	**Distance (feet [meters]) to No Effects Level**
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	NA	NA	0.0002	above reservoir
	H_2S	NA	NA	Not released	
Release through existing faults due to effects of increased pressure	CO_2	NA	NA	0.0004	above reservoir
	H_2S	NA	NA	0.3	above reservoir
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	NA	NA	0.0002	above reservoir
	H_2S	NA	NA	0.2	above reservoir
Upward leakage through the CO_2 injection well(s)	CO_2	0.007	near well	0.006	above reservoir
	H_2S	0.08	near well	**4**	**745 (227)**
Upward leakage through deep oil and gas wells	CO_2	0.01	near well	0.006	above reservoir
	H_2S	0.08	near well	**4**	**745 (227)**
Upward leakage through undocumented, abandoned, or poorly constructed wells (days)	CO_2	0.007	near well	0.006	above reservoir
	H_2S	0.08	near well	**4**	**745 (227)**

Legend:

	General Populace	**Risk Ratios**
🟪	Population center impacted by maximum release case	Risk ratio ≥10
🟨	Population center immediately outside of no effects levels	Risk ratio > 1 to 10
▨	Population center distant from no effects level	Risk ratio < 1

Definitions:
NA -not applicable

Table 6-8. Predicted Post-Sequestration Human Health Risk Estimates Summary, Mattoon, IL

Release Scenario	Gas	General Populace Risk Ratios			
Plume Footprint		**Rapid Release**		**Slow Release**	
		Risk Ratio	**Distance (feet [meters]) to No Effects Level**	**Risk Ratio**	**Distance (feet [meters]) to No Effects Level**
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	NA	NA	0.000008	above reservoir
	H_2S	NA	NA	Not released	
Release through existing faults due to effects of increased pressure	CO_2	NA	NA	0.0004	above reservoir
	H_2S	NA	NA	0.3	above reservoir
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	NA	NA	0.006	above reservoir
	H_2S	NA	NA	0.1	above reservoir
Upward leakage through the CO_2 injection well(s)	CO_2	0.02	near well	0.006	above reservoir
	H_2S	0.1	near well	**4**	**745 (227)**
Upward leakage through deep oil and gas wells	CO_2	No wells			
	H_2S				
Upward leakage through undocumented, abandoned, or poorly constructed wells (days)	CO_2	0.01	near well	0.006	above reservoir
	H_2S	0.1	near well	**4**	**745 (227)**

Legend:

	General Populace	**Risk Ratios**
🟥	Population center impacted by maximum release case	Risk ratio ≥10
🟨	Population center immediately outside of no effects levels	Risk ratio > 1 to 10
▨	Population center distant from no effects level	Risk ratio < 1

Definitions:
NA -not applicable

Table 6-9. Predicted Post-Sequestration Human Health Risk Estimates Summary, Tuscola, IL

Release Scenario	Gas	General Populace Risk Ratios			
Plume Footprint		Rapid Release		Slow Release	
		Risk Ratio	Distance (feet [meters]) to No Effects Level	Risk Ratio	Distance (feet [meters]) to No Effects Level
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	NA	NA	0.000008	above reservoir
	H_2S	NA	NA	Not released	
Release through existing faults due to effects of increased pressure	CO_2	NA	NA	0.0004	above reservoir
	H_2S	NA	NA	0.3	above reservoir
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	NA	NA	0.0002	above reservoir
	H_2S	NA	NA	0.1	above reservoir
Upward leakage through the CO_2 injection well(s)	CO_2	0.01	near well	0.006	above reservoir
	H_2S	0.2	near well	**4**	**745 [227]**
Upward leakage through deep oil and gas wells	CO_2	No wells			
	H_2S				
Upward leakage through undocumented, abandoned, or poorly constructed wells (days)	CO_2	0.01	near well	0.006	above reservoir
	H_2S	0.2	near well	**4**	**745 [227]**

Legend:

	General Populace	**Risk Ratios**
🟥	Population center impacted by maximum release case	Risk ratio ≥10
🟨	Population center immediately outside of no effects levels	Risk ratio > 1 to 10
▩	Population center distant from no effects level	Risk ratio < 1

Definitions:
NA -not applicable

The number of injection wells influences the area of the sequestration reservoir. This, in turn, also influences the area within which the general populace could experience health effects from H_2S releases. Odessa has the greatest number of injection wells (10), and they are spread across the widest area of any of the candidate sites, although the population density is relatively low above the predicted sequestration plume. The Jewett Site has three injection wells located in two different areas, which means that a greater number of individuals could potentially be impacted. A larger area for the sequestration plume also means that there could be more existing wells providing a conduit from the sequestration reservoir to the land surface.

The number of people potentially affected by slow leakage of H_2S at the CO_2 injection well or other deep wells is one person at Mattoon, less than one at Odessa, six at Tuscola, and 26 for the Texas Department of Criminal Justice (TDCJ) injection well at Jewett and less than one for the two other injection wells at Jewett. The effect level used for this evaluation is US EPA IRIS RfC of 0.0014 ppmv of H_2S. The RfC for H_2S is defined as the chronic RfC that over a long exposure may cause lesions of the olfactory mucosa (7/28/2003). However, as shown in Table 6-11, the frequency of failure for one of these wells is expected to be quite low. In addition, the number of people affected at the time of such a release would depend on wind direction, speed, and atmospheric stability could be less.

Table 6-10 shows the probabilities of CO_2 and H_2S entering into non-target groundwater aquifers and surface water due to releases from either pipelines or the sequestration reservoirs. Potential impacts to groundwater are dependent on the depth to groundwater, while surface water impacts are dependent on the planned proximity of the pipeline(s) to surface water bodies. In general, the probability of groundwater impacts from pipeline releases and wellhead failures was considered to be low. A higher probability for surface water impacts was assigned to sites where the pipeline is planned to cross major rivers or where a large number of wetlands or ponds exist. At both the Jewett and Odessa Sites, the planned pipeline alignments cross a river. Aquatic biota could be affected at these sites if a release occurred, or humans could be affected if the river is used as a source of drinking water. Releases to surface water from the sequestration reservoir were not considered to be a concern for either CO_2 or H_2S, based on their respective solubility in deep groundwater and minimal effects on pH and TDS. Plants were not predicted to be affected by releases into the soil, except near the segment of a pipeline that ruptured or leaked.

Table 6-10. Probabilities of Releases into Non-target Aquifers and Surface Water

	Releases of Sequestered Gas[1]			**Releases of Gas Prior to Sequestration[2]**			
	Leakage into non-target aquifers due to		**Leakage of non-target aquifer into**	**Discharge from pipeline into**		**Discharge from wellhead rupture into**	
Candidate Site	**Unknown structural or stratigraphic connections**	**Lateral migration from the target zone**	**Surface water**	**Ground water[3]**	**Surface water[4]**	**Ground water[3]**	**Surface water[4]**
Jewett, TX	1E-05	1E-06	1E-08 to 1E-06	Low	High	Low	Low
Odessa, TX	1E-05	1E-06	1E-08 to 1E-06	Low	High	Low	Low
Mattoon, IL	1E-05	1E-06	1E-05 to 1E-04	Low	Medium	Low	Medium
Tuscola, IL	1E-05	1E-06	1E-05 to 1E-04	Low	Medium	Low	Medium

Notes:

1 – over 5,000 years

2 – over 50 years of plant operation

3 - Groundwater: Low = discharge unlikely to infiltrate to groundwater at depth of >20 feet (6 meters);

4 - Surface Water: High = pipeline near or crosses major river; Medium = wetlands or ponds present; Low = no river crossing or no significant wetlands or ponds.

Groundwater impacts or indirect releases to surface water, from leakage into non-target aquifers are possible, but are considered to have a low probability of occurrence, as the analyses in this report have shown. Also, while radon releases from subsurface soil gas and subsequent intrusion into residences may be enhanced as a result of CO_2 leakage beneath residences, the analyses performed at the four candidate FutureGen sites indicate that the risks associated with radon intrusion are not likely to change appreciably from present conditions.

6.2 Predicted Probabilities of Releases for each Scenario

Table 6-11 shows the estimated range of failure frequencies and probabilities for pre- and post-sequestration scenarios by candidate site. The values for the lifetime over which failure could occur and the number of items that could fail correspond to operating assumptions and site characteristics. 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. DOE chose to categorize the two accidents with the largest CO_2 releases (4,000 barrels and 7,408 barrels) as rupture type releases, and the next four highest releases (772 barrels to 3,600 barrels) as puncture type releases. For comparison, five miles of FutureGen pipeline would contain about 6,500 barrels, depending on the pipeline diameter. Assuming the total length of pipeline involved was approximately 1,616 miles (2,600 kilometers) based on data in Gale and Davison (2004), the rupture and puncture failure frequencies were calculated to be 3.68×10^{-5}/(miles-year) [5.92×10^{-5}/(kilometer-year)] and 0.73×10^{-5}/(miles-year) [1.18×10^{-4}/(kilometer-year)], respectively. The annual pipeline failure frequencies used in this assessment were calculated based on the site-specific pipeline lengths.

The failure rate of wellhead equipment during operation is estimated as 2.02×10^{-5} per well per year based on natural gas injection-well experience from an IEA GHG Study (Papanikolau et al., 2006). The estimated failure rates for upward slow leakage through CO_2 injection wells, deep oil and gas wells, undocumented deep wells, and caprock is based on data from the analog site database (Section 5.2).

The predictions shown in the table consist of the following:

- **Probability of at least one failure or release by scenario over the lifetime of interest**. For the pipeline and wellhead, the lifetime is 50 years. For all other releases the period of interest ranges from 1,000 years to 5,000 years. Probabilities are calculated under the assumption that once a failure occurs (such as a puncture to a pipeline), the item that fails is repaired, and thereafter has the same failure probability as before. The formula used for this calculation is:

$$P1 = 1-(1-f)^{NW \cdot NY}$$

where

P1 = probability of at least one failure from the NW items over a period NY (years)

f = frequency of failure over a particular period of time (a year in this case)

NW = number of items that may fail with frequency “f” (such as number of abandoned wells)

NY = number of time periods over which failures can occur (years)

Table 6-11. Estimated Range of Failure Probabilities for Each Release Scenario by Candidate FutureGen Site

a) Jewett, TX

Release Scenario	**Lifetime over which failure could occur, years**	**frequency of failure for one item, annually**	**Number of items that could fail**	**Probability of at least one failure**
Pipeline Rupture, Woodbine[1, 2]	50	5.6E-3	1	0.24
Pipeline Rupture, Travis Peak[1]	50	5.0E-3	1	0.22
Pipeline Puncture, Woodbine[1]	50	1.1E-2	1	0.43
Pipeline Puncture, Travis Peak[1]	50	9.9E-3	1	0.39
Wellhead Equipment Rupture[3]	50	2.0E-5	3	3.0E-3
Upward rapid[4] leakage through caprock	1,000 to 5,000	2.0E-10	1	2.0E-7 to 1.0E-6
Upward slow leakage through caprock	1,000 to 5,000	4.0E-5	1	0.04 to 0.18
Release through existing faults	1,000 to 5,000	2.0E-8	1	2.0E-5 to 1.0E-04
Release through induced faults	1,000 to 5,000	2.0E-8	1	2.0E-5 to 1.0E-4
Upward rapid leakage through CO_2 injection well	1,000 to 5,000	0.000001 to 0.00001	3	0.003 to 0.14
Upward slow leakage through CO_2 injection well	1,000 to 5,000	0.000001 to 0.00001	3	0.003 to 0.14
Upward rapid leakage through deep oil & gas wells	1,000 to 5,000	0.000001 to 0.001	1 to 57	0.001 to 1
Upward slow leakage through deep oil & gas wells	1,000 to 5,000	0.000001 to 0.001	1 to 57	0.001 to 1
Leaks due to undocumented deep wells, high rate	1,000 to 5,000	0.00001 to 0.001	1 to 13	0.01 to 1
Leaks due to undocumented deep wells, low rate	1,000 to 5,000	0.00001 to 0.001	1 to 13	0.01 to 1

[1] Pipeline lengths: Woodbine = 59 miles (95 kilometers); Travis Peak = 52 miles (83.7 kilometers)

[2] Failure frequencies for pipeline ruptures and punctures are calculated as the product of the pipeline length and the failure frequencies obtained from the national database (ruptures: 3.68 x 10^{-5}/(miles-year) [5.92 x 10^{-5}/kilometer-year]; punctures: 0.73 x 10^{-5}/ (miles-year) [1.18 x 10^{-4}/kilometer-year]).

[3] Assumes active operation of wells into both Woodbine and Travis Peak formations.

[3] Failure frequencies for leakage scenarios are obtained from the analog database.

b) Odessa, TX				
Release Scenario	**Lifetime over which failure could occur, years**	**frequency of failure for one item, annually**	**Number of items that could fail**	**Probability of at least one failure**
Pipeline Rupture[1, 2]	50	5.9E-3	1	0.25
Pipeline Puncture	50	1.2E-2	1	0.48
Wellhead Equipment Rupture	50	2.0E-5	10	1.0E-2
Upward rapid[3] leakage through caprock	1,000 to 5,000	2.0E-10	1	2.0E-7 to 1.0E-6
Upward slow leakage through caprock	1,000 to 5,000	4.0E-5	1	0.04 to 0.18
Release through existing faults	1,000 to 5,000	2.0E-8	1	2.0E-5 to 1.0E-4
Release through induced faults	1,000 to 5,000	2.0E-8	1	2.0E-5 to 1.0E-4
Upward rapid leakage through CO_2 injection well	1,000 to 5,000	0.000001 to 0.00001	10	0.01 to 0.39
Upward slow leakage through CO_2 injection well	1,000 to 5,000	0.000001 to 0.00001	10	0.01 to 0.39
Upward rapid leakage through deep oil & gas wells	1,000 to 5,000	0.000001 to 0.001	0	0
Upward slow leakage through deep oil & gas wells	1,000 to 5,000	0.000001 to 0.001	0	0
Leaks due to undocumented deep wells, high rate	1,000 to 5,000	0.00001 to 0.001	1 to 2	0.01 to 0.99
Leaks due to undocumented deep wells, low rate	1,000 to 5,000	0.00001 to 0.001	1 to 2	0.01 to 0.99

[1] Pipeline length = 61.5 miles (99 kilometers)

[2] Failure frequencies for pipeline ruptures and punctures are calculated as the product of the pipeline length and the failure frequencies obtained from the national database (ruptures: 3.68 x 10^{-5}/(miles-year) [5.92 x 10^{-5}/kilometer-year]; punctures: 0.73 x 10^{-5}/ (miles-year) [1.18 x 10^{-4}/kilometer-year]).

[3] Failure frequencies for leakage scenarios are obtained from the analog database.

c) Tuscola, IL				
Release Scenario	**Lifetime over which failure could occur,years**	**frequency of failure for one item, annually**	**Number of items that could fail**	**Probability of at least one failure**
Pipeline Rupture[1, 2]	50	1.1E-3	1	0.05
Pipeline Puncture	50	2.1E-3	1	0.10
Wellhead Equipment Rupture	50	2.0E-5	1	1.0E-3
Upward rapid[3] leakage through caprock	1,000 to 5,000	2.0E-10	1	2.0E-7 to 1.0E-6
Upward slow leakage through caprock	1,000 to 5,000	4.0E-5	1	0.04 to 0.18
Release through existing faults	1,000 to 5,000	2.0E-8	1	2.0E-5 to 1.0E-4
Release through induced faults	1,000 to 5,000	2.0E-8	1	2.0E-5 to 1.0E-4
Upward rapid leakage through CO_2 injection well	1,000 to 5,000	0.000001 to 0.00001	1	0.001 to 0.049
Upward slow leakage through CO_2 injection well	1,000 to 5,000	0.000001 to 0.00001	1	0.001 to 0.049
Upward rapid leakage through deep oil & gas wells	1,000 to 5,000	0.000001 to 0.001	0	0
Upward slow leakage through deep oil & gas wells	1,000 to 5,000	0.000001 to 0.001	0	0
Leaks due to undocumented deep wells, high rate	1,000 to 5,000	0.00001 to 0.001	1 to 3	0.01 to 0.99
Leaks due to undocumented deep wells, low rate	1,000 to 5,000	0.00001 to 0.001	1 to 3	0.01 to 0.99

[1] Pipeline length = 11 miles (18 kilometers)

[2] Failure frequencies for pipeline ruptures and punctures are calculated as the product of the pipeline length and the failure frequencies obtained from the national database (ruptures: 3.68 x 10^{-5}/(miles-year) [5.92 x 10^{-5}/kilometer-year]; punctures: 0.73 x 10^{-5}/ (miles-year) [1.18 x 10^{-4}/kilometer-year]).

[3] Failure frequencies for leakage scenarios are obtained from the analog database.

d) Mattoon, IL

Release Scenario	Lifetime over which failure could occur, years	frequency of failure for one item, annually	Number of items that could fail	Probability of at least one failure
Pipeline Rupture[1, 2]	50	4.7E-5	1	2.4E-3
Pipeline Puncture	50	9.4E-5	1	4.7E-3
Wellhead Equipment Rupture	50	2.0E-5	1	1.0E-3
Upward rapid[3] leakage through caprock	1,000 to 5,000	2.0E-10	1	2.0E-7 to 1.0E-6
Upward slow leakage through caprock	1,000 to 5,000	4.0E-5	1	0.04 to 0.18
Release through existing faults	1,000 to 5,000	2.0E-8	1	2.0E-5 to 1.0E-4
Release through induced faults	1,000 to 5,000	2.0E-8	1	2.0E-5 to 1.0E-4
Upward rapid leakage through CO_2 injection well	1,000 to 5,000	0.000001 to 0.00001	1	0.001 to 0.049
Upward slow leakage through CO_2 injection well	1,000 to 5,000	0.000001 to 0.00001	1	0.001 to 0.049
Upward rapid leakage through deep oil & gas wells	1,000 to 5,000	0.000001 to 0.001	0	0
Upward slow leakage through deep oil & gas wells	1,000 to 5,000	0.000001 to 0.001	0	0
Leaks due to undocumented deep wells, high rate	1,000 to 5,000	0.00001 to 0.001	1 to 2	0.01 to 0.99
Leaks due to undocumented deep wells, low rate	1,000 to 5,000	0.00001 to 0.001	1 to 2	0.01 to 0.99

[1] Pipeline length = 0.5 miles (0.8 kilometers)

[2] Failure frequencies for pipeline ruptures and punctures are calculated as the product of the pipeline length and the failure frequencies obtained from the national database (ruptures: 3.68 x 10^{-5}/(miles-year) [5.92 x 10^{-5}/kilometer-year]; punctures: 0.73 x 10^{-5}/ (miles-year) [1.18 x 10^{-4}/kilometer-year]).

[3] Failure frequencies for leakage scenarios are obtained from the analog database.

A range of input data has been incorporated into the tables to help illustrate how release probabilities respond to uncertainties in data. The upper limits of the input data and release probabilities are based on the information that has been previously used in Sections 4 and 5 of this report. The lower limits are based on the following:

- **A lifetime of 1000 years for leakage from the subsurface, rather than 5000 years.**

- **Number of existing wells per category and per site that could fail is limited to one.** This assumes that, for example, should many existing deep abandoned wells be present at a site that could possibly fail, all but one of those wells are assumed to have a zero probability of failure, perhaps based on monitoring and mitigation of each of those wells.

- **Failure frequencies are uniformly decreased for wells.** It is assumed that failure frequencies for wells are at the lower end of data found in the same literature cited previously in Sections 4 and 5.

Table 6-11 indicates that the range of data used in the sensitivity analysis produces large ranges in failure predictions. In general, the predicted probabilities and rates of failure are dramatically less when the lower end of the range of data is used. These changes are particularly significant for calculated probabilities of at least one failure. While probabilities of lifetime releases also drop, those probabilities are very small regardless of the data used to generate the failure estimates. The table shows that there are also significant differences between sites. Probabilities of pipeline failures are smaller at sites with shorter pipelines (for example, Mattoon) and larger at sites with long pipelines (for example, Odessa). Also, probabilities of releases from existing deep wells are higher at sites with the more deep wells (such as Jewett), and lower at sites with fewer deep wells (such as Tuscola).

6.3 Uncertainties in Risk Assessment Results

The following summarizes the major uncertainties that are contained in this risk assessment:

1. **Uncertainties associated with using the analog database.** There are intrinsic uncertainties associated with the analog database because the sites in the database are all different, in one way or another, from the candidate FutureGen sites, and because additional uncertainties exist due to the limited data that are available for this analysis. Even so, this approach is a reasonable one to use for this risk assessment given the uncertainties that also exist in computer modeling of target reservoirs and data available to simulate the release scenarios.

2. **Uncertainties in release rates and their probabilities.** Very little information is available regarding release rates from geological sites that sequester CO_2, given that carbon sequestration is still in its infancy, and time intervals for leakage to occur into the biosphere may be large.

3. **This risk analysis is based on affected populations remaining the same throughout the 5,000-year period of analysis**, and does not consider that population densities and patterns might change over time.

4. **The design of the FutureGen *Power Plant*, pipelines, and sequestration methodology is still evolving**. The information used in this risk analysis has largely come from the EIVs prepared by the FutureGen Alliance (December 1, 2006). There are small differences in different parts of the EIVs. Not all of these differences have been reconciled in this analysis.

5. **Exposure and toxicity parameters have been conservatively chosen**. To reduce the possibility that risks are underestimated, a health protective approach has been used to estimate potential exposures and to select the concentrations for potential health effects. This was done to ensure that predicted risks are conservatively high.

6. **Peer reviewed health effect levels were not available for CO_2 for all exposure durations.** For H_2S, peer reviewed health effect levels were available for all exposure durations evaluated.

However, this was not the case for CO_2. Some of the health effect levels for CO_2 used in this report were based on observational data that did not incorporate safety factors.

7. **The approach to ecological and other environmental risks is at the screening level.** Due to the highly uncertain nature of potential exposures to biota, such as the presence or absence of critical habitats, it was possible to complete only a qualitative screening of ecological risks.

6.4 Data Gaps and Recommendations to Address Issues of Concern

Further refinements of the risk assessment could be provided if the information to address the uncertainties identified in the preceding section were available. The data needed and the types of data analyses that could be performed using those data are described below.

1. Additional data on existing wells in the vicinity of the injection sites could be used to improve determination of release characteristics and probabilities. Particularly important are depths of wells, quality of well seals, and general well condition.

2. Experimental determination of the behavior of trace gases, in particular H_2S, is needed for mixtures with CO_2, when new phases, in particular solid phases are forming and subliming. Such information would allow more accurate representation of pipeline rupture and puncture source behavior.

3. Further experimental and modeling work is needed on the behavior of the supercritical fluid within the pipeline immediately following rupture and puncture. Key questions are: To what extent may the release be slowed by formation of liquid and solid phases in the pipe? There is some indication that pressure waves may occur. If so, will these waves interfere with pipeline control equipment?

4. A more detailed accounting of the minor components in the captured gas is needed. If available, estimates of potential effects from release of these substances could be conducted using approaches and models similar to those used for CO_2 and H_2S. Some of these trace components may be relatively harmless at low concentrations (e.g., alkanes), others may cause risk (e.g., SO_x, NO_x, NH_3)

5. Groundwater quality data could be compiled for both the analog database and the four candidate sites. The site-specific information could be used to predict the resulting CO_2 and H_2S concentrations in the groundwater and the potential effects on pH, alkalinity, sulfate, and TDS from the gradual release of sequestered gas into the aquifers.

6. There are many established techniques for minimizing the chances and consequences of a pipeline rupture or puncture. These include the use of SCADA computer monitoring systems, thicker pipe walls, armored pipe guards, the establishment of setback areas, construction of protective barriers near population centers, underground vaulting of pipeline control valves, and the use of on-line inspection vehicles. There are also design and operating options that can be implemented to minimize the effects of pipeline ruptures or punctures. These options would include routing of pipelines away from and downwind rather than upwind of populated areas, and burying the pipes deeper than 3 feet beneath the surface to reduce the chance of accidental puncture. The CO_2 pipelines are expected to have safety shut-off valves spaced at about 5-mile (8-kilometer) intervals to reduce the quantity of CO_2 that could be released in the event of a pipeline rupture or puncture. The pipeline-release modeling results have shown that the affected area associated with a release event is reduced approximately linearly with a reduction in the

distance between emergency shut-off valves. Such valves could be sited at shorter intervals (e.g., 3 or 1 mile [4.8 to 1.6 kilometers]) near populated areas to reduce the volume of potential releases. Strategically placed automatic release valves could also be used to minimize the amount of gas discharged into more populated areas. Perhaps these valves could be designed to maximize the production of dry ice snow. This would reduce the peak atmospheric concentrations of pipeline gases; the much slower sublimation process would control a portion of the actual release.

7. Further evaluation of potential ecological effects could be conducted using specific information on the location of present habitats of endangered species and other biota of concern. Additional information on the surface waterbodies such as water depth, water quality characteristics (e.g., alkalinity, pH, and TDS), and areal extent and type of wetlands would enable some quantitative analyses to be performed on the effects of gas releases into surface water.

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APPENDIX A

Table A-1 Air Criteria for FutureGen

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
ATSDR	MRL - inh. Acute	Acute		CO_2			
ATSDR	MRL - inh.Int	Intermediate		CO_2			
Cal EPA	Chronic REL	Chronic		CO_2			
Cal EPA	Acute REL	Acute		CO_2			
US DOE - ESH	TEEL-0	Acute	15 min	CO_2	7,500	5,000	
US DOE - ESH	TEEL-1	Acute	15 min	CO_2	50,000	30,000	
US DOE - ESH	TEEL-2	Acute	15 min	CO_2	50,000	30,000	
US DOE - ESH	TEEL-3	Acute	15 min	CO_2	75,000	40,000	life-threatening health effects
US EPA	AEGL 1	Acute	10 min	CO_2			
US EPA	AEGL 1	Acute	30 min	CO_2			
US EPA	AEGL 1	Acute	60 min	CO_2			
US EPA	AEGL 1	Acute	4 hr	CO_2			
US EPA	AEGL 1	Acute	8 hr	CO_2			
US EPA	AEGL 2	Acute	10 min	CO_2			
US EPA	AEGL 2	Acute	30 min	CO_2			
US EPA	AEGL 2	Acute	60 min	CO_2			
US EPA	AEGL 2	Acute	4 hr	CO_2			
US EPA	AEGL 2	Acute	8 hr	CO_2			
US EPA	AEGL 3	Acute	10 min	CO_2			
US EPA	AEGL 3	Acute	30 min	CO_2			
US EPA	AEGL 3	Acute	60 min	CO_2			
US EPA	AEGL 3	Acute	4 hr	CO_2			
US EPA	AEGL 3	Acute	8 hr	CO_2			
AIHA	ERPG-1	Acute		CO_2			
AIHA	ERPG-2	Acute		CO_2			
AIHA	ERPG-3	Acute		CO_2			
USEPA (2000)	Maximum Exposure Limit	Indefinite	Indefinite	CO_2		5,000	0.5 percent; for health males under exercising conditions
USEPA (2000)	Maximum Exposure Limit	Indefinite	Indefinite	CO_2		10,000	1 percent; for health males under exercising conditions

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
USEPA (2000)	Maximum Exposure Limit		480 minutes	CO_2		15,000	1.5 percent; for health males under exercising conditions
USEPA (2000)	Maximum Exposure Limit		60 minutes	CO_2		20,000	2 percent; for health males under exercising conditions
USEPA (2000)	Maximum Exposure Limit	Acute/Short term	20 minutes	CO_2		30,000	3 percent; for health males under exercising conditions
USEPA (2000)	Maximum Exposure Limit	Acute/Short term	10 minutes	CO_2		40,000	4 percent; for health males under exercising conditions
USEPA (2000)	Maximum Exposure Limit	Acute/Short term	7 minutes	CO_2		50,000	5 percent; for health males under exercising conditions
USEPA (2000)	Maximum Exposure Limit	Acute/Short term	5 minutes	CO_2		60,000	6 percent; for health males under exercising conditions
USEPA (2000)	Maximum Exposure Limit		Less than 3 minutes	CO_2		70,000	7 percent; for health males under exercising conditions
USEPA (2000)	Unconsciousness	Acute	Few minutes	CO_2		70,000 to 100,000	7 to 10 percent
USEPA (2000)	Unconsciousness, etc.	Acute	1 to several minutes	CO_2		>100,000 to 150,000	>10 to 15 percent; dizziness, drowsiness, severe muscle twitching, unconsciousness
USEPA (2000)	Death	Acute	< 1 minute	CO_2		170,000 to 300,000	17 to 30 percent; loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death
USEPA (2000)	Headache, plus respiratory symptoms	Acute	1.5 to 1 hour	CO_2		70,000 to 100,000	Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing
USEPA (2000)	Headache, dyspnea	Acute	< 16 minutes	CO_2		60,000	Hearing and visual disturbances
USEPA (2000)	Hearing and visual disturbances	Acute	1 to 2 minutes	CO_2		60,000	Headache, dyspnea
USEPA (2000)	Tremors	Acute	Several hours	CO_2		60,000	Tremors
USEPA (2000)	Headache, dizziness, etc	Acute	Within a few minutes	CO_2		40,000 to 50,000	Headache, dizziness, increased blood pressure, uncomfortable dyspnea; possible respiratory stimulant

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
USEPA (2000)	Mild headache, sweating, etc	Acute; respiratory stimulant	1 hour	CO_2		30,000	Mild headache, sweating, and dyspnea at rest; respiratory stimulant (i.e., increasing pulmonary ventilation, cardiac output, etc.)
USEPA (2000)	Headache, dyspnea upon mild exertion	Acute; possible respiratory stimulant	Several hours	CO_2		20,000	Headache, dyspnea upon mild exertion
Saripalli et al. 2003	Low	Chronic-Human	Human	CO_2	18,296	10,000	human, discomfort
Saripalli et al. 2003	Moderate	Chronic-Human	Human	CO_2	91,478	50,000	human, injury
Saripalli et al. 2003	Severe	Chronic-Human	Human	CO_2	182,956	100,000	human, lethal
Saripalli et al. 2003	Normal Air	Normal		CO_2		280	air
NIOSH	IDLH	Acute	30 min	CO_2	72,000	40,000	
NIOSH	NIOSH REL TWA	Chronic	10 hr	CO_2	9,000	5,000	Headache, dizziness, restlessness, paresthesia; dyspnea (breathing difficulty); sweating, malaise (vague feeling of discomfort); increased heart rate, cardiac output, blood pressure; coma; asphyxia; convulsions; frostbite (liquid, dry ice)
NIOSH	NIOSH REL ST	Acute	15 min	CO_2	54,000	30,000	
NIOSH	NIOSH IDLH	Immediate	Maximum 30 minutes	CO_2	73,200	40,000	Immediately dangerous to life or health; AIHA [1971] reported that 100,000 ppm of CO2 is the atmospheric concentration immediately dangerous to life. In addition, Hunter [1975] noted that exposure to 100,000 ppm for only a few minutes can cause loss of consciousness.
OSHA	OSHA PEL TWA	Chronic	8 hr	CO_2	9,000	5,000	
ACGIH	TWA	Chronic	8 hr	CO_2	9,000	5,000	Asphyxiation

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
ACGIH	STEL	Acute		CO_2	54,000	30,000	Asphyxiation
Health Canada	ALTER	Chronic	Long-term	CO_2	6,300	3,500	The lowest concentration at which adverse health effects have been observed in humans is 12 600 mg/m^3 (7000 ppm), at which level increased blood acidity has been observed after several weeks of continuous exposure.
Health Canada	ASTER	Acute	Short-term	CO_2			
Biota				CO_2			
Heart of Brazos EIV	Threshold, animals			CO_2		>1,000	All animals, respiratory stimulation
Heart of Brazos EIV	Threshold, animals			CO_2		>50,000	All animals, respiratory poisoning
Heart of Brazos EIV	Threshold, fungi			CO_2		>10,000	Abnormal growth and reduced reporductive fitness
Heart of Brazos EIV	Threshold, plants			CO_2		>700	Variable increases and ecreases in plant respiration
Heart of Brazos EIV	Threshold, plants			CO_2		>380	Increased growth, biomass, reduced carbon to nitrogen ratios in biomass
Heart of Brazos EIV	Threshold, insects			CO_2		>10,000	Regulation of spiracle aperture
Heart of Brazos EIV	Behavioral, insects			CO_2		10 to 500	Olfactory sensation/activation (mosquitoes, ticks, fire bugs, tsetse flies); changes in CO2 result in signaling of responses including locomotion, social location, prey location, and flight or searching behavior.
Heart of Brazos EIV	Behavioral, insects			CO_2		1,000	Olfactory sensation/locomotion (mosquitoes, ticks, fire bugs, tsetse flies)
Heart of Brazos EIV	Behavioral, insects			CO_2		5,000	Olfactory sensation (ants, bees, termites)

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
Heart of Brazos EIV	Behavioral, insects			CO_2		5,000	Olfactory sensation (beetles, nematodes)
Heart of Brazos EIV	Behavioral, insects			CO_2		0.5 to 300	Olfactory sensation (moths, butterflies)
ATSDR	MRL - inh. Acute	Acute		CO			
ATSDR	MRL - inh.Int	Intermediate		CO			
Cal EPA	Chronic REL	Chronic		CO			
Cal EPA	Acute REL	Acute	1 hr	CO	23	19.75	mild, cardiovascular system effects; California Ambient Air Quality Standard
US DOE - ESH	TEEL-0	Acute	15 min	CO	58	50	
US DOE - ESH	TEEL-1	Acute	15 min	CO	96.28	83	ERPG-1,
US DOE - ESH	TEEL-2	Acute	15 min	CO	96.28	83	ERPG-2, interim AEGL-2
US DOE - ESH	TEEL-3	Acute	15 min	CO	382.8	330	ERPG-3, interim AEGL-3
US EPA	AEGL 1	Acute	10 min	CO		NR	NR = Not recommended due to insufficient data
US EPA	AEGL 1	Acute	30 min	CO		NR	
US EPA	AEGL 1	Acute	60 min	CO		NR	
US EPA	AEGL 1	Acute	4 hr	CO		NR	
US EPA	AEGL 1	Acute	8 hr	CO		NR	
US EPA	AEGL 2	Acute	10 min	CO	487.2	420	Interim AEGL (6/11/01)
US EPA	AEGL 2	Acute	30 min	CO	174	150	Interim AEGL (6/11/01)
US EPA	AEGL 2	Acute	60 min	CO	96.28	83	Interim AEGL (6/11/01)
US EPA	AEGL 2	Acute	4 hr	CO	38.28	33	Interim AEGL (6/11/01)
US EPA	AEGL 2	Acute	8 hr	CO	31.32	27	Interim AEGL (6/11/01)
US EPA	AEGL 3	Acute	10 min	CO	1972	1,700	Interim AEGL (6/11/01)
US EPA	AEGL 3	Acute	30 min	CO	696	600	Interim AEGL (6/11/01)
US EPA	AEGL 3	Acute	60 min	CO	382.8	330	Interim AEGL (6/11/01)
US EPA	AEGL 3	Acute	4 hr	CO	174	150	Interim AEGL (6/11/01)
US EPA	AEGL 3	Acute	8 hr	CO	150.8	130	Interim AEGL (6/11/01)
AIHA	ERPG-1	Acute	1 hour	CO		200	

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
AIHA	ERPG-2	Acute	1 hour	CO		350	
AIHA	ERPG-3	Acute	1 hour	CO		500	
USEPA (2000)				CO			
Saripalli et al. 2003				CO			
NIOSH	NIOSH REL TWA	Chronic	10 hr	CO	40	35	Headache, tachypnea, nausea, lassitude (weakness, exhaustion), dizziness, confusion, hallucinations; cyanosis; depressed S-T segment of electrocardiogram, angina, syncope
NIOSH	NIOSH REL ST	Acute	15 min	CO			
NIOSH	NIOSH REL C	Acute	Ceiling	CO	229	200	
NIOSH	NIOSH IDLH	Immediate	Maximum 30 minutes	CO	1,392	1200	Immediately dangerous to life or health
OSHA	OSHA PEL TWA	Chronic	8 hr	CO	55	50	
ACGIH	TWA	Chronic	8 hr	CO	29	25	BEI; anoxia, CVS, CNS, reproductive
ACGIH	STEL	Acute		CO			
Health Canada	ALTER	Chronic		CO			
Health Canada	ASTER	Acute	1 hr average	CO	<= 29.11	<= 25	Experimental results suggest that sensitive individuals can tolerate increases in carboxyhaemoglobin levels of up to 1.5 COHb%: the guidelines ensure that increases remain below this limit. Exposure leading to carboxyhaemoglobin concentrations of approximately 2.5% to 10% has been shown to cause adverse effects on the cardio-vascular system, to decrease exercise capacity and to impair psychomotor performance

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
Health Canada	ASTER	Chronic	8 hr average	CO	<= 12.81	<= 11	
USEPA	NAAQS	Primary	8 hr average	CO	10	9	Not to be exceeded more than once per year
USEPA	NAAQS	Acute/Primary	1 hr average	CO	40	35	Not to be exceeded more than once per year
ATSDR	MRL - inh. Acute	Acute	1-14 days	H_2S	0.28	0.2	Respiratory effect
ATSDR	MRL - inh.Int	Intermediate	>14-365 days	H_2S	0.03	0.02	Respiratory effect
Cal EPA	Chronic REL	Chronic	365 days or longer	H_2S	0.01	0.0071	respiratory system (nasal histological changes)
Cal EPA	Acute REL	Acute	1 hr	H_2S	0.042	0.0296	
US DOE - ESH	TEEL-0	Acute	15 min	H_2S	0.72	0.51	
US DOE - ESH	TEEL-1	Acute	15 min	H_2S	0.72	0.51	ERPG-1, interim AEGL-1
US DOE - ESH	TEEL-2	Acute	15 min	H_2S	38	27	ERPG-2, interim AEGL-2
US DOE - ESH	TEEL-3	Acute	15 min	H_2S	71	50	ERPG-3, interim AEGL-3
US EPA	AEGL 1	Acute	10 min	H_2S	1.065	0.75	Interim AEGL (9/10/02); level of odor awareness = 0.01 ppm
US EPA	AEGL 1	Acute	30 min	H_2S	0.852	0.6	Interim AEGL (9/10/02)
US EPA	AEGL 1	Acute	60 min	H_2S	0.7242	0.51	Interim AEGL (9/10/02)
US EPA	AEGL 1	Acute	4 hr	H_2S	0.5112	0.36	Interim AEGL (9/10/02)
US EPA	AEGL 1	Acute	8 hr	H_2S	0.4686	0.33	Interim AEGL (9/10/02)
US EPA	AEGL 2	Acute	10 min	H_2S	58.22	41	Interim AEGL (9/10/02)
US EPA	AEGL 2	Acute	30 min	H_2S	45.44	32	Interim AEGL (9/10/02)
US EPA	AEGL 2	Acute	60 min	H_2S	38.34	27	Interim AEGL (9/10/02)
US EPA	AEGL 2	Acute	4 hr	H_2S	28.4	20	Interim AEGL (9/10/02)
US EPA	AEGL 2	Acute	8 hr	H_2S	24.14	17	Interim AEGL (9/10/02)
US EPA	AEGL 3	Acute	10 min	H_2S	107.92	76	Interim AEGL (9/10/02)
US EPA	AEGL 3	Acute	30 min	H_2S	83.78	59	Interim AEGL (9/10/02)
US EPA	AEGL 3	Acute	60 min	H_2S	71	50	Interim AEGL (9/10/02)
US EPA	AEGL 3	Acute	4 hr	H_2S	52.54	37	Interim AEGL (9/10/02)
US EPA	AEGL 3	Acute	8 hr	H_2S	44.02	31	Interim AEGL (9/10/02)
AIHA	ERPG-1	Acute		H_2S			

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
AIHA	ERPG-2	Acute		H_2S			
AIHA	ERPG-3	Acute		H_2S			
USEPA (2000)				H_2S			
Saripalli et al. 2003				H_2S			
NIOSH	IDLH	Acute	30 min	H_2S	142	100	100 ppm, see 7783064
NIOSH	NIOSH REL TWA	Chronic		H_2S			Irritation eyes, respiratory system; apnea, coma, convulsions; conjunctivitis, eye pain, lacrimation (discharge of tears), photophobia (abnormal visual intolerance to light), corneal vesiculation; dizziness, headache, lassitude (weakness, exhaustion), irritability, insomnia; gastrointestinal disturbance; liquid frostbite
NIOSH	NIOSH REL ST	Acute		H_2S			
NIOSH	NIOSH REL C	Ceiling	10 minutes	H_2S	15	10	
NIOSH	NIOSH IDLH	Immediate	Maximum 30 minutes	H_2S	142	100	Immediately dangerous to life or health
OSHA	OSHA PEL TWA	Chronic		H_2S			
OSHA	OSHA PEL C			H_2S	28	20	
OSHA	OSHA PEL 10 min maximum peak		10 min maximum	H2S	H_2S	50	
ACGIH	TWA	Chronic	8 hr	H_2S	14	10	
ACGIH	STEL	Acute		H_2S	21	15	
Health Canada	Long term	Chronic		H_2S			
Health Canada	ASTER	Acute	1 hr average	H_2S			
Health Canada	ASTER	Chronic	8 hr average	H_2S			
US EPA IRIS	RfC	Chronic		H_2S	0.002	0.0014	Nasal lesions of the olfactory mucosa (7/28/2003)
LEL	10% Explosive Limit			H_2S	5,680	4,000	
ATSDR	MRL - inh. Acute	Acute	1-14 days	SO_2	0.027	0.01	Respiratory effect

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
ATSDR	MRL - inh.Int	Intermediate		SO_2			
Cal EPA	Chronic REL	Chronic		SO_2			
Cal EPA	Acute REL	Acute	1 hr	SO_2	0.66	0.248	mild, respiratory irritation
US DOE - ESH	TEEL-0	Acute	15 min	SO_2	0.52	0.20	
US DOE - ESH	TEEL-1	Acute	15 min	SO_2	0.52	0.20	AEGL-1, ERPG-1
US DOE - ESH	TEEL-2	Acute	15 min	SO_2	2	0.75	AEGL-2, ERPG-2
US DOE - ESH	TEEL-3	Acute	15 min	SO_2	72	27	AEGL-3, ERPG-3
US EPA	AEGL 1	Acute	10 min	SO_2	0.53	0.2	Interim AEGL (10/25/04)
US EPA	AEGL 1	Acute	30 min	SO_2	0.53	0.2	Interim AEGL (10/25/04)
US EPA	AEGL 1	Acute	60 min	SO_2	0.53	0.2	Interim AEGL (10/25/04)
US EPA	AEGL 1	Acute	4 hr	SO_2	0.53	0.2	Interim AEGL (10/25/04)
US EPA	AEGL 1	Acute	8 hr	SO_2	0.53	0.2	Interim AEGL (10/25/04)
US EPA	AEGL 2	Acute	10 min	SO_2	2.00	0.75	Interim AEGL (10/25/04)
US EPA	AEGL 2	Acute	30 min	SO_2	2.00	0.75	Interim AEGL (10/25/04)
US EPA	AEGL 2	Acute	60 min	SO_2	2.00	0.75	Interim AEGL (10/25/04)
US EPA	AEGL 2	Acute	4 hr	SO_2	2.00	0.75	Interim AEGL (10/25/04)
US EPA	AEGL 2	Acute	8 hr	SO_2	2.00	0.75	Interim AEGL (10/25/04)
US EPA	AEGL 3	Acute	10 min	SO_2	111.7	42	Interim AEGL (10/25/04)
US EPA	AEGL 3	Acute	30 min	SO_2	85.1	32	Interim AEGL (10/25/04)
US EPA	AEGL 3	Acute	60 min	SO_2	71.8	27	Interim AEGL (10/25/04)
US EPA	AEGL 3	Acute	4 hr	SO_2	50.5	19	Interim AEGL (10/25/04)
US EPA	AEGL 3	Acute	8 hr	SO_2	42.6	16	Interim AEGL (10/25/04)
AIHA	ERPG-1	Acute	1 hour	SO_2		0.3	
AIHA	ERPG-2	Acute	1 hour	SO_2		3	
AIHA	ERPG-3	Acute	1 hour	SO_2		15	
USEPA (2000)				SO_2			
Saripalli et al. 2003				SO_2			
NIOSH	NIOSH IDLH	Immediate	30 minutes maximum	SO_2	266.06	100	Immediately dangerous to life and health

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
NIOSH	NIOSH REL TWA	Chronic	10 hr	SO_2	5	2	Irritation eyes, nose, throat; rhinorrhea (discharge of thin mucus); choking, cough; reflex bronchoconstriction; liquid frostbite
NIOSH	NIOSH REL ST	Acute	15 min	SO_2	13	5	
NIOSH	NIOSH REL C			SO_2			
OSHA	OSHA PEL TWA	Chronic	8 hr	SO_2	13	5	
OSHA	OSHA PEL C			SO_2			
OSHA	OSHA PEL 10 min maximum peak		10 min maximum	SO_2			
ACGIH	TWA	Chronic	8 hr	SO_2	5	2	Irritation
ACGIH	STEL	Acute		SO_2	13	5	Irritation
Health Canada	ASTER	Acute	5 min average	SO_2	£ 1	<0.038	ASTER (acceptable short-term exposure range)
Health Canada	ALTER	Chronic	8 hr average	SO_2	£ 0.05	<0.019	Increased prevalence of acute and chronic respiratory symptoms and impaired pulmonary function
US EPA IRIS	RfC	Chronic		SO_2			
LEL	10% Explosive Limit			SO_2			
ATSDR	MRL - inh. Acute	Acute		SO_3			
ATSDR	MRL - inh.Int	Intermediate		SO_3			
Cal EPA	Chronic REL	Chronic		SO_3			
Cal EPA	Acute REL	Acute		SO_3			
US DOE - ESH	TEEL-0	Acute	15 min	SO_3	0.6	0.18	
US DOE - ESH	TEEL-1	Acute	15 min	SO_3	2	0.60	ERPG-1
US DOE - ESH	TEEL-2	Acute	15 min	SO_3	10	2.98	ERPG-2
US DOE - ESH	TEEL-3	Acute	15 min	SO_3	30	8.93	ERPG-3
US EPA	AEGL 1	Acute	10 min	SO_3	0.2	0.06	Proposed AEGL
US EPA	AEGL 1	Acute	30 min	SO_3	0.2	0.06	Proposed AEGL
US EPA	AEGL 1	Acute	60 min	SO_3	0.2	0.06	Proposed AEGL
US EPA	AEGL 1	Acute	4 hr	SO_3	0.2	0.06	Proposed AEGL

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
US EPA	AEGL 1	Acute	8 hr	SO_3	0.2	0.06	Proposed AEGL
US EPA	AEGL 2	Acute	10 min	SO_3	8.7	2.6	Proposed AEGL
US EPA	AEGL 2	Acute	30 min	SO_3	8.7	2.6	Proposed AEGL
US EPA	AEGL 2	Acute	60 min	SO_3	8.7	2.6	Proposed AEGL
US EPA	AEGL 2	Acute	4 hr	SO_3	8.7	2.6	Proposed AEGL
US EPA	AEGL 2	Acute	8 hr	SO_3	8.7	2.6	Proposed AEGL
US EPA	AEGL 3	Acute	10 min	SO_3	270	80.3	Proposed AEGL
US EPA	AEGL 3	Acute	30 min	SO_3	200	59.5	Proposed AEGL
US EPA	AEGL 3	Acute	60 min	SO_3	160	47.6	Proposed AEGL
US EPA	AEGL 3	Acute	4 hr	SO_3	110	32.7	Proposed AEGL
US EPA	AEGL 3	Acute	8 hr	SO_3	93	27.7	Proposed AEGL
AIHA	ERPG-1	Acute	1 hour	SO_3	2	0.595	oleum, sulfur trioxide and sulfuric acid
AIHA	ERPG-2	Acute	1 hour	SO_3	10	2.975	oleum, sulfur trioxide and sulfuric acid
AIHA	ERPG-3	Acute	1 hour	SO_3	30	8.925	oleum, sulfur trioxide and sulfuric acid
USEPA (2000)				SO_3			
Saripalli et al. 2003				SO_3			
NIOSH	IDLH	Acute	30 min	SO_3			
NIOSH	NIOSH REL TWA	Chronic	10 hr	SO_3			
NIOSH	NIOSH REL ST	Acute	15 min	SO_3			
NIOSH	NIOSH REL C			SO_3			
OSHA	OSHA PEL TWA	Chronic	8 hr	SO_3			
OSHA	OSHA PEL C			SO_3			
OSHA	OSHA PEL 10 min maximum peak		10 min maximum	SO_3			
ACGIH	TWA	Chronic	8 hr	SO_3			
ACGIH	STEL	Acute		SO_3			
Health Canada	Long term	Chronic		SO_3			
Health Canada	ALTER	Chronic		SO_3			
Health Canada	ASTER	Acute	1 hr average	SO_3			

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
Health Canada	ASTER	Acute	5 min average	SO_3			
Health Canada	ASTER	Chronic	8 hr average	SO_3			
US EPA IRIS	RfC	Chronic		SO_3			
LEL	10% Explosive Limit						
USEPA	NAAQS	Primary	Annual (Arith Mean)	Sulfur oxides		0.03	
USEPA	NAAQS	Primary	24-hour	Sulfur oxides		0.14	Not to be exceeded more than once per year
USEPA	NAAQS	Acute/Primary	3-hour	Sulfur oxides		-	
USEPA	NAAQS	Acute/Secondary	3-hour	Sulfur oxides	1.3	0.5	Not to be exceeded more than once per year
ATSDR	MRL - inh. Acute	Acute		CH_4			
ATSDR	MRL - inh.Int	Intermediate		CH_4			
Cal EPA	Chronic REL	Chronic		CH_4			
Cal EPA	Acute REL	Acute		CH_4			
US DOE - ESH	TEEL-0	Acute	15 min	CH_4	667	1,000	TLV-TWA for aliphatic hydrocarbon gas.
US DOE - ESH	TEEL-1	Acute	15 min	CH_4	1,334	2,000	TLV-TWA for aliphatic hydrocarbon gas.
US DOE - ESH	TEEL-2	Acute	15 min	CH_4	3,334	5,000	TLV-TWA for aliphatic hydrocarbon gas; 10% LEL <= TEEL < 50% LEL.
US DOE - ESH	TEEL-3	Acute	15 min	CH_4	16,670	25,000	TLV-TWA for aliphatic hydrocarbon gas; 50% LEL <= TEEL < 100% LEL.
US EPA	AEGL 1	Acute	10 min	CH_4			
US EPA	AEGL 1	Acute	30 min	CH_4			
US EPA	AEGL 1	Acute	60 min	CH_4			
US EPA	AEGL 1	Acute	4 hr	CH_4			
US EPA	AEGL 1	Acute	8 hr	CH_4			
US EPA	AEGL 2	Acute	10 min	CH_4			
US EPA	AEGL 2	Acute	30 min	CH_4			
US EPA	AEGL 2	Acute	60 min	CH_4			
US EPA	AEGL 2	Acute	4 hr	CH_4			

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
US EPA	AEGL 2	Acute	8 hr	CH_4			
US EPA	AEGL 3	Acute	10 min	CH_4			
US EPA	AEGL 3	Acute	30 min	CH_4			
US EPA	AEGL 3	Acute	60 min	CH_4			
US EPA	AEGL 3	Acute	4 hr	CH_4			
US EPA	AEGL 3	Acute	8 hr	CH_4			
AIHA	ERPG-1	Acute		CH_4			
AIHA	ERPG-2	Acute		CH_4			
AIHA	ERPG-3	Acute		CH_4			
USEPA (2000)				CH_4			
Saripalli et al. 2003				CH_4			
NIOSH	IDLH	Acute	30 min	CH_4			
NIOSH	NIOSH REL TWA	Chronic	10 hr	CH_4			
NIOSH	NIOSH REL ST	Acute	15 min	CH_4			
NIOSH	NIOSH REL C			CH_4			
OSHA	OSHA PEL TWA	Chronic	8 hr	CH_4			
OSHA	OSHA PEL C			CH_4			
OSHA	OSHA PEL 10 min maximum peak		10 min maximum	CH_4			
ACGIH	TWA	Chronic	8 hr	CH_4	667	1000	(as aliphatic hydrocarbon [alkane, C1-Cr] gases); CNS, depression, cardiac sensitization
ACGIH	STEL	Acute		CH_4			
Health Canada	Long term	Chronic		CH_4			
Health Canada	ALTER	Chronic		CH_4			
Health Canada	ASTER	Acute	1 hr average	CH_4			
Health Canada	ASTER	Acute	5 min average	CH_4			
Health Canada	ASTER	Chronic	8 hr average	CH_4			
US EPA IRIS	RfC	Chronic		CH_4			
LEL	10% Explosive Limit			CH_4			

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
ATSDR	MRL - inh. Acute	Acute		Hg			
ATSDR	MRL - inh.Int	Chronic	365 days or more	Hg	0.0002		Neurological effects
Cal EPA	Chronic REL	Chronic		Hg	0.00009		mercury and mercury compounds (inorganic); nervous system (hand tremor, memory disturbances, neurobehavioral and autonomic dysfunction
Cal EPA	Acute REL	Acute	1 hour	Hg	0.0018		inorganic; reproductive/developmental, severe
US DOE - ESH	TEEL-0	Acute	15 min	Mercurous chloride	0.03		
US DOE - ESH	TEEL-1	Acute	15 min	Mercurous chloride	0.075		
US DOE - ESH	TEEL-2	Acute	15 min	Mercurous chloride	0.1		
US DOE - ESH	TEEL-3	Acute	15 min	Mercurous chloride	10		
US DOE - ESH	TEEL-0	Acute	15 min	Mercury vapor	0.025		
US DOE - ESH	TEEL-1	Acute	15 min	Mercury vapor	0.1		
US DOE - ESH	TEEL-2	Acute	15 min	Mercury vapor	2.05		ERPG-2
US DOE - ESH	TEEL-3	Acute	15 min	Mercury vapor	4.1		ERPG-3
US EPA	AEGL 1	Acute	10 min	Hg			
US EPA	AEGL 1	Acute	30 min	Hg			
US EPA	AEGL 1	Acute	60 min	Hg			
US EPA	AEGL 1	Acute	4 hr	Hg			
US EPA	AEGL 1	Acute	8 hr	Hg			
US EPA	AEGL 2	Acute	10 min	Hg			
US EPA	AEGL 2	Acute	30 min	Hg			
US EPA	AEGL 2	Acute	60 min	Hg			
US EPA	AEGL 2	Acute	4 hr	Hg			

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
US EPA	AEGL 2	Acute	8 hr	Hg			
US EPA	AEGL 3	Acute	10 min	Hg			
US EPA	AEGL 3	Acute	30 min	Hg			
US EPA	AEGL 3	Acute	60 min	Hg			
US EPA	AEGL 3	Acute	4 hr	Hg			
US EPA	AEGL 3	Acute	8 hr	Hg			
AIHA	ERPG-1	Acute	1 hour	Mercury vapor		NA	
AIHA	ERPG-2	Acute	1 hour	Mercury vapor		0.25	
AIHA	ERPG-3	Acute	1 hour	Mercury vapor		0.5	
USEPA (2000)				Hg			
Saripalli et al. 2003				Hg			
NIOSH	IDLH	Acute	30 min	Mercury compounds (as Hg)	10		not organo alkyls
NIOSH	NIOSH REL TWA	Chronic	10 hr	Mercury compounds (as Hg)	0.05		not organo alkyls; skin [target organs = eyes, skin, respiratory system, CNS, kidneys]
NIOSH	NIOSH REL ST	Acute	15 min	Mercury compounds (as Hg)			not organo alkyls
NIOSH	NIOSH REL C			Mercury compounds (as Hg)	0.1		not organo alkyls; skin [target organs = eyes, skin, respiratory system, CNS, kidneys]
OSHA	OSHA PEL TWA	Chronic	8 hr	Mercury compounds (as Hg)			not organo alkyls
OSHA	OSHA PEL C			Mercury compounds (as Hg)	0.1		not organo alkyls
OSHA	OSHA PEL 10 min maximum peak		10 min maximum	Mercury compounds (as Hg)			not organo alkyls
NIOSH	IDLH	Acute	30 min	(organo) alkyl compounds (as Hg)	2		target organs = eyes, skin, CNS, peripheral nervous system, kidneys

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
NIOSH	NIOSH REL TWA	Chronic	10 hr	(organo) alkyl compounds (as Hg)	0.01		
NIOSH	NIOSH REL ST	Acute	15 min	(organo) alkyl compounds (as Hg)	0.03		skin; [target organs = eyes, skin, CNS, peripheral nervous system, kidneys]
NIOSH	NIOSH REL C			(organo) alkyl compounds (as Hg)			
OSHA	OSHA PEL TWA	Chronic	8 hr	(organo) alkyl compounds (as Hg)	0.01		target organs = eyes, skin, CNS, peripheral nervous system, kidneys
OSHA	OSHA PEL C			(organo) alkyl compounds (as Hg)	0.04		target organs = eyes, skin, CNS, peripheral nervous system, kidneys
OSHA	OSHA PEL 10 min maximum peak		10 min maximum	(organo) alkyl compounds (as Hg)			
ACGIH	TWA	Chronic	8 hr	Hg, Alkyl compounds	0.01		skin; CNS
ACGIH	STEL	Acute		Hg, Alkyl compounds	0.03		skin; CNS
ACGIH	TWA	Chronic	8 hr	Hg, Aryl compounds	0.1		skin, CNS, neuropathy, vision, kidney
ACGIH	STEL	Acute		Hg, Aryl compounds			
ACGIH	TWA	Chronic	8 hr	Hg, elemental and inorganic	0.025		skin, CNS, kidney, reproductive
ACGIH	STEL	Acute		Hg, elemental and inorganic			
Health Canada	Long term	Chronic		Hg			
Health Canada	ALTER	Chronic		Hg			
Health Canada	ASTER	Acute	1 hr average	Hg			
Health Canada	ASTER	Acute	5 min average	Hg			
Health Canada	ASTER	Chronic	8 hr average	Hg			

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
US EPA IRIS	RfC	Chronic		Mercury, elemental	0.0003		Hand tremor, increases in memory disturbance, slight subjective and objective evidence of autonomic dysfunction
LEL	10% Explosive Limit			Hg			
ATSDR	MRL - inh. Acute	Acute		Cyanide			
ATSDR	MRL - inh.Int	Intermediate		Cyanide			
Cal EPA	Chronic REL	Chronic		Cyanide			
Cal EPA	Acute REL	Acute	1 hour	Cyanide, hydrogen	0.34	0.31	CNS effects, severe
US DOE - ESH	TEEL-0	Acute	15 min	Cyanide, hydrogen	2.2	2	Hydrocyanic acid
US DOE - ESH	TEEL-1	Acute	15 min	Cyanide, hydrogen	2.2	2	Hydrocyanic acid
US DOE - ESH	TEEL-2	Acute	15 min	Cyanide, hydrogen	7.8	7.1	ERPG-2; Hydrocyanic acid
US DOE - ESH	TEEL-3	Acute	15 min	Cyanide, hydrogen	16.5	15	ERPG-3; Hydrocyanic acid
US EPA	AEGL 1	Acute	10 min	Cyanide, hydrogen	2.8	2.5	Final (2002) (nondisabling)
US EPA	AEGL 1	Acute	30 min	Cyanide, hydrogen	2.8	2.5	Final (2002) (nondisabling)
US EPA	AEGL 1	Acute	60 min	Cyanide, hydrogen	2.2	2	Final (2002) (nondisabling)
US EPA	AEGL 1	Acute	4 hr	Cyanide, hydrogen	1.4	1.3	Final (2002) (nondisabling)
US EPA	AEGL 1	Acute	8 hr	Cyanide, hydrogen	1.1	1	Final (2002) (nondisabling)
US EPA	AEGL 2	Acute	10 min	Cyanide, hydrogen	18.7	17	Final (2002) (disabling)
US EPA	AEGL 2	Acute	30 min	Cyanide, hydrogen	11	10	Final (2002) (disabling)
US EPA	AEGL 2	Acute	60 min	Cyanide, hydrogen	7.8	7.1	Final (2002) (disabling)
US EPA	AEGL 2	Acute	4 hr	Cyanide, hydrogen	3.9	3.5	Final (2002) (disabling)

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
US EPA	AEGL 3	Acute	10 min	Cyanide, hydrogen	29.7	27	Final (2002) (lethal)
US EPA	AEGL 3	Acute	30 min	Cyanide, hydrogen	23.1	21	Final (2002) (lethal)
US EPA	AEGL 3	Acute	60 min	Cyanide, hydrogen	16.5	15	Final (2002) (lethal)
US EPA	AEGL 3	Acute	4 hr	Cyanide, hydrogen	9.5	8.6	Final (2002) (lethal)
US EPA	AEGL 3	Acute	8 hr	Cyanide, hydrogen	7.3	6.6	Final (2002) (lethal)
AIHA	ERPG-1	Acute	1 hour	Cyanide, hydrogen		NA	
AIHA	ERPG-2	Acute	1 hour	Cyanide, hydrogen		10	
AIHA	ERPG-3	Acute	1 hour	Cyanide, hydrogen		25	
USEPA (2000)				Cyanide			
Saripalli et al. 2003				Cyanide			
NIOSH	IDLH	Acute	30 min	Cyanide, hydrogen	55	50	inhalation; CNS, cardiovascular system, thyroid [asphyxia, lassitude, headache, confusion, nausea, vomiting, increased rate and epth of respiration or respiration slow and gasping;thyroid, blood changes]
NIOSH	NIOSH REL TWA	Chronic	10 hr	Cyanide, hydrogen			
NIOSH	NIOSH REL ST	Acute	15 min	Cyanide, hydrogen	5	4.7	skin; CNS, cardiovascular system, thyroid [asphyxia, lassitude, headache, confusion, nausea, vomiting, increased rate and epth of respiration or respiration slow and gasping;thyroid, blood changes]
NIOSH	NIOSH REL C			Cyanide, hydrogen			

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
OSHA	OSHA PEL TWA	Chronic	8 hr	Cyanide, hydrogen	11	10	skin; CNS, cardiovascular system, thyroid [asphyxia, lassitude, headache, confusion, nausea, vomiting, increased rate and epth of respiration or respiration slow and gasping;thyroid, blood changes]
OSHA	OSHA PEL C			Cyanide, hydrogen			
OSHA	OSHA PEL 10 min maximum peak		10 min maximum	Cyanide, hydrogen			
ACGIH	TWA	Chronic	8 hr	Cyanide			
ACGIH	STEL	Acute		Cyanide			
Health Canada	Long term	Chronic		Cyanide			
Health Canada	ALTER	Chronic		Cyanide			
Health Canada	ASTER	Acute	1 hr average	Cyanide			
Health Canada	ASTER	Acute	5 min average	Cyanide			
Health Canada	ASTER	Chronic	8 hr average	Cyanide			
US EPA IRIS	RfC	Chronic		Cyanide, hydrogen	0.003	0.0027	CNS symptoms and thyroid effects
LEL	10% Explosive Limit			Cyanide		5,600	5.60%
ATSDR	MRL - inh. Acute	Acute		Nitrogen dioxide			
ATSDR	MRL - inh.Int	Chronic	365 days or more	Nitrogen dioxide			
Cal EPA	Chronic REL	Chronic		Nitrogen dioxide			
Cal EPA	Acute REL	Acute	1 hour	Nitrogen dioxide	0.47	0.26	respiratory irritation; mild
US DOE - ESH	TEEL-0	Acute	15 min	Nitrogen dioxide	0.9	0.5	
US DOE - ESH	TEEL-1	Acute	15 min	Nitrogen dioxide	0.9	0.5	ERPG-1, AEGL-1
US DOE - ESH	TEEL-2	Acute	15 min	Nitrogen dioxide	22.5	12.5	ERPG-2, AEGL-2
US DOE - ESH	TEEL-3	Acute	15 min	Nitrogen dioxide	36	20	ERPG-3, AEGL-3

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
US EPA	AEGL 1	Acute	10 min	Nitrogen dioxide	0.9	0.5	Interim (12/13/04)
US EPA	AEGL 1	Acute	30 min	Nitrogen dioxide	0.9	0.5	Interim (12/13/04)
US EPA	AEGL 1	Acute	60 min	Nitrogen dioxide	0.9	0.5	Interim (12/13/04)
US EPA	AEGL 1	Acute	4 hr	Nitrogen dioxide	0.9	0.5	Interim (12/13/04)
US EPA	AEGL 1	Acute	8 hr	Nitrogen dioxide	0.9	0.5	Interim (12/13/04)
US EPA	AEGL 2	Acute	10 min	Nitrogen dioxide	36	20	Interim (12/13/04)
US EPA	AEGL 2	Acute	30 min	Nitrogen dioxide	27	15	Interim (12/13/04)
US EPA	AEGL 2	Acute	60 min	Nitrogen dioxide	21.6	12	Interim (12/13/04)
US EPA	AEGL 2	Acute	4 hr	Nitrogen dioxide	14.76	8.2	Interim (12/13/04)
US EPA	AEGL 2	Acute	8 hr	Nitrogen dioxide	12.06	6.7	Interim (12/13/04)
US EPA	AEGL 3	Acute	10 min	Nitrogen dioxide	61.2	34	Interim (12/13/04)
US EPA	AEGL 3	Acute	30 min	Nitrogen dioxide	45	25	Interim (12/13/04)
US EPA	AEGL 3	Acute	60 min	Nitrogen dioxide	36	20	Interim (12/13/04)
US EPA	AEGL 3	Acute	4 hr	Nitrogen dioxide	25.2	14	Interim (12/13/04)
US EPA	AEGL 3	Acute	8 hr	Nitrogen dioxide	19.8	11	Interim (12/13/04)
AIHA	ERPG-1	Acute	1 hour	Nitrogen dioxide		1	
AIHA	ERPG-2	Acute	1 hour	Nitrogen dioxide		15	
AIHA	ERPG-3	Acute	1 hour	Nitrogen dioxide		30	
USEPA (2000)				Nitrogen dioxide			
Saripalli et al. 2003				Nitrogen dioxide			

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
NIOSH	IDLH	Acute	30 min	Nitrogen dioxide	36	20	Eyes, respiratory system, cardiovascular system; irritation eyes, nose, throat; cough, mucoid frothy sputum, decreased pulmonary function, chronic bronchitis, dyspnea; chest pain; pulmonary edema, cyanosis, tachypnea, tachycardia
NIOSH	NIOSH REL TWA	Chronic	10 hr	Nitrogen dioxide			
NIOSH	NIOSH REL ST	Acute	15 min	Nitrogen dioxide	1.8	1	Eyes, respiratory system, cardiovascular system ; irritation eyes, nose, throat; cough, mucoid frothy sputum, decreased pulmonary function, chronic bronchitis, dyspnea; chest pain; pulmonary edema, cyanosis, tachypnea, tachycardia
NIOSH	NIOSH REL C			Nitrogen dioxide			
OSHA	OSHA PEL TWA	Chronic	8 hr	Nitrogen dioxide			
OSHA	OSHA PEL C			Nitrogen dioxide	9	5	Eyes, respiratory system, cardiovascular system ; irritation eyes, nose, throat; cough, mucoid frothy sputum, decreased pulmonary function, chronic bronchitis, dyspnea; chest pain; pulmonary edema, cyanosis, tachypnea, tachycardia
OSHA	OSHA PEL 10 min maximum peak		10 min maximum	Nitrogen dioxide			
ACGIH	TWA	Chronic	8 hr	Nitrogen dioxide	5.6	3	
ACGIH	STEL	Acute	15 minutes	Nitrogen dioxide	9.4	5	

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
Health Canada	ALTER	Chronic		Nitrogen dioxide	<100	< 0.05	increased prevalence of respiratory illness was observed in adults and children chronically exposed to mean levels of near 200 µg/m^3 (0.10 ppm) nitrogen dioxide.
Health Canada	ASTER	Acute	1 hr average	Nitrogen dioxide	<480	<0.25	The results of clinical studies indicate that both normal and asthmatic subjects can experience detrimental respiratory effects when exposed for brief periods to concentrations of approximately 960 µg/m^3 (0.5 ppm). Applied a safety factor of 2.
Health Canada	ASTER	Acute	5 min average	Nitrogen dioxide			
Health Canada	ASTER	Chronic	8 hr average	Nitrogen dioxide			
US EPA IRIS	RfC	Chronic		Nitrogen dioxide			Not derived because a National Ambient Air Quality Standard (NAAQS) is available
LEL	10% Explosive Limit			Nitrogen dioxide			
USEPA	NAAQS	Primary	Annual (Arith Mean)	Nitrogen dioxide	0.1	0.053 ppm	(100 µg/m^3)
Health Canada	Action Level	Chronic	Annual average	Radon		800 Bq/m^3 (21.6 pCi/L)	Annual average in normal living area. The average worldwide concentration of radium in soil is 25 Bq/kg; this medium constitutes the main source of radon in the global atmosphere. The outdoor concentration range in continental North America is 0.7 to 35 Bq/m^3, with an average concentration of 7.0 Bq/m^3.

Table A-1 Air Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/m^3	Units- ppmv	Notes
US EPA IRIS	Carcinogenicity			Radon			The carcinogen assessment summary for Radon-222 has been withdrawn following further review.
ATSDR	MRL - Acute	Acute	1-14 days	Ionizing radiation		4 mSv	
ATSDR	MRL - Chr	Chronic	365 days or more	Ionizing radiation		1 mSv/year	
NAS (1999)	Action Level	Chronic		Radon		4 pCi/L	The USEPA has set 4 pCi/L as the Action Level, the level at which residents should take steps to reduce radon levels. (NAS) National Academy of Sciences. Health Effects of Exposure to Radon: BEIR VI
USEPA		Lifetime	Lifetime Risk	Radon			Lifetime Risk of Lung Cancer Death (per person) from Radon Exposure in Homes
USEPA		Lifetime	Lifetime Risk	Radon		20 pCi/L	11 out of 100
USEPA		Lifetime	Lifetime Risk	Radon		10 pCi/L	56 out of 1,000
USEPA		Lifetime	Lifetime Risk	Radon		8 pCi/L	45 out of 1,000
USEPA		Lifetime	Lifetime Risk	Radon		4 pCi/L	23 out of 1,000
USEPA		Lifetime	Lifetime Risk	Radon		2 pCi/L	12 out of 1,000
USEPA		Lifetime	Lifetime Risk	Radon		1.25 pCi/L	73 out of 10,000
USEPA		Lifetime	Lifetime Risk	Radon		0.4 pCi/L	23 out of 10,000

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Table A-2 Conversion Factors for Airborne Constituents

Chemical	Units-mg/m^3	Units- ppmv		Notes
CO_2	1	0.54658		
CO_2	1.83	1		
CO	1	0.8588		
CO	1.16	1		
H_2S	1	0.70584		
H_2S	1.42	1		
SO_2	1	0.3755		MW=64.054 used in conversion
SO_2	2.66	1		
SO_3	1	0.2975		MW = 80.86 used in conversion
SO_3	3.36	1		
CH_4	1	1.5		
CH_4	0.6668	1		
Hg	8.2	1		from Cal EPA (2005) chronic REL
Cyanide, hydrogen	1.1	1		from NIOSH (2005)
Cyanide, hydrogen	1	0.91		
Nitrogen dioxide	1.8	1		from NIOSH (2005)
Nitrogen dioxide	1	0.56		

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Table A-3 Water Quality Criteria for FutureGen

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/L	Units- other	Notes
USEPA	Secondary MCL			H_2S		0.029 ug/L	Taste and Odor Threshold (National AWQC). Water-dilution odor threshold calculated from air odor threshold using equilibrium distributions.
USEPA	Freshwater CCC	Chronic		H_2S	0.002		Unassociated H_2S for fish and other aquatic life The degree of hazard exhibited by sulfide to aquatic animal life is dependent on the temperature, pH, and dissolved oxygen. A t lower pH values a greater proportion is in the form of the toxic undissociated H_2S. (USEPA, Red Book [1976]; Gold Book [1986]). On the basis of chronic tests evaluating growth and survival, the safe H_2S level for bluegill (*Lepomis macrochirus*) juveniles and adults was 2 ug/L. (USEPA, Red Book [1976]; Gold Book [1986]).
USEPA	Saltwater CCC	Chronic		H_2S	0.002		Unassociated H_2S for fish and other aquatic life
USEPA	MCLG	Proposed (1999)		Radon	0		Non-enforceable goal
USEPA	MCLG	Proposed (1999)		Radon		300 pCi/L	300 picoCuries per liter
USEPA	AMCL	Proposed (1999)		Radon		4000 pCi/L	Alternative Maximum Contaminant Level
USEPA	Drinking Water Health Advisory			Radon		150 pCi/L	at cancer risk of 1 x 10-6 (one in a million)
USEPA	Secondary MCL			pH	6.5 to 8.5	pH units	Gold Book 1986; USEPA 2006
USEPA	Freshwater CCC	Chronic		pH	6.5 to 9	pH units	Gold Book 1986
USEPA	Saltwater CCC	Chronic		pH	6.5 to 8.5	pH units	Gold Book 1986
USEPA	Human health consumption			pH	5 to 9	pH units	Human health consumption of water and organism
USEPA	Secondary MCL			Sulfate	250		Taste and Odor Threshold (National AWQC)

Table A-3 Water Quality Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/L	Units- other	Notes
USEPA	MCL	Chronic		Cyanide (as free cyanide)	0.2		Nerve damage or thyroid problems
USEPA	MCLG	Chronic		Cyanide (as free cyanide)	0.2		Nerve damage or thyroid problems
ATSDR	MRL - oral Int		Intermediate	Cyanide, sodium	1.825	0.05 mg/kg/day	Reproductive effects
US EPA IRIS	RfD, oral	Chronic		Cyanide, hydrogen	0.73	0.02 mg/kg/day	Weight loss, thyroid effects, and myelin degeneration
USEPA	Freshwater CCC	Chronic		Cyanide		5.2 g (CN)/L	g free cyanide (as CN/L) (1995 Updates: Water Quality Criteria Documents for the Protection of Aquatic Life in Ambient Water, (EPA-820-B-96-001, September 1996). Does not account for uptake via the food chain
USEPA	Freshwater CMC	Acute		Cyanide		22 g (CN)/L	g free cyanide (as CN/L) (1995 Updates: Water Quality Criteria Documents for the Protection of Aquatic Life in Ambient Water, (EPA-820-B-96-001, September 1996). Does not account for uptake via the food chain
	ATSDR	MRL - oral Acute	Acute	Mercuric chloride		0.007 mg/kg/day	Renal
	ATSDR	MRL - oral Int	Intermediate	Mercuric chloride		0.002 mg/kg/day	Renal
US EPA IRIS	RfD, oral	Chronic		Mercuric chloride	0.011	0.0003 mg/kg/day	Autoimmune effects
USEPA	MCL			Mercury (inorganic)	0.002		Final 1987; kidney damage
USEPA	MCLG			Mercury (inorganic)	0.002		Final 1987; kidney damage
USEPA	Health Advisory	10-kg Child	One-day	Mercury (inorganic)	0.002		Final 1987
USEPA	Health Advisory	10-kg Child	Ten-day	Mercury (inorganic)	0.002		Final 1987
USEPA	Health Advisory	Chronic	RfD	Mercury (inorganic)		0.0003 mg/kg/day	Final 1987
USEPA	Health Advisory	Chronic	DWEL	Mercury (inorganic)	0.01		Final 1987
USEPA	Health Advisory	Chronic	Lifetime	Mercury (inorganic)	0.04		Final 1987

Table A-3 Water Quality Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/L	Units- other	Notes
USEPA	Freshwater CCC	Chronic		Mercury	0.00077		dissolved metal concentration (1995 Updates: Water Quality Criteria Documents for the Protection of Aquatic Life in Ambient Water, (EPA-820-B-96-001, September 1996). Does not account for uptake via the food chain
USEPA	Freshwater CMC	Acute		Mercury	0.0014		dissolved metal concentration (1995 Updates: Water Quality Criteria Documents for the Protection of Aquatic Life in Ambient Water, (EPA-820-B-96-001, September 1996). Does not account for uptake via the food chain
	ATSDR	MRL - oral Chr	Chronic	Methylmercury		0.0003 mg/kg/day	Developmental effects
US EPA IRIS	RfD, oral	Chronic		Methylmercury		0.0001 mg/kg/day	Developmental neuorpsychological impairment
USEPA	Freshwater CCC	Chronic		Mercury	0.000012		EPA 440/5-84-026, January 1985; protective of bioaccumulative impacts
USEPA	Fish consumption	Chronic		Methylmercury		0.3 mg/kg (fish tissue)	Based on a total fish consumption rate of 0.0175 kg/day (EPA 823-R-02-001, January 2001)
USEPA	Freshwater CCC	Chronic		Methylmercury	0.00077		dissolved metal concentration (1995 Updates: Water Quality Criteria Documents for the Protection of Aquatic Life in Ambient Water, (EPA-820-B-96-001, September 1996). Does not account for uptake via the food chain
USEPA	Freshwater CMC	Acute		Methylmercury	0.0014		dissolved metal concentration (1995 Updates: Water Quality Criteria Documents for the Protection of Aquatic Life in Ambient Water, (EPA-820-B-96-001, September 1996). Does not account for uptake via the food chain
US EPA IRIS	RfD, oral	Chronic		Nitrogen dioxide			The RfD for nitrogen dioxide has been withdrawn from IRIS as of 09/01/1994 based on the fact that nitrogen dioxide does not exist per se in water, since it reacts instantaneously with water to form nitric and nitrous acids (U.S. EPA, 1993).

Table A-3 Water Quality Criteria for FutureGen (Continued)

Agency	Criteria Type	Timeframe	Exposure Time	Chemical	Units- mg/L	Units- other	Notes
USEPA	Human health consumption			TDS	250		Human health consumption of water + organism; for solids dissolved and salinity (originally in Red Book; same criterion in Gold Book, USEPA 1986)
USEPA	Secondary MCL			TDS	500		Final; 2006
Saripalli et al. 2003	Severe	Chronic		CO_2		>6%	Groundwater; acidity, well corrosion, irrigation loss
Saripalli et al. 2003	Moderate	Chronic		CO_2		>2%	Groundwater; mild acidity and corrosion
Saripalli et al. 2003	Low	Chronic		CO_2		>0.2%	Groundwater; elevated, low acidity without significant impacts
Saripalli et al. 2003	Severe	Chronic		CO_2		>2%	Surface water; acidity, CO2 explosion, fish kills
Saripalli et al. 2003	Moderate	Chronic		CO_2		>1%	Surface water; higher acidity, mild toxicity effect on irrigation
Saripalli et al. 2003	Low	Chronic		CO_2		>0.022%	Surface water; elevated, low acidity with no significant impacts
Saripalli et al. 2003	Severe	Chronic-Biota	Biota	CO_2		>4%	aquatic biota, O2 depletion, lethal
Saripalli et al. 2003	Moderate	Chronic-Biota	Biota	CO_2		>2%	aquatic biota, Injure life functions
Saripalli et al. 2003	Low	Chronic-Biota	Biota	CO_2		>0.5%	aquatic biota, Mild toxicity
Saripalli et al. 2003	Normal biota	Normal, biota	Biota	CO_2		10-5M	10-5 M (normal for aquatic biota)
Saripalli et al. 2003	Normal			CO_2		10-4M or 0.2%	Groundwater
Saripalli et al. 2003	Normal			CO_2		10-5M or 0.022%	Surface water
				CH_4			
				CO			
				SO_2			

Table A-4 Soil Quality Criteria for FutureGen

Agency	Criteria Type	Timeframe	Exposure Media	Chemical	Units- mg/kg	Units- other	Notes
Saripalli et al., 2003	Severe	Chronic	Soil	CO_2		>8%	Low pH, tree kills, animal deaths
Saripalli et al., 2003	Moderate	Chronic	Soil	CO_2		>3%	Moderate acidity, tree/crop/soil cover loss
Saripalli et al., 2003	Low	Chronic	Soil	CO_2		>2%	Mild suppression in pH with no significant impacts
Saripalli et al., 2003	Normal	Normal	Soil	CO_2		1-2%	Normal concentration
Pearce and West, 2006	Harmful, plants		Soil	CO_2		> 5%	Root asphyxiation in the root zone
Pearce and West, 2006	Phytotoxic		Soil	CO_2		> 20%	Root asphyxiation in the root zone
Heart of Brazos EIV	Threshold		Plants (soil air)	CO_2		> 25,000 ppmv	Reduced root biomass and growth
Heart of Brazos EIV	Threshold		Plants (soil air)	CO_2		>100,000 to 200,000 ppmv	Lethality depending on length of exposure

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APPENDIX B

Table B-1. Calculated Risk Estimates for Air Exposures at the Jewett Site

	Acute Human Health Effects													
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratios		Hazard Quotient
Site	**Release Scenario**	**Gas**	**Level (ppmv)**	**Type**	**Conc (ppmv) at 20 m**	**Conc (ppmv) at 250 m**	**Level (ppmv)**	**Type**		**Radius (m)**		**At 20 m**	**At 250 m**	
Pre-sequestration														
Jewett	Pipeline (19.3" I.D.) rupture (minutes)	CO_2	30,000	NIOSH REL ST	119,880	18,204	30,000	TEEL-1	Only mild transient effects	202 m	-	4	0.6	-
			40,000	IDLH	119,880	18,204	30,000	TEEL-2	No serious or irreversible effects	202 m	-	3	0.4	-
			-	-	-	-	40,000	TEEL-3	No life-threatening effects	136 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	Life-threatening	66 m	-	-	-	-
		H_2S	10	NIOSH REL C	74	72	0.51	TEEL-1	Only mild transient effects	6,885 m	-	7.4	7.2	-
			15	STEL	74	72	27	TEEL-2	No serious or irreversible effects	593 m	-	4.9	4.8	-
			-	-	-	-	50	TEEL-3	No life-threatening effects	373 m	-	-	-	-

Table B-1 (continued). Calculated Risk Estimates for Air Exposures at the Jewett Site

	Acute Human Health Effects													
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratios		Hazard Quotient
Site	Release Scenario	Gas	Level (ppmv)	Type	Conc (ppmv) at 20 m	Conc (ppmv) at 250 m	Level (ppmv)	Type		Radius (m)		At 20 m	At 250 m	
	3"x1" Pipeline Puncture (hours)	CO_2	30,000	NIOSH REL ST	103,452	8,991	15,000	Maximum Exposure - Healthy male	USEPA 2000	265 m	-	3.4	0.3	-
			40,000	IDLH	103,452	8,991	20,000	Headache, etc.	Possible respiratory stimulant	168m	-	2.6	0.2	-
			-	-	-	-	60,000	Tremors	USEPA 2000	44 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	USEPA 2000	35 m	-	-	-	-
		H_2S	10	NIOSH REL C	74	8.1	0.20	MRL - inh. Acute	No effects	2,356 m	-	7.4	0.8	-
			15	STEL	74	8.1	0.33	AEGL 1 (8 hr)	No transient effects	1,741 m	-	4.9	0.5	-
			-	-	-	-	17	AEGL 2 (8 hr)	No serious or irreversible effects	168 m	-	-	-	-
			-	-	-	-	31	AEGL 3 (8 hr)	No life-threatening effects	115 m	-	-	-	-

Table B-1 (continued). Calculated Risk Estimates for Air Exposures at the Jewett Site

	Acute Human Health Effects													
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratios		Hazard Quotient
Site	Release Scenario	Gas	Level (ppmv)	Type	Conc (ppmv) at 20 m	Conc (ppmv) at 250 m	Level (ppmv)	Type		Radius (m)		At 20 m	At 250 m	
	Equipment rupture at Woodbine 5,500' Deep Wellhead (minutes)	CO_2	30,000	NIOSH REL ST	7,920	1,480	30,000	TEEL-1	Only mild transient effects	3 m	-	0.3	0.05	-
			40,000	IDLH	7,920	1,480	30,000	TEEL-2	No serious or irreversible effects	3 m	-	0.2	0.04	-
			-	-	-	-	40,000	TEEL-3	No life-threatening effects	2 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	Life-threatening	<1 m	-	-	-	-
		H_2S	10	NIOSH REL C	83	2	0.51	TEEL-1	Only mild transient effects	534 m	-	8	0.2	-
			15	STEL	83	2	27	TEEL-2	No serious or irreversible effects	49 m	-	6	0.1	-
			-	-	-	-	50	TEEL-3	No life-threatening effects	30 m	-	-	-	-

Table B-1 (continued). Calculated Risk Estimates for Air Exposures at the Jewett Site

	Acute Human Health Effects													
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratios		Hazard Quotient
Site	Release Scenario	Gas	Level (ppmv)	Type	Conc (ppmv) at 20 m	Conc (ppmv) at 250 m	Level (ppmv)	Type		Radius (m)		At 20 m	At 250 m	
Jewett	Equipment rupture at Travis Peak 11,000' Deep Wellhead (minutes)	CO_2	30,000	NIOSH REL ST	18,350	2,170	30,000	TEEL-1	Only mild transient effects	8 m	-	0.6	0.1	-
			40,000	IDLH	18,350	2,170	30,000	TEEL-2	No serious or irreversible effects	8 m	-	0.5	0.05	-
			-	-	-	-	40,000	TEEL-3	No life-threatening effects	6 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	Life-threatening	3 m	-	-	-	-
		H_2S	10	NIOSH REL C	100	4	0.51	TEEL-1	Only mild transient effects	788 m	-	10	0.4	-
			15	STEL	100	4	27	TEEL-2	No serious or irreversible effects	82 m	-	7	0.3	-
			-	-	-	-	50	TEEL-3	No life-threatening effects	53 m	-	-	-	-

Table B-2. Calculated Risk Estimates for Air Exposures at the Odessa Site

Acute Human Health Effects														
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratios		Hazard Quotient
Site	Release Scenario	Gas	Level (ppmv)	Type	Conc (ppmv) at 20 m	Conc (ppmv) at 250 m	Level (ppmv)	Type		Radius (m)		At 20 m	At 250 m	
Pre-sequestration														
Odessa	Pipeline (12.8" I.D.) rupture (minutes)	CO_2	30,000	NIOSH REL ST	89,466	12,099	30,000	TEEL-1	Only mild transient effects	121 m	-	3	0.4	-
			40,000	IDLH	89,466	12,099	30,000	TEEL-2	No serious or irreversible effects	121 m	-	2.2	0.3	-
			-	-	-	-	40,000	TEEL-3	No life-threatening effects	82 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	Life-threatening	41 m	-	-	-	-
		H_2S	10	NIOSH REL C	74	47	0.51	TEEL-1	Only mild transient effects	4,275 m	-	7.4	4.7	-
			15	STEL	74	47	27	TEEL-2	No serious or irreversible effects	363 m	-	4.9	3.1	-
			-	-	-	-	50	TEEL-3	No life-threatening effects	229 m	-	-	-	-

Table B-2 (continued). Calculated Risk Estimates for Air Exposures at the Odessa Site

Acute Human Health Effects														
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratios		Hazard Quotient
Site	Release Scenario	Gas	Level (ppmv)	Type	Conc (ppmv) at 20 m	Conc (ppmv) at 250 m	Level (ppmv)	Type		Radius (m)		At 20 m	At 250 m	
	3"x1" Pipeline puncture (hours)	CO_2	30,000	NIOSH REL ST	105,080	10,064	15,000	Maximum Exposure - Healthy male	USEPA 2000	265 m	-	3.5	0.3	-
			40,000	IDLH	105,080	10,064	20,000	Headache, etc.	Possible respiratory stimulant	191 m	-	2.6	0.2	-
			-	-	-	-	60,000	Tremors	USEPA 2000	44 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	USEPA 2000	36 m	-	-	-	-
		H_2S	10	NIOSH REL C	74	9.6	0.20	MRL - inh. Acute	No effects	2,356 m	-	7.4	0.9	-
			15	STEL	74	9.6	0.33	AEGL 1 (8 hr)	No transient effects	1,735 m	-	4.9	0.6	-
			-	-	-	-	17	AEGL 2 (8 hr)	No serious or irreversible effects	169 m	-	-	-	-
			-	-	-	-	31	AEGL 3 (8 hr)	No life-threatening effects	116 m	-	-	-	-

Table B-2 (continued). Calculated Risk Estimates for Air Exposures at the Odessa Site

Acute Human Health Effects														
			Population Affected									**Population Affected**		
			Workers				**Residents**					**Workers**		**Residents**
			Effects		**Exposures**		**Effects**			**Exposures**		**Risk Ratios**		**Hazard Quotient**
Site	**Release Scenario**	**Gas**	**Level (ppmv)**	**Type**	**Conc (ppmv) at 20 m**	**Conc (ppmv) at 250 m**	**Level (ppmv)**	**Type**		**Radius (m)**		**At 20 m**	**At 250 m**	
	Equipment rupture at 5,500' Deep Wellhead (minutes)	CO_2	30,000	NIOSH REL ST	4,160	814	30,000	TEEL-1	Only mild transient effects	2 m	-	0.1	0.03	-
			40,000	IDLH	4,160	814	30,000	TEEL-2	No serious or irreversible effects	2 m	-	0.1	0.02	-
			-	-	-	-	40,000	TEEL-3	No life-threatening effects	< 1 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	Life-threatening	< 1 m	-	-	-	-
		H_2S	10	NIOSH REL C	22	0.6	0.51	TEEL-1	Only mild transient effects	290 m	-	2.2	0.1	-
			15	STEL	22	0.6	27	TEEL-2	No serious or irreversible effects	20 m	-	1.5	0.04	-
			-	-	-	-	50	TEEL-3	No life-threatening effects	17 m	-	-	-	-

Table B-3. Calculated Risk Estimates for Air Exposures at the Mattoon Site

	Acute Human Health Effects													
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratio		Hazard Quotient
Site	Release Scenario	Gas	Level (ppmv)	Type	Conc (ppmv) at 20 m	Conc (ppmv) at 250 m	Level (ppmv)	Type		Radius (m)		At 20 m	At 250 m	
Pre-sequestration														
Mattoon	Pipeline (14.5" I.D.) rupture (minutes)	CO_2	30,000	NIOSH REL ST	9,990	1,850	30,000	TEEL-1	Only mild transient effects	< 1 m	-	0.3	0.06	-
			40,000	IDLH	9,990	1,850	30,000	TEEL-2	No serious or irreversible effects	< 1 m	-	0.2	0.04	-
			-	-	-	-	40,000	TEEL-3	No life-threatening effects	< 1 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	Life-threatening	< 1 m	-	-	-	-
		H_2S	10	NIOSH REL C	51	3.7	0.51	TEEL-1	Only mild transient effects	1,271 m	-	5.1	0.4	-
			15	STEL	51	3.7	27	TEEL-2	No serious or irreversible effects	40 m	-	3.4	0.2	-
			-	-	-	-	50	TEEL-3	No life-threatening effects	4 m	-	-	-	-

Table B-3 (continued). Calculated Risk Estimates for Air Exposures at the Mattoon Site

	Acute Human Health Effects													
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratio		Hazard Quotient
Site	**Release Scenario**	**Gas**	**Level (ppmv)**	**Type**	**Conc (ppmv) at 20 m**	**Conc (ppmv) at 250 m**	**Level (ppmv)**	**Type**		**Radius (m)**		**At 20 m**	**At 250 m**	
	3"x1" Pipeline puncture (hours)	CO_2	30,000	NIOSH REL ST	102,194	8,754	15,000	Maximum Exposure - Healthy male	USEPA 2000	272 m	-	3.4	0.3	-
			40,000	IDLH	102,194	8,754	20,000	Headache, etc.	Possible respiratory stimulant	197 m	-	2.6	0.2	-
			-	-	-	-	60,000	Tremors	USEPA 2000	46 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	USEPA 2000	38 m	-	-	-	-
		H_2S	10	NIOSH REL C	74	8	0.20	MRL - inh. Acute	No effects	2,136 m	-	7.4	0.8	-
			15	STEL	74	8	0.33	AEGL 1 (8 hr)	No transient effects	1,628 m	-	4.9	0.5	-
			-	-	-	-	17	AEGL 2 (8 hr)	No serious or irreversible effects	167 m	-	-	-	-
			-	-	-	-	31	AEGL 3 (8 hr)	No life-threatening effects	115 m	-	-	-	-

Table B-3 (continued). Calculated Risk Estimates for Air Exposures at the Mattoon Site

	Acute Human Health Effects													
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratio		Hazard Quotient
Site	Release Scenario	Gas	Level (ppmv)	Type	Conc (ppmv) at 20 m	Conc (ppmv) at 250 m	Level (ppmv)	Type		Radius (m)		At 20 m	At 250 m	
	Equipment rupture at 8,000' Deep Wellhead (minutes)	CO_2	30,000	NIOSH REL ST	12,570	1,580	30,000	TEEL-1	Only mild transient effects	5 m	-	0.4	0.05	-
			40,000	IDLH	12,570	1,580	30,000	TEEL-2	No serious or irreversible effects	5 m	-	0.3	0.04	-
			-	-	-	-	40,000	TEEL-3	No life-threatening effects	4 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	Life-threatening	2 m	-	-	-	-
		H_2S	10	NIOSH REL C	100	3	0.51	TEEL-1	Only mild transient effects	688 m	-	10	0.3	-
			15	STEL	100	3	27	TEEL-2	No serious or irreversible effects	42 m	-	7	0.2	-
			-	-	-	-	50	TEEL-3	No life-threatening effects	<20 m	-	-	-	-

Table B-4. Calculated Risk Estimates for Air Exposures at the Tuscola Site

Acute Human Health Effects														
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratios		Hazard Quotient
Site	Release Scenario	Gas	Level (ppmv)	Type	Conc (ppmv) at 20 m	Conc (ppmv) at 250 m	Level (ppmv)	Type		Radius (m)		At 20 m	At 250 m	
Pre-sequestration														
Tuscola	Pipeline (14.4" I.D.) rupture (minutes)	CO_2	30,000	NIOSH REL ST	99,160	14,134	30,000	TEEL-1	Only mild transient effects	140 m	-	**3.3**	0.5	-
			40,000	IDLH	99,160	14,134	30,000	TEEL-2	No serious or irreversible effects	140 m	-	**2.5**	0.4	-
			-	-	-	-	40,000	TEEL-3	No life-threatening effects	96 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	Life-threatening	47 m	-	-	-	-
		H_2S	10	NIOSH REL C	74	56	0.51	TEEL-1	Only mild transient effects	4,972 m	-	**7.4**	**5.6**	-
			15	STEL	74	56	27	TEEL-2	No serious or irreversible effects	422 m	-	**4.9**	**3.7**	-
			-	-	-	-	50	TEEL-3	No life-threatening effects	266 m	-	-	-	-

Table B-4 (continued). Calculated Risk Estimates for Air Exposures at the Tuscola Site

Acute Human Health Effects														
			Population Affected									**Population Affected**		
			Workers				**Residents**					**Workers**		**Residents**
			Effects		**Exposures**		**Effects**			**Exposures**		**Risk Ratios**		**Hazard Quotient**
Site	**Release Scenario**	**Gas**	**Level (ppmv)**	**Type**	**Conc (ppmv) at 20 m**	**Conc (ppmv) at 250 m**	**Level (ppmv)**	**Type**		**Radius (m)**		**At 20 m**	**At 250 m**	
	3"x1" Pipeline puncture (hours)	CO_2	30,000	NIOSH REL ST	72,416	13,128	15,000	Maximum Exposure - Healthy male	USEPA 2000	265 m	-	**2.4**	0.4	-
			40,000	IDLH	72,416	13,128	20,000	Headache, etc.	Possible respiratory stimulant	190 m	-	**1.8**	0.3	-
			-	-	-	-	60,000	Tremors	USEPA 2000	44 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	USEPA 2000	36 m	-	-	-	-
		H_2S	10	NIOSH REL C	74	9	0.20	MRL - inh. Acute	No effects	2,356 m	-	**7.4**	**0.9**	-
			15	STEL	74	9	0.33	AEGL 1 (8 hr)	No transient effects	1,735 m	-	**4.9**	0.6	-
			-	-	-	-	17	AEGL 2 (8 hr)	No serious or irreversible effects	168 m	-	**-**	**-**	-
			-	-	-	-	31	AEGL 3 (8 hr)	No life-threatening effects	116 m	-	-	-	-

Table B-4 (continued). Calculated Risk Estimates for Air Exposures at the Tuscola Site

Acute Human Health Effects														
			Population Affected									Population Affected		
			Workers				Residents					Workers		Residents
			Effects		Exposures		Effects			Exposures		Risk Ratios		Hazard Quotient
Site	Release Scenario	Gas	Level (ppmv)	Type	Conc (ppmv) at 20 m	Conc (ppmv) at 250 m	Level (ppmv)	Type		Radius (m)		At 20 m	At 250 m	
	Equipment rupture at 7,750' Deep Wellhead (minutes)	CO_2	30,000	NIOSH REL ST	11,450	2,040	30,000	TEEL-1	Only mild transient effects	5 m	-	0.4	0.07	-
			40,000	IDLH	11,450	2,040	30,000	TEEL-2	No serious or irreversible effects	5 m	-	0.3	0.05	-
			-	-	-	-	40,000	TEEL-3	No life-threatening effects	3 m	-	-	-	-
			-	-	-	-	70,000	Unconsciousness	Life-threatening	1 m	-	-	-	-
		H_2S	10	NIOSH REL C	100	3	0.51	TEEL-1	Only mild transient effects	620 m	-	**10**	0.3	-
			15	STEL	100	3	27	TEEL-2	No serious or irreversible effects	70 m	-	**7**	0.2	-
			-	-	-	-	50	TEEL-3	No life-threatening effects	50 m	-	-	-	-

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Appendix B Maps

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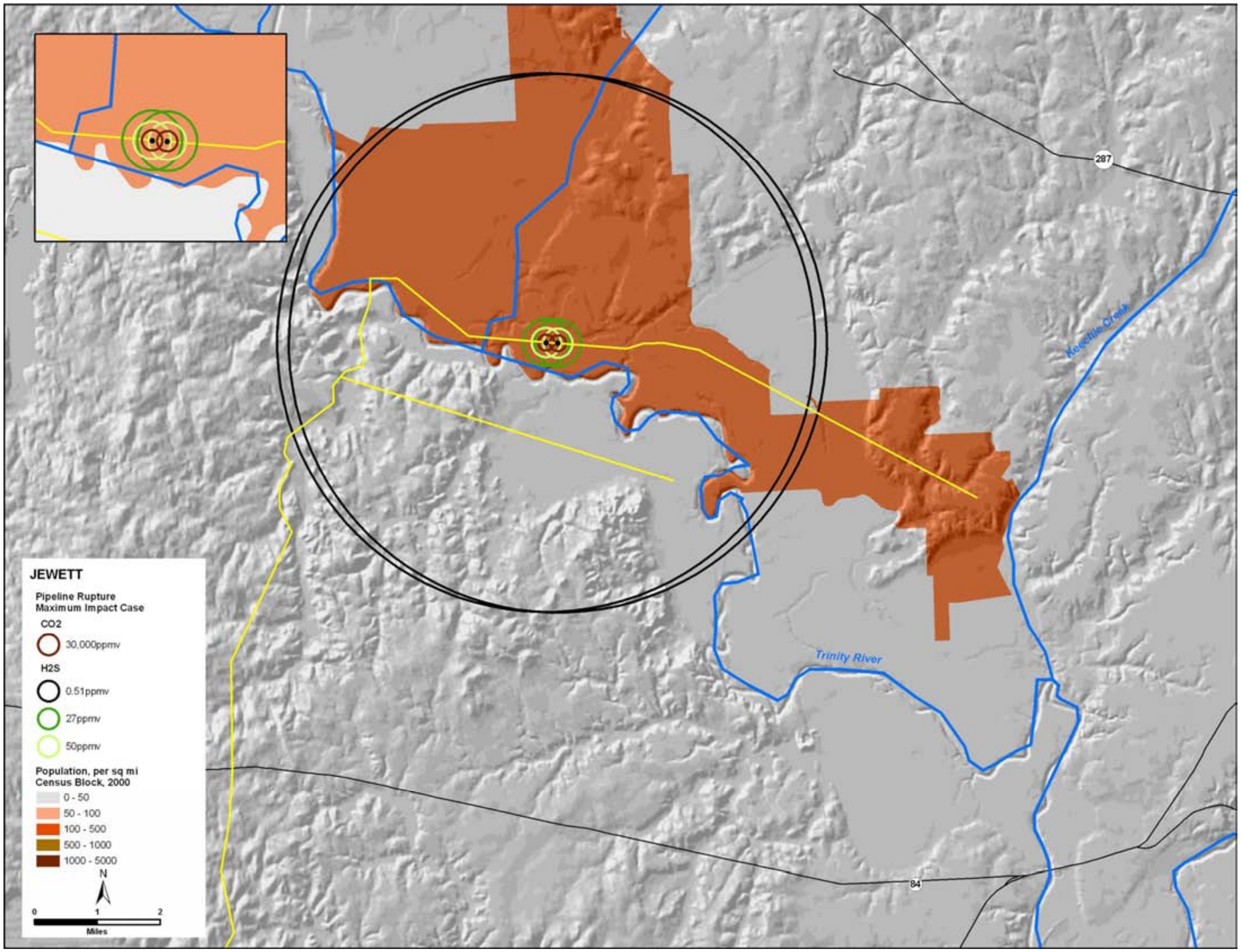
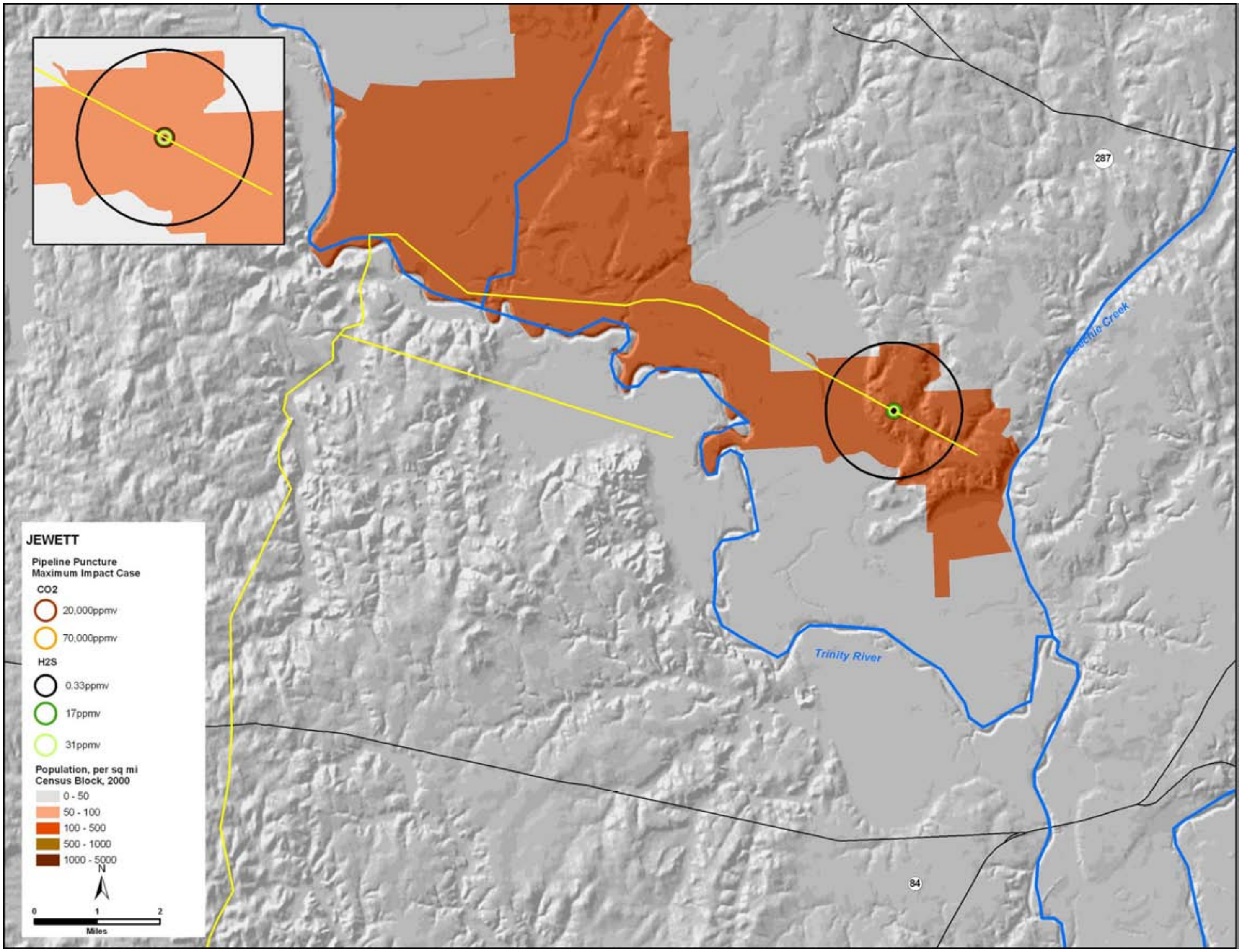

JEWETT
Pipeline Rupture Maximum Impact Case
CO2
30,000ppmv
H2S
0.51ppmv
27ppmv
50ppmv
Population, per sq mi Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
1
2
Miles
287
84
Keechie Creek
Trinity River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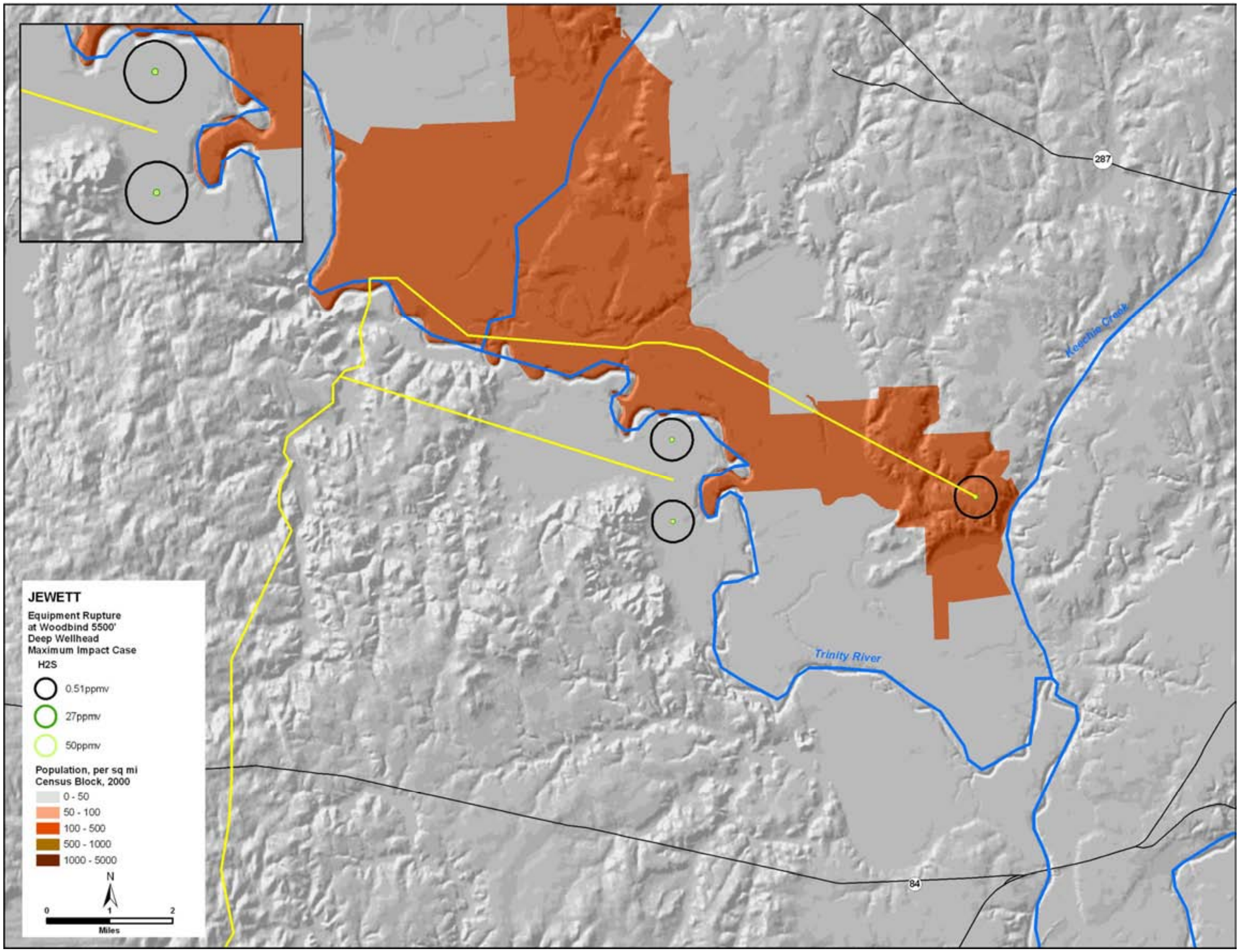
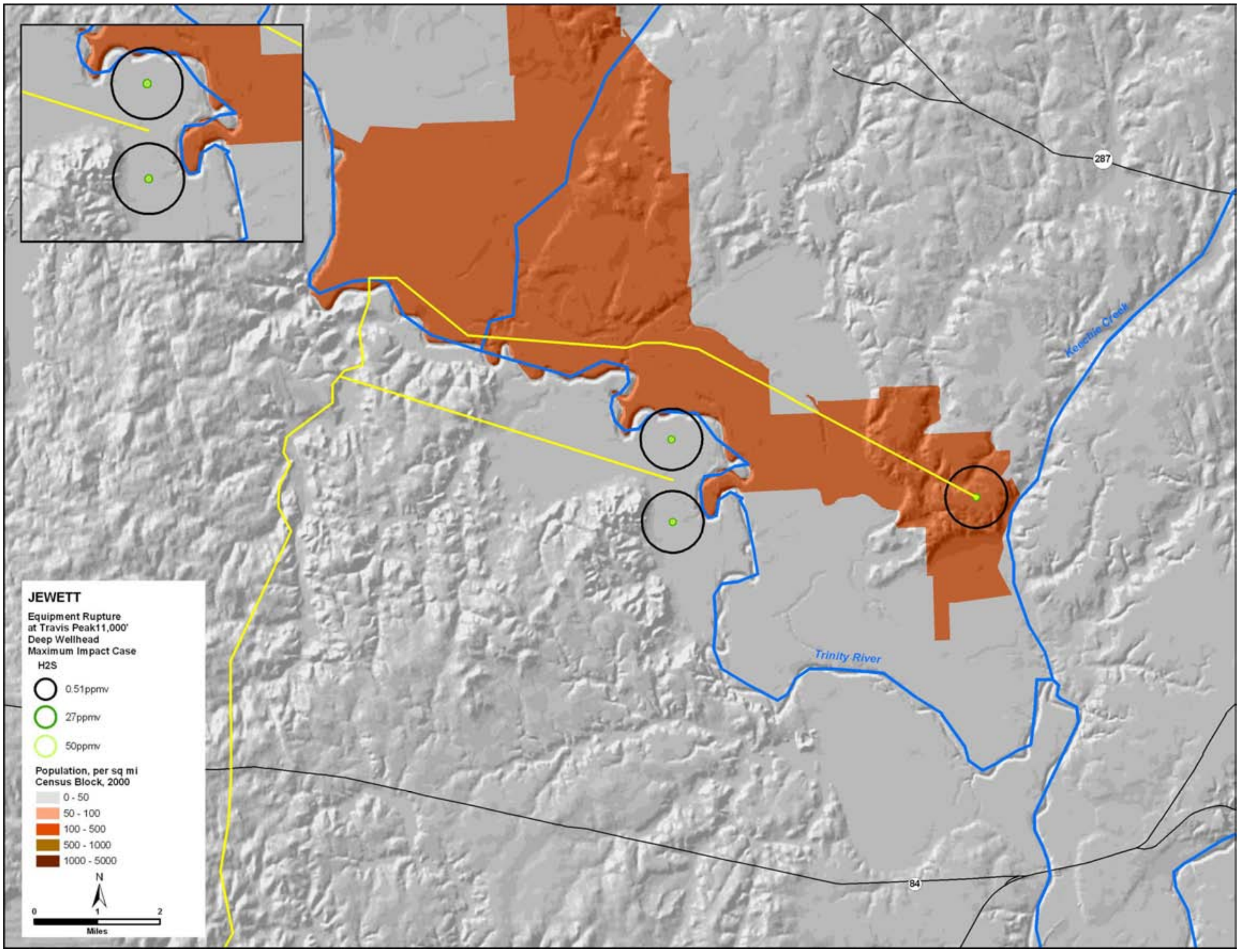
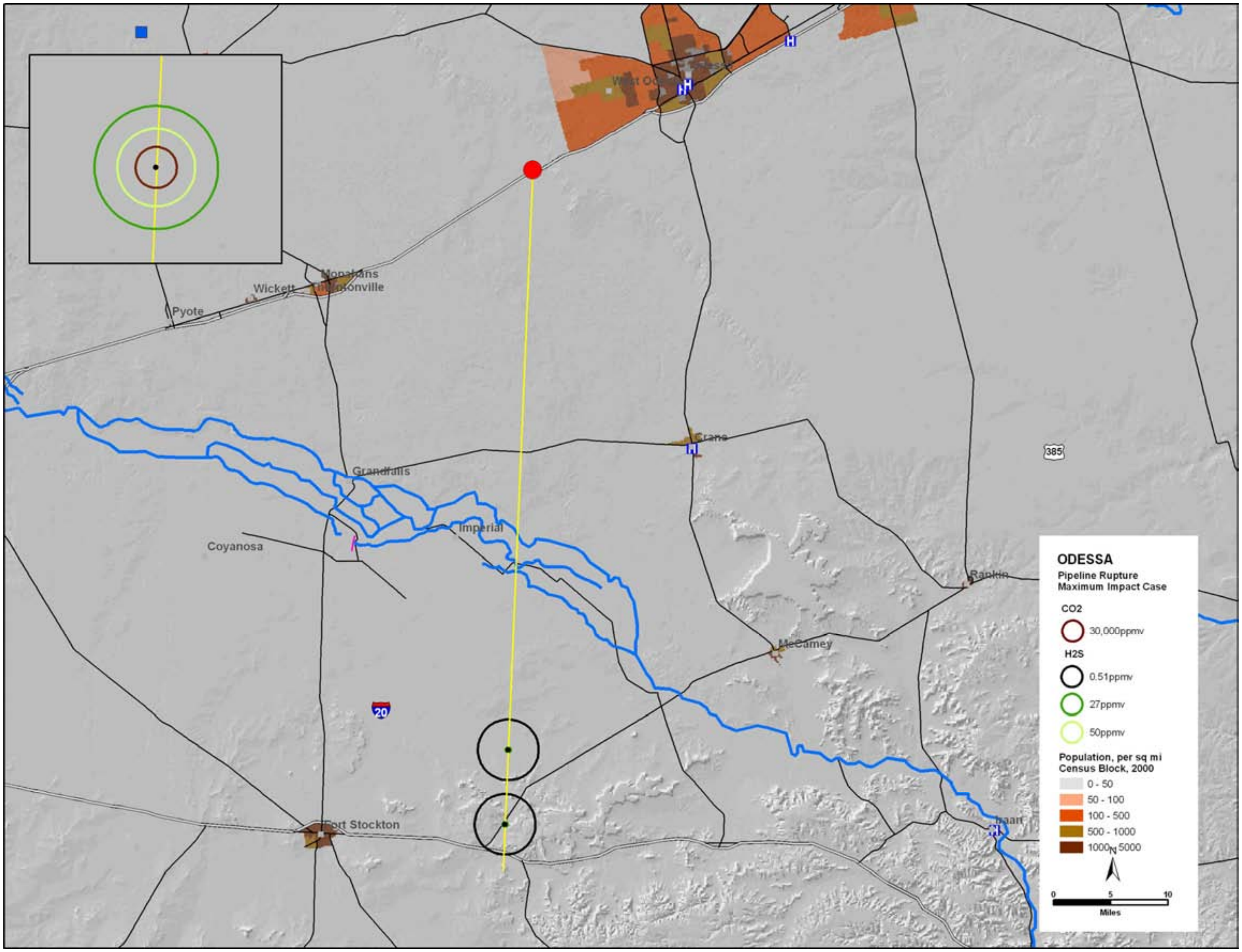
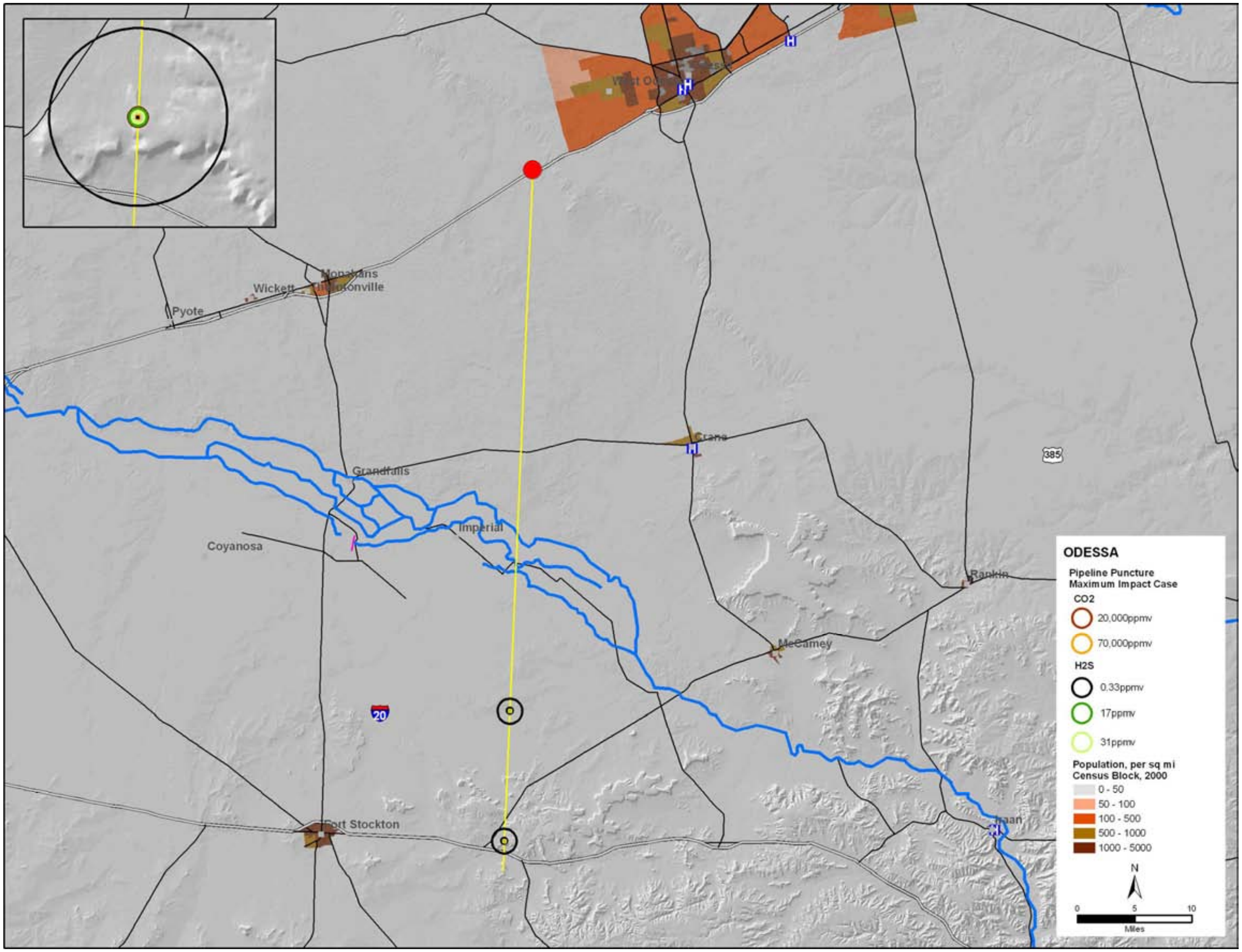
Pipeline Puncture Maximum Impact Case
CO2
20,000ppmv
70,000ppmv
H2S
0.33ppmv
17ppmv
31ppmv
Population, per sq mi Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
1
2
Miles
287
Creek
Trinity River
84


JEWETT
Equipment Rupture at Woodbind 5500' Deep Wellhead Maximum Impact Case
H2S
0.51ppmv
27ppmv
50ppmv
Population, per sq mi Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
1
2
Miles
287
84
Keechie Creek
Trinity River


JEWETT
Equipment Rupture
at Travis Peak11,000'
Deep Wellhead
Maximum Impact Case
H2S
0.51ppmv
27ppmv
50ppmv
Population, per sq mi
Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
1
2
Miles
287
Keechie Creek
Trinity River
84


West Odessa
Monahans
Thorntonville
Wickett
Pyote
Crane
385
Grandfalls
Imperial
Coyanosa
Rankin
McCamey
20
Fort Stockton
Iraan
ODESSA
Pipeline Rupture
Maximum Impact Case
CO2
30,000ppmv
H2S
0.51ppmv
27ppmv
50ppmv
Population, per sq mi
Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
5
10
Miles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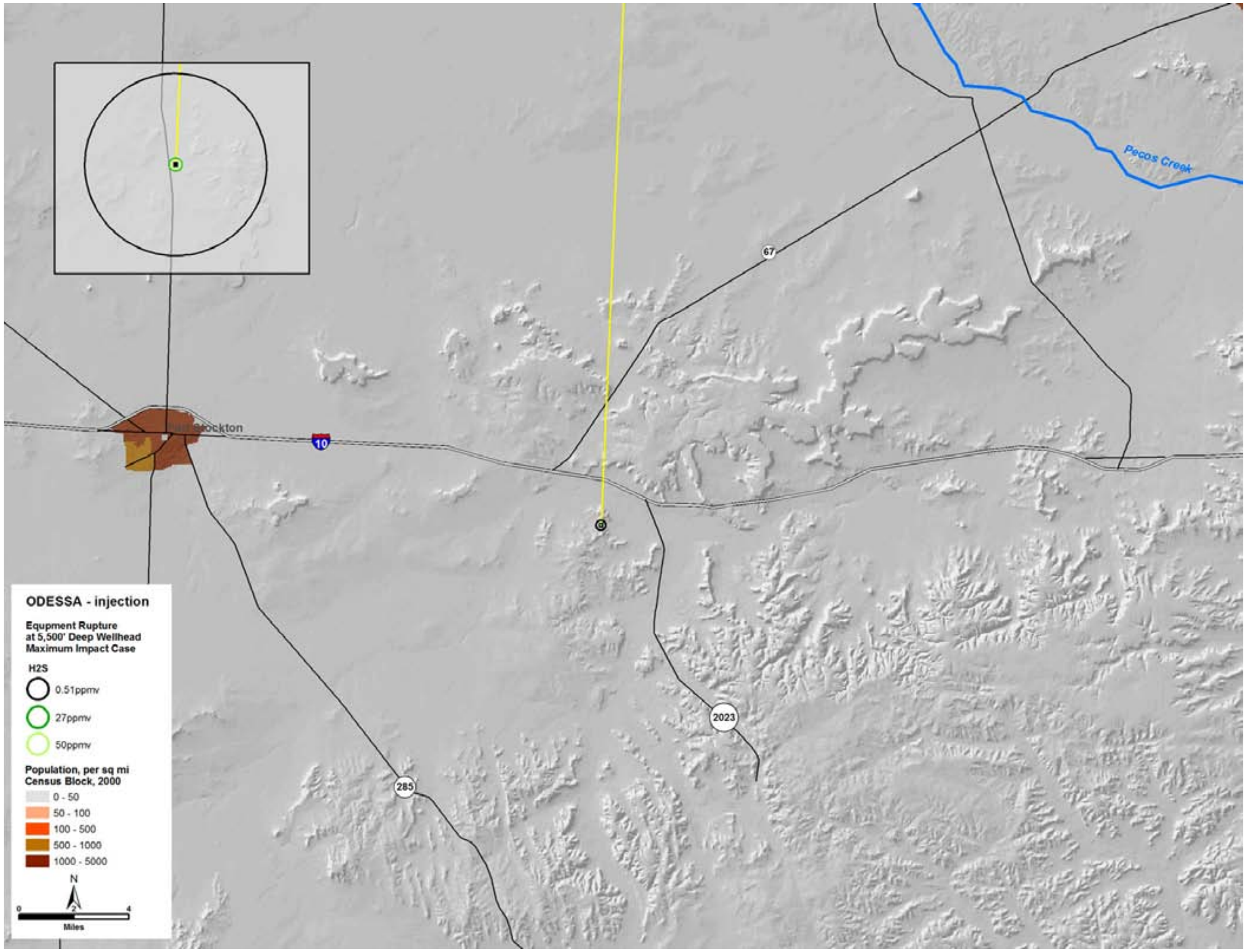
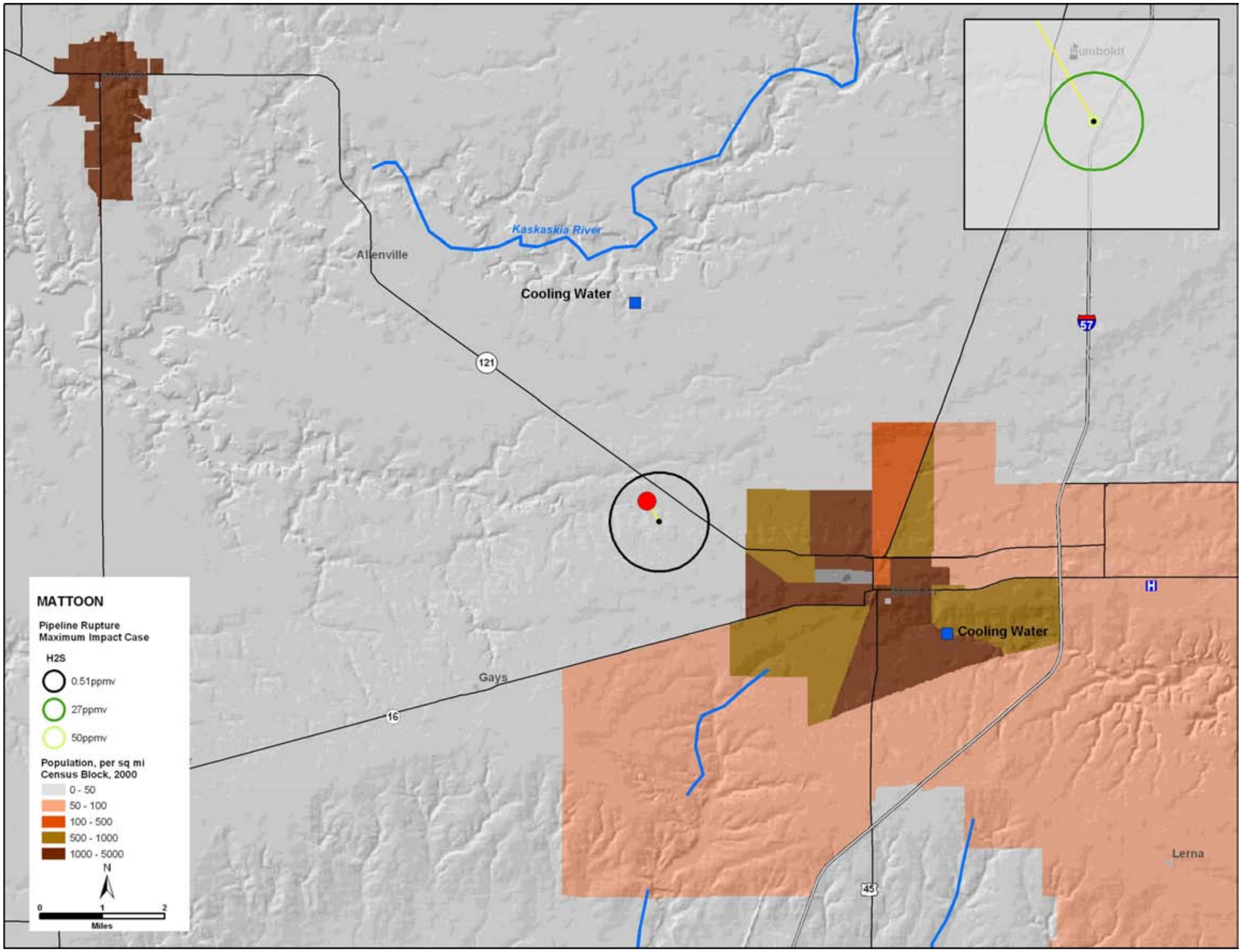
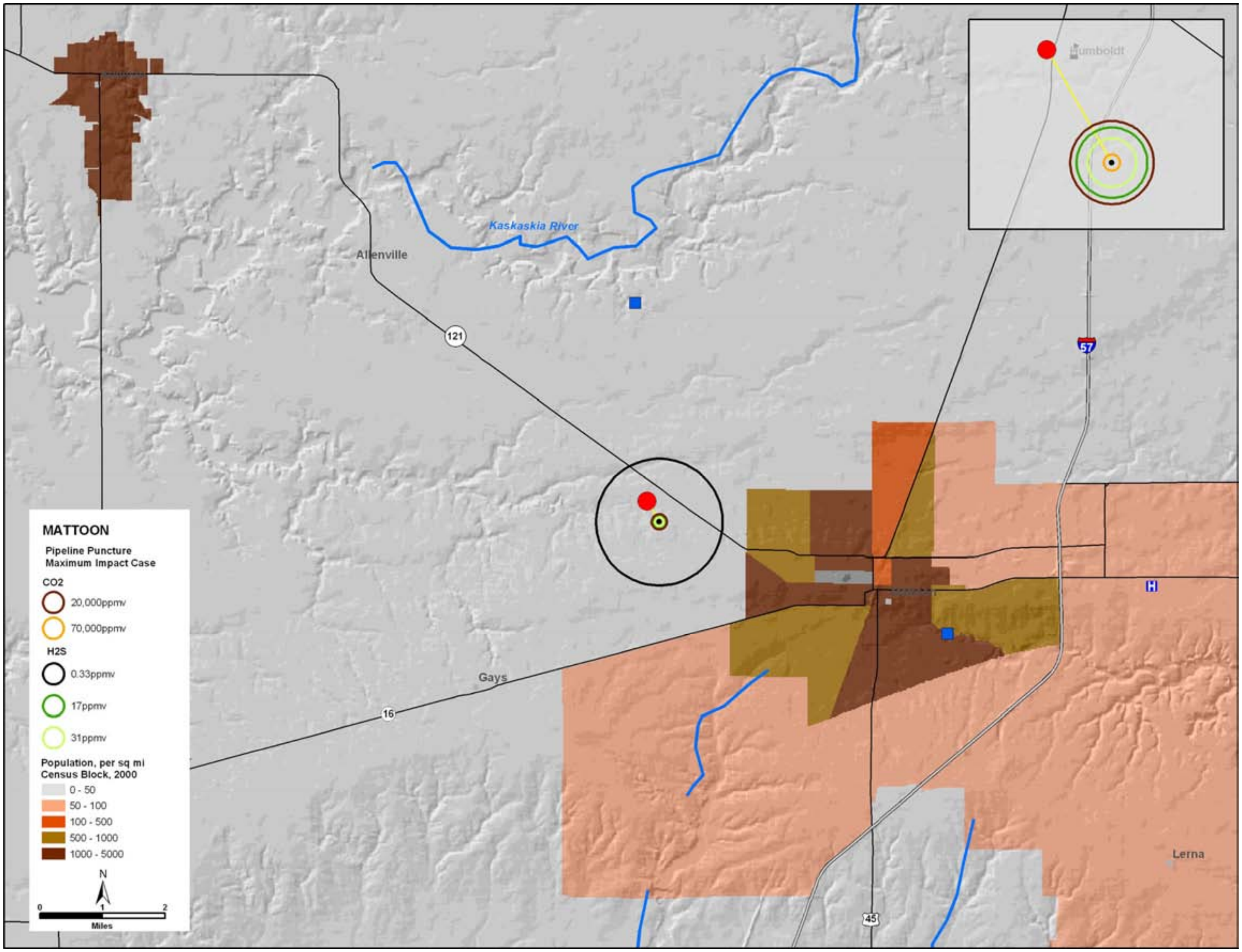
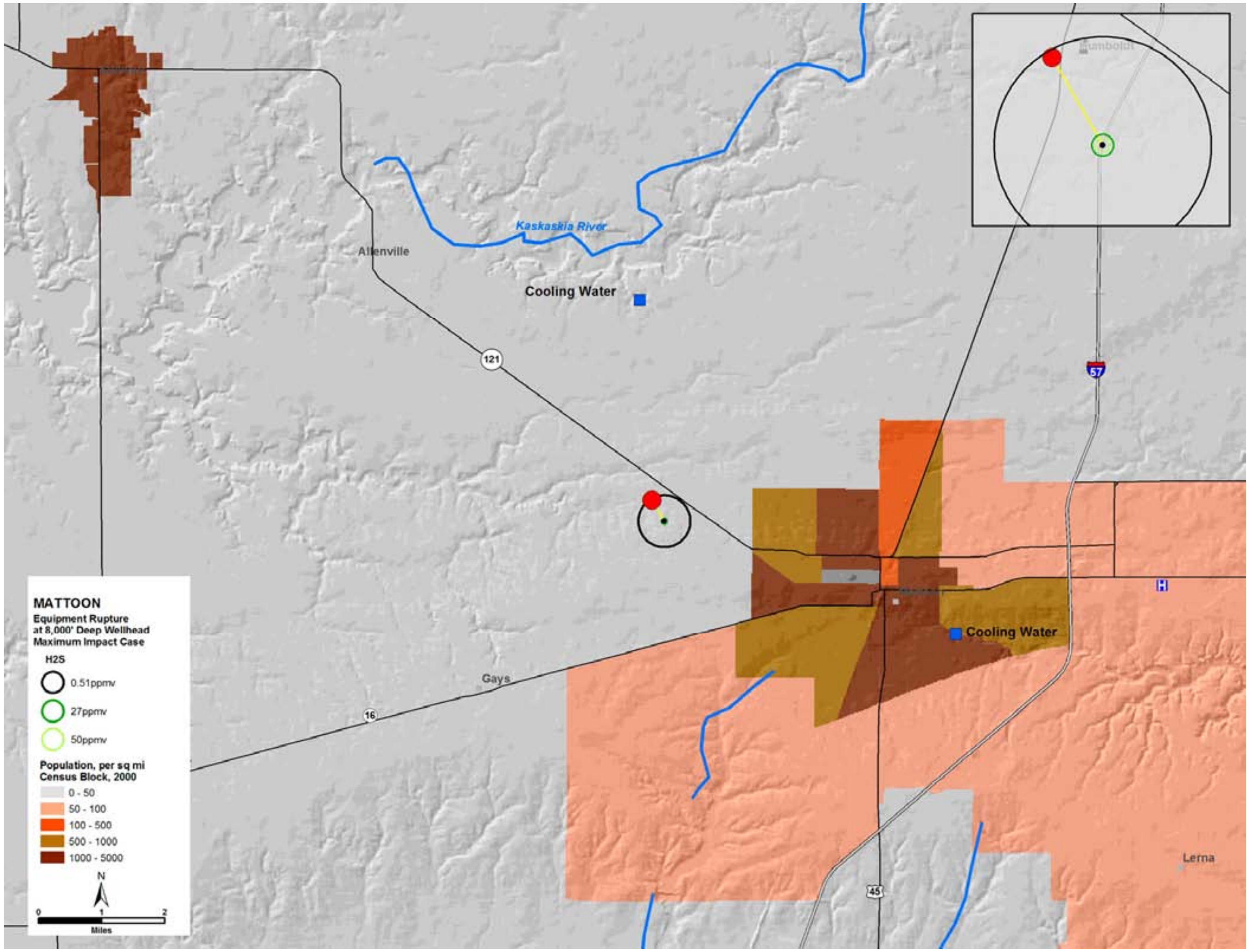
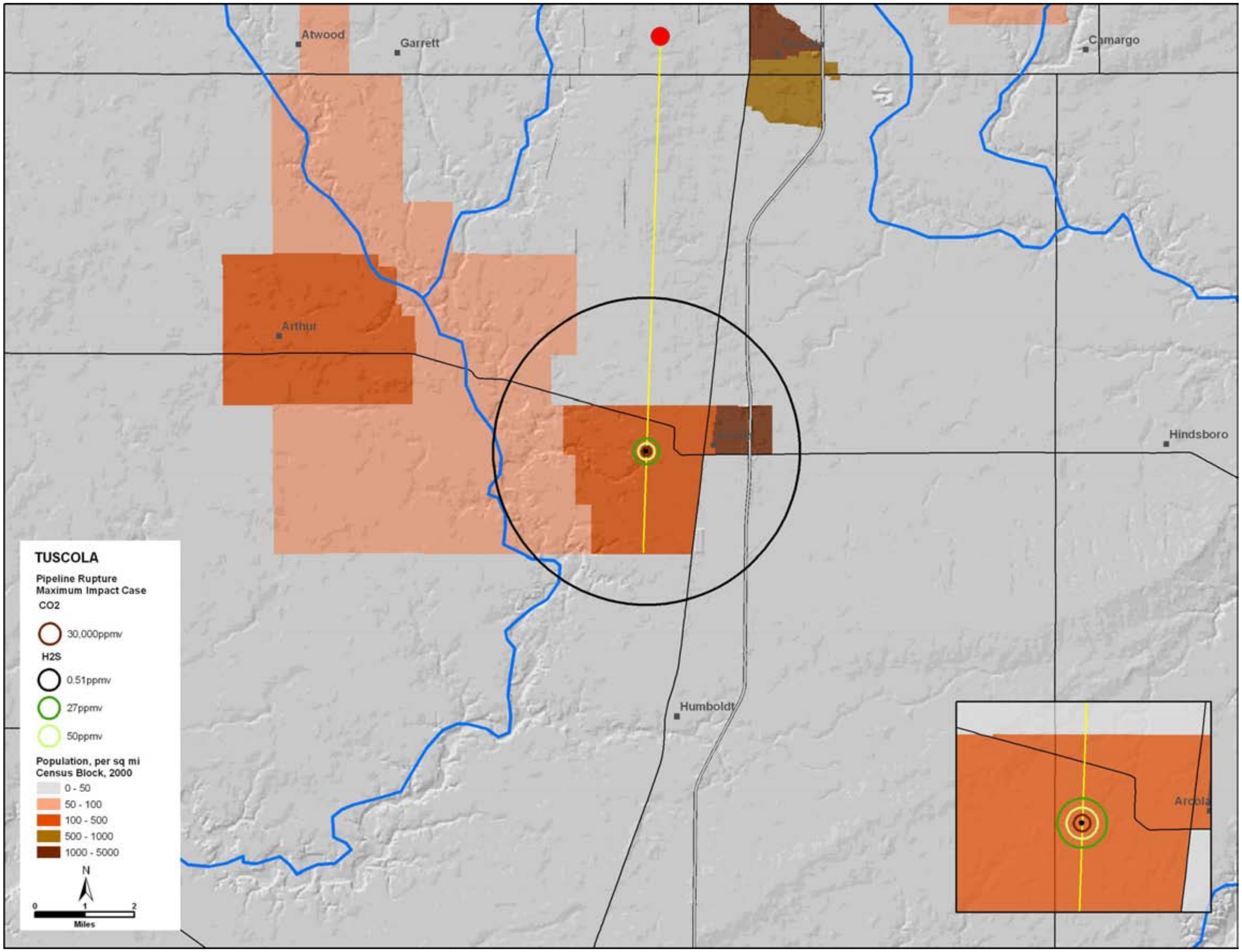
Monahans
Thorntonville
Wickett
Pyote
Crane
Grandfalls
Imperial
Coyanosa
Rankin
McCamey
Fort Stockton
Iraan
385
20
ODESSA
Pipeline Puncture Maximum Impact Case
CO2
20,000ppmv
70,000ppmv
H2S
0.33ppmv
17ppmv
31ppmv
Population, per sq mi Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
5
10
Miles

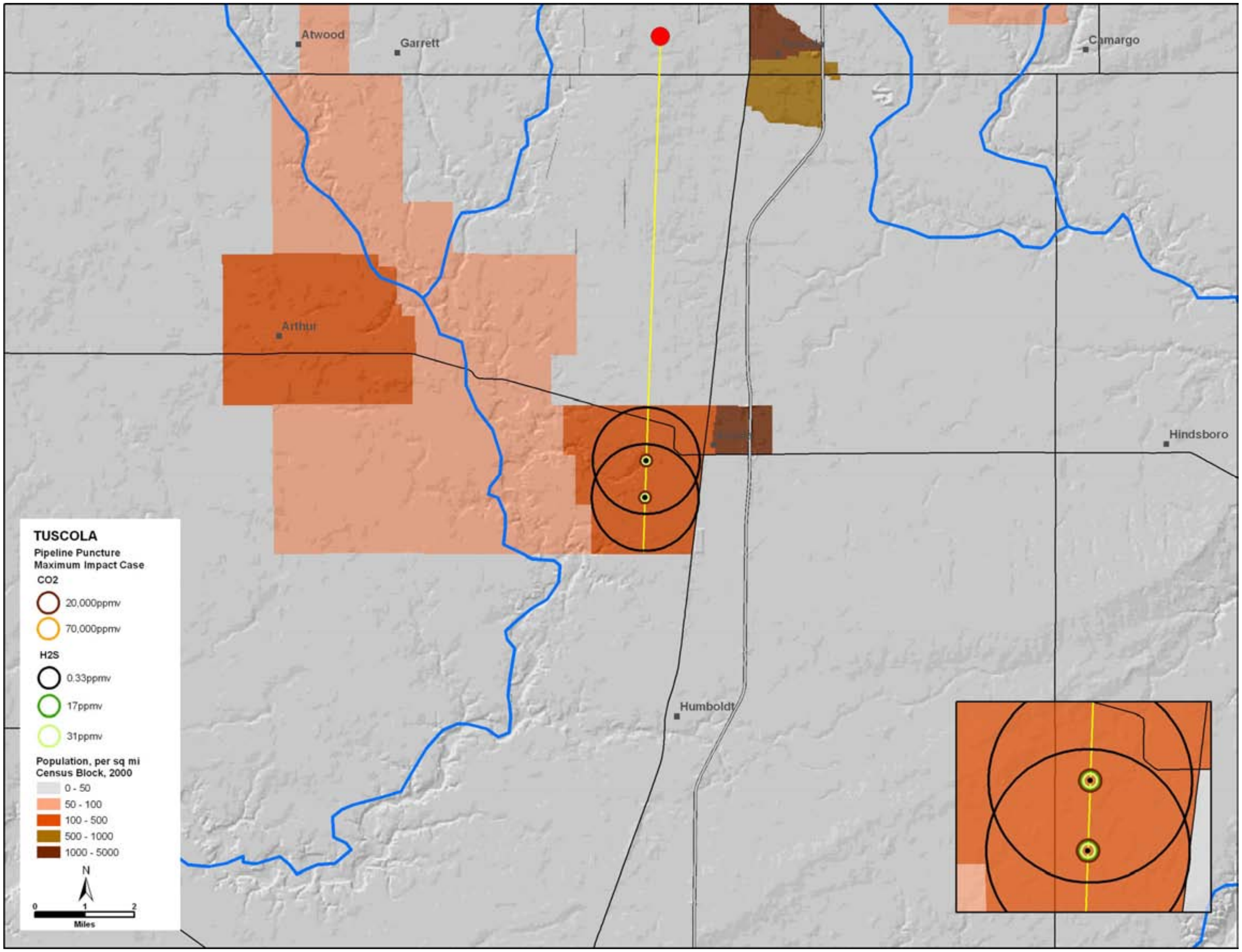

Pecos Creek
67
Fort Stockton
10
285
2023
ODESSA - injection
Equpment Rupture
at 5,500' Deep Wellhead
Maximum Impact Case
H2S
0.51ppmv
27ppmv
50ppmv
Population, per sq mi
Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
2
4
Miles


Humboldt
Kaskaskia River
Allenville
Cooling Water
121
57
Gays
16
Cooling Water
H
Lerna
45
MATTOON
Pipeline Rupture Maximum Impact Case
H2S
0.51ppmv
27ppmv
50ppmv
Population, per sq mi Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
1
2
Miles


Humboldt
Kaskaskia River
Allenville
121
57
Gays
16
45
Lerna
MATTOON
Pipeline Puncture
Maximum Impact Case
CO2
20,000ppmv
70,000ppmv
H2S
0.33ppmv
17ppmv
31ppmv
Population, per sq mi
Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
1
2
Miles


Humboldt
Kaskaskia River
Allenville
Cooling Water
121
57
H
Cooling Water
Gays
16
45
Lerna
MATTOON
Equipment Rupture
at 8,000' Deep Wellhead
Maximum Impact Case
H2S
0.51ppmv
27ppmv
50ppmv
Population, per sq mi
Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
1
2
Miles


Atwood
Garrett
Camargo
Arthur
Hindsboro
Humboldt
Arcola
TUSCOLA
Pipeline Rupture
Maximum Impact Case
CO2
30,000ppmv
H2S
0.51ppmv
27ppmv
50ppmv
Population, per sq mi
Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0 1 2
Miles


Atwood
Garrett
Camargo
Arthur
Hindsboro
Humboldt
TUSCOLA
Pipeline Puncture
Maximum Impact Case
CO2
20,000ppmv
70,000ppmv
H2S
0.33ppmv
17ppmv
31ppmv
Population, per sq mi
Census Block, 2000
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50 - 100
100 - 500
500 - 1000
1000 - 5000
N
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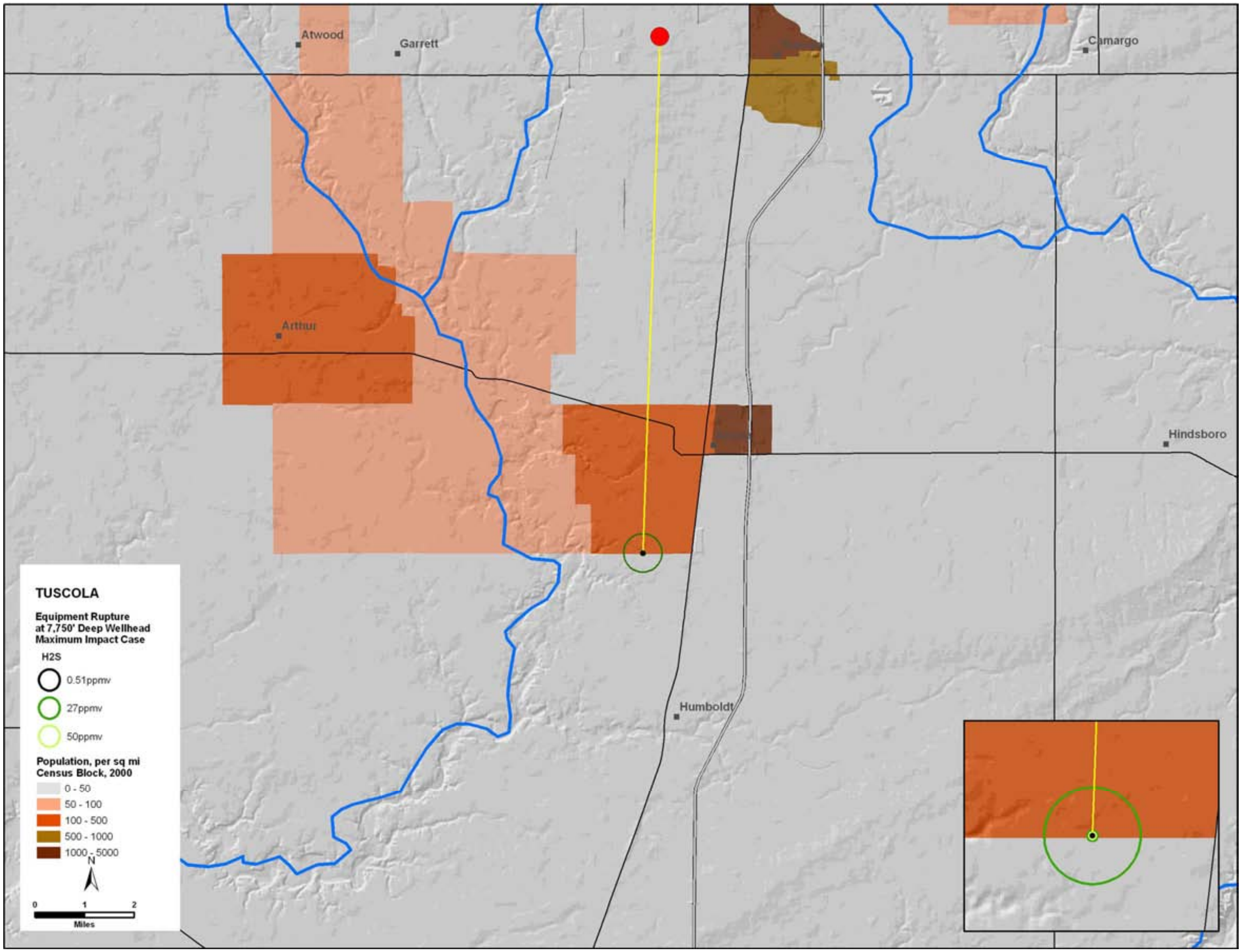
Miles


Atwood
Garrett
Camargo
Arthur
Hindsboro
Humboldt
TUSCOLA
Equipment Rupture
at 7,750' Deep Wellhead
Maximum Impact Case
H2S
0.51ppmv
27ppmv
50ppmv
Population, per sq mi
Census Block, 2000
0 - 50
50 - 100
100 - 500
500 - 1000
1000 - 5000
N
0
1
2
Miles

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APPENDIX C

C.1 Pipeline and Wellbore Modeling

C.1.1 CARBON DIOXIDE

Carbon dioxide is transported by pipelines as a supercritical fluid with a density of about 70 to 90 percent of that of liquid water (IPCC, 2005; Annex I). If a leak develops along the pipeline or at an injection well, carbon dioxide will escape. A portion of the escaping fluid will quickly expand to carbon dioxide gas, the remainder will form a carbon dioxide solid (so called dry-ice snow). Carbon dioxide gas is about 50 percent heavier than air. Atmospheric transport models are used to properly simulate the behavior of such denser-than-air gases as they disperse into the atmosphere.

C.1.2 ATMOSPHERIC TRANSPORT MODELS USED

The SLAB model (Version 2) was developed for the US Department of Energy to simulate the three-dimensional atmospheric dispersion of gases that are denser than air (Ermak, 1990). The processes of air entrainment and gravity spread associated with dense gases are accounted for by the model. The crosswind-averaged properties of a released gas cloud are calculated as a function of downwind distance. The specified wind velocity is held constant during the simulation. The model simulates finite duration releases and horizontal and vertical jet sources. It can also simulate cloud dispersion of neutrally buoyant releases and cloud lofting for lighter-than air gases.

EPA’s SCREEN3 model was used to simulate gas releases from the wellbores. SCREEN3 estimates atmospheric concentrations from point and simple area sources. The model algorithms are described in EPA’s user’s guide (US EPA, 1995a & 1995b). The same meteorological factors as used with SLAB are accounted for with SCREEN3 — the six Pasquill stability classes (Turner, 1994) and wind-speeds. EPA intends to distribute AERScreen in the future for such calculations but AERScreen is currently in beta testing. SCREEN3 remains the screening model of choice until the AERScreen testing has been completed.

C.1.3 CHEMICAL & PHYSICAL PROPERTIES USED IN TRANSPORT MODELING OF PIPELINE RELEASES

The parameters presented here are used in the models to estimate potential risks to plant workers and the general public from any pipeline ruptures and punctures. The basic properties of the fluid in the pipeline as it leaves the plant boundary are presented in Table C-1.1. Tables C-1.2 through C-1.4 present pipeline release parameters and properties of carbon dioxide and hydrogen sulfide. Tables C-1.5 and C-1.6 present calculated masses and release durations for CO_2 and H_2S from a five mile section of pipe. Five miles is the estimated distance between safety valves in the pipeline. Both the properties shown in Table C-1.1 and the safety valve interval are critical to the model calculations. Computed masses of CO_2 and H_2S in an injection well bore are provided for each site in Tables C-1.7 and C-1.8. Tables C-1.9 and C-1.10 present calculated masses and release durations for CO_2 and H_2S from a 3 inch by 1 inch pipeline puncture. The puncture scenario is used to represent a hole that a bucket tooth from a 30 to 60 ton excavator might make while digging.

Table C-1.1. Properties of Supercritical Carbon Dioxide in Pipeline

Parameter	Specified	Reference
CO_2	95 %	EIV
H_2S	0.01%	EIV
Safety valve interval	5 miles	EIV
Temperature	95°F	EIV
Pressure	2,200 psi	EIV

Table C-1.2. Modeling Parameters Used for Simulation of Pipeline Break with Meteorological Scenarios D5 & F2

Model Parameter	Value
Release Parameters	
Release Height	0 meters
Release Scenario	Completely severed; Horizontal jet
Calculation Height	1.5 meters
Meteorological Parameters	
Wind-speed & Pasquill stability class	D5: 5 m/sec & D-neutral
	F2: 2 m/sec & F-stable
Ambient temperature	35°C
Surface roughness height (z_o)	0.1 meters

Table C-1.3. Physical Properties of Carbon Dioxide Used in Modeling Pipeline Break (IPCC, 2005; Annex I).

Property	Value	Units
Carbon Dioxide	*CO_2*	--
Molecular weight	44.01	g/mole
Vapor heat capacity	873	Joules/(kg °K)
Boiling point temperature	194.7	°K
Heat of vaporization	571,100	Joules/kg
Liquid heat capacity	3,048	Joules/(kg °K)
Supercritical Density	850 @310°K & 2200 psi	Kg/m^3
	600 @330°K & 2200 psi	Kg/m^3
	750 @310°K & 1800 psi	Kg/m^3
Specific heat ratio C_{hp}/C_{hv}	0.872/0.684=1.31	unitless

Table C-1.4. Physical Properties of Hydrogen Sulfide Used in Modeling Pipeline Break (CRC, 1995)

Property	Value	Units
Hydrogen Sulfide	H_2S	--
Molecular weight	34.08	g/mole
Vapor heat capacity	1,004	Joules/(kg °K)
Boiling point temperature	213.5	°K
Heat of vaporization	547,980	Joules/kg
Liquid heat capacity	2,010	Joules/(kg °K)
Liquid density	960	Kg/m^3
Specific heat ratio C_{hp}/C_{hv}	1.30	unitless

Table C-1.5. Choked Flow Conditions for Carbon Dioxide Released from a Section of Pipeline

Site	Pipe ID and Orifice Area	Section Length	Pipeline Temperature (°C)	Absolute Pressure (psia)	CO_2 Mass (kg)	$Q_{choked-CO_2}{}^*$ (kg/sec)	Release Duration (sec)
Jewett, TX	19.312 in. 0.189 m^2	5 mi	35	2,200.	1,290,000	7,950	162
Tuscola, IL	14.438 in. 0.106 m^2	5 mi	35	2,200.	723,100	4,444	162
Odessa, TX	12.812 in. 0.0832 m^2	5 mi	35	2,200.	568,000	3,500	162
Mattoon, IL	14.438 in. 0.106 m^2	0.5 mi	35	2,200.	72,310	4,444	16

[*] Supercritical density = 850 Kg/m^3 at 35°C and 2,200 psi. Choked flow $Q_{choked-CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline.

Table C-1.6. Simulation Conditions for Hydrogen Sulfide Released from a Section of Pipeline

Site	ID and Orifice Area	Section Length	Pipeline Temperature (°C)	Absolute Pressure (psi)	H_2S Mass (kg)	$Q_{choked-H_2S}$ * (kg/sec)	Release Duration (sec)
Jewett, TX	19.312 in. 0.189 m^2	5 mi	35	2,200	129.	0.79	162
Tuscola, IL	14.438 in. 0.106 m^2	5 mi	35	2,200	72.	0.44	162
Odessa, TX	12.812 in. 0.0832 m^2	5 mi	35	2,200	56.8	0.35	162
Mattoon, IL	14.438 in. 0.106 m^2	0.5 mi	35	2,200	7.2	0.44	16

* Choked flow $Q_{choked\text{-}H2S}$ = 0.0001*$Q_{choked\text{-}CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline. Unit Conversions: 1 psi = 0.06895 bars; 1 psi = 6,895 (Newtons/m^2 or Pascals); 1 psi = 0.06805 (*atmospheres*); 1 atm = 101,325 (Newtons/m^2 or Pascals).

Table C-1.7. Site-Specific Volume Estimates of Carbon Dioxide for Well Borings

Site	Injection Zone	Tubing ID (inches)	Tubing Depth (feet)	Total Depth (feet)	Well Volume* (m^3)	Mass CO_2 (tonne) @2200 psi, 95°F	Mass Rate (Kg/sec)	Duration (sec)
Jewett, TX	Woodbine	3.83	4,800	5,500	13.3	11.3	313	36
	Travis Peak	3.83	9,200	11,000	26.6	22.6	313	72
Tuscola, IL	Mt. Simon	4.89	6,150	7,750	26.6	22.6	510	44
Odessa, TX	Mountain	1.99	5,600	5,600	3.4	2.9	84.8	35
Mattoon, IL	Mt. Simon	3.83	6,950	8,000	19.3	16.4	313	52

*Wellbore volume is based on the total depth of hole. ID = Inner Diameter. CO_2 density = 850 kg/m^3 @95°F & 2,200 psi; 1 tonne = 1 metric ton = 1,000 kg.

Table C-1.8. Simulation Conditions for Hydrogen Sulfide Released from Injection Well Borings.

Site	Injection Zone	Tubing ID (inches)	Tubing Depth (feet)	Total Depth (feet)	Well Volume* (m^3)	Mass H_2S (tonne) @2200 psi, 95°F	Mass Rate (Kg/sec)	Duration (sec)
Jewett, TX	Woodbine	3.83	4,800	5,500	13.3	0.00113	0.0313	36
	Travis Peak	3.83	9,200	11,000	26.6	0.00226	0.0313	72
Tuscola, IL	Mt. Simon	4.89	6,150	7,750	26.6	0.00226	0.0510	44
Odessa, TX	Mountain	1.99	5,600	5,600	3.4	0.00029	0.00848	35
Mattoon, IL	Mt. Simon	3.83	6,950	8,000	19.3	0.00164	0.0313	52

*Wellbore volume is based on the total depth of hole. ID = Inner Diameter. CO_2 density = 850 kg/m^3 @95°F & 2,200 psi; 1 tonne = 1 metric ton = 1000 kg. Units Conversion: 1 tonne = 1 metric ton = 1,000 kg.

Table C-1.9. Simulation Conditions for Carbon Dioxide Released from a 3x1 Inch Puncture (an area of 0.00194 m^2) in a Section of Pipeline

Site	Pipeline ID	Section Length	Pipeline Temperature (°C)	Absolute Pressure (psi)	H_2S Mass (kg)	$Q_{choked-CO_2}{}^*$ (kg/sec)	Release Duration (sec)
Jewett, TX	19.312 inch	5 mi	35	2,200	1,290,000	81.4	15,800
Tuscola, IL	14.438 inch	5 mi	35	2,200	723,100	81.4	8,880
Odessa, TX	12.812 inch	5 mi	35	2,200	568,000	81.4	6,980
Mattoon, IL	14.438 inch	0.5 mi	35	2,200	72,310	81.4	888

* Supercritical density = 850 Kg/m^3 at 35°C & 2,200 psi. Choked flow $Q_{choked-CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline.

Table C-1.10. Simulation Conditions for Hydrogen Sulfide Released from a 3x1 Inch Puncture (an area of 0.00194 m^2) in a Section of Pipeline

Site	Pipeline ID	Section Length	Pipeline Temperature (℃)	Absolute Pressure (psi)	H_2S Mass (kg)	$Q_{choked-H_2S}$ * (kg/sec)	Release Duration (sec)
Jewett, TX	19.312 inch	5 mi	35	2,200	129	0.00814	15,800
Tuscola, IL	14.438 inch	5 mi	35	2,200	72.3	0.00814	8,880
Odessa, TX	12.812 inch	5 mi	35	2,200	56.8	0.00814	6,980
Mattoon, IL	14.438 inch	0.5 mi	35	2,200	7.2	0.00814	888

* Choked flow $Q_{choked-H2S}$ = 0.0001*$Q_{choked-CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline. Unit Conversions: 1 psi = 0.06895 bars; 1 psi = 6,895 (Newtons/m^2 or Pascals); 1 psi = 0.06805 (*atmospheres*); 1 atm = 101,325 (Newtons/m^2 or Pascals).

C.1.4 CHOKED FLOW: GENERAL EXPRESSIONS AND MODEL INPUT DATA

Fluid moving at the speed of sound is called choked or critical flow. The speed of sound in a particular gas depends upon its temperature and pressure. Choked flow results from an opening in a pressurized vessel when the internal pressure exceeds the external pressure by a ratio dependent upon specific gas properties. Choked flow is the fastest a fluid can flow without an additional source of energy.

The gas emission rate through an opening can be evaluated as follows for both choked and non-choked flow conditions (Hanna & Drivas 1987, page 20):

$$\left.\begin{aligned}
Q_{choked}(t) &= C_v A_{exit}\, P_{pipe}(t)\sqrt{\frac{\gamma m_{wt}}{R^* T_{gas}(t)}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \\
Q_{non-choked}(t) &= C_v A_{exit}\, P_{pipe}(t)\sqrt{\frac{2 m_{wt}}{R^* T_{gas}(t)}\left(\frac{\gamma}{\gamma-1}\right)\left(\left(\frac{P_{atm}}{P_{pipe}(t)}\right)^{\frac{2}{\gamma}}-\left(\frac{P_{atm}}{P_{pipe}(t)}\right)^{\frac{\gamma+1}{\gamma}}\right)}
\end{aligned}\right\}$$

The term $Q_{choked}(t)$ $(kg/\sec)$ is the gas mass emission rate at time t under choked conditions; $Q_{non-choked}(t)$ $(kg/\sec)$ is the gas mass emission rate at time t under non-choked conditions; γ $(unitless)$ is the gas specific heat ratio (the heat capacity at constant pressure, C_{hp}, divided by the heat capacity at constant volume, C_{hv}; $P_{pipe}(t)$ (Newtons/m^2 or Pascals) is the absolute pipeline pressure at time t; C_v $(unitless)$ is the discharge coefficient (0-1) for the orifice (values are typically near one); A_{exit} (m^2) is the orifice area through which the gas escapes; m_{wt} $(kg/mole)$ is the gas molecular weight; R^* $\left(joule/\left(mole\ ^\circ K\right)\right)$ is the universal gas constant (i.e., 8.31); and $T_{gas}(t)$ $\left(^\circ K\right)$ is the absolute gas temperature in the pipeline at time t.

Choked or critical flow means the gas is flowing at its sonic velocity, which is the speed of sound in the gas. Escaping gas will remain at choked flow conditions as long as the pipeline pressure remains above the following pressure criterion:

$$\frac{P_{pipe}(t)}{P_{atm}} \geq \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma}{\gamma - 1}}$$

The term P_{atm} (Newtons/m^2 or Pascals) is the absolute atmosphere pressure, which is taken to be 101,325 N/m^2. The $P_{pipe-CO_2}/P_{atm}$ criterion is equal to 1.88 for carbon dioxide, such that:

$$\frac{P_{pipe-CO_2}}{P_{atm}} \geq 1.88$$

Hence, carbon dioxide will flow from an opening in the pipeline at its sonic velocity as the pipeline pressure decreases with time until the absolute pipeline pressure drops below 1.88 atms, or about 27-28 psia. The mass flow rate $Q_{choked}(t)$ steadily decreases with time as the pressure $P_{pipe}(t)$ in the pipeline decreases. All pipeline releases will be assumed to occur under adiabatic conditions since the emissions occurs at a rapid rate.

For sensitivity to the assumption of constant mass emission the following equation can be used. This equation gives the fraction of the initial mass discharged as a function of time (Bird, Stewart, & Lightfoot, 2002):

$$t - t_0 = \frac{\left(F^{\frac{1}{2}(1-\gamma)} - 1\right)\left(\frac{2}{\gamma - 1}\right)\left(\frac{V_{pipe}}{C_v A_{exit}}\right)}{\sqrt{\frac{\gamma P_{pipe}(t_0)}{\rho_{gas}(t_0)}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}}$$

The term $t - t_0$ $(\sec)$ is the time interval since the start of gas emissions; F $(unitless)$ is the fraction (0-1) of initial gas weight remaining in the pressurized pipe at time t;. V_{pipe} $\left(m^3\right)$is the internal volume of the pipe; $P_{pipe}(t_0)$ (Newtons/m^2 or Pascals) is the absolute pipeline pressure at time t_0; and $\rho_{gas}(t_0)$ $\left(kg/m^3\right)$ is the initial density of the pressurized gas in the pipe.

The absolute pressure $P_{pipe}(t)$ (Newtons/m^2 or Pascals) and absolute temperature $T_{pipe}(t)$ $\left(^\circ K\right)$ of the remaining gas in the pipe is predicted using the following equations that assume isenthalpic expansion of an ideal gas, such that:

$$\left.\begin{aligned} P_{pipe}(t) &= P_{pipe}(t_0)F(t)^{\gamma} \\ T_{pipe}(t) &= T_{pipe}(t_0)F(t)^{(\gamma-1)} \end{aligned}\right\}$$

The term $F(t)$ is the fraction of mass remaining in the pipe at time t.

The physical and chemical properties used in the SLAB model to simulate choked flow were presented in Tables C-1.5 and C-1.6 above. On the pipeline, pressure and temperature will decrease during a release but for purposes of simulation (SLAB) the release mass flow rate is kept at that of the initial choked flow.

C.1.5 C-1 REFERENCES:

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C.2 Estimating the Effects of Gas Expansion from Pipelines and Wellbores with SLAB: Selected Sensitivity Analyses

Consider the scenario where a pipeline with a supercritical fluid is severed or punctured. The fluid will exit the hole in the pipeline at the sonic velocity of the gas, which is the maximum possible speed. This velocity is a function of the pressure and temperature of the fluid in the pipeline. This is called choked or critical flow since it defines the upper limit on the rate at which a gas can escape from a hole. The pressure and temperature of the fluid remaining within the pipeline will vary as the discharge continues. Carbon dioxide can exist in a liquid phase, a gas phase, a solid phase, or as supercritical fluid. The diagrams of Figure C-2.1 and Figures C-3.1 and C-3.2 (next section) show that the carbon dioxide phase depends on both the temperature and pressure. The pressure and temperature of CO_2 in the pipeline do not remain constant as the CO_2 discharges into the atmosphere. Pressure and temperature variation with time are approximated in the Figures C-2.2 and C-2.3 for CO_2 fluid discharging from a five-mile long section of pipeline.

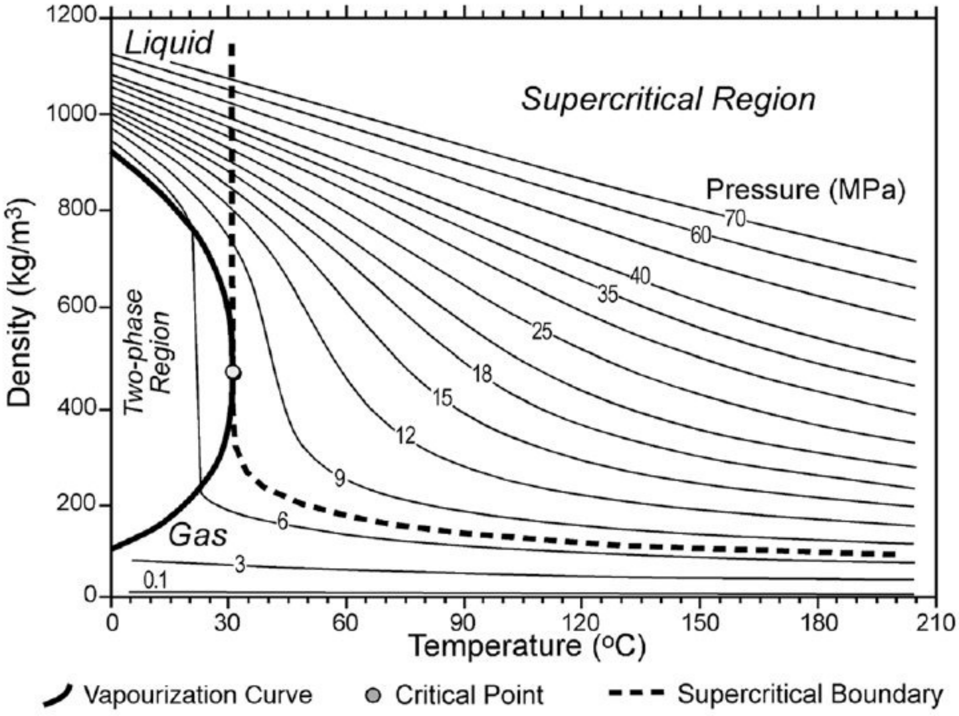

Figure C-2.1. The Supercritical Region of Carbon Dioxide is a Function *of* both Pressure and Temperature.

Taken from Bachu (2003) and IPCC (Annex I, 2005). Note that 1 MPa = 145 psi.

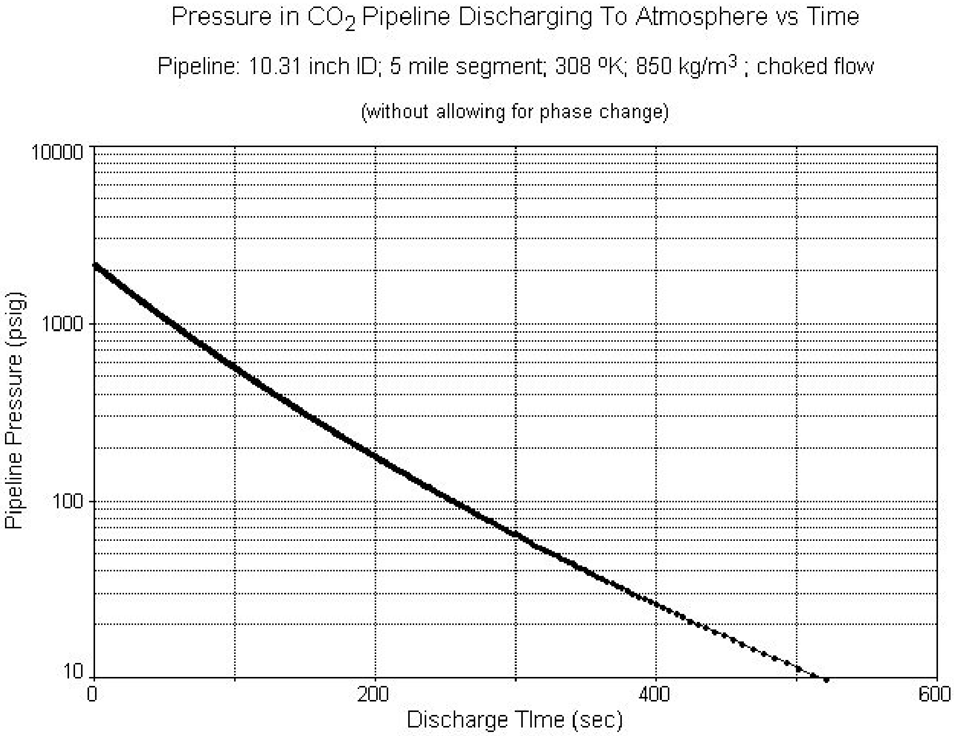

Figure C-2.2. CO_2 Pipeline Pressure Plotted as a Function of Time for the Case of Choked Flow Following a Complete Severing of the Pipeline.

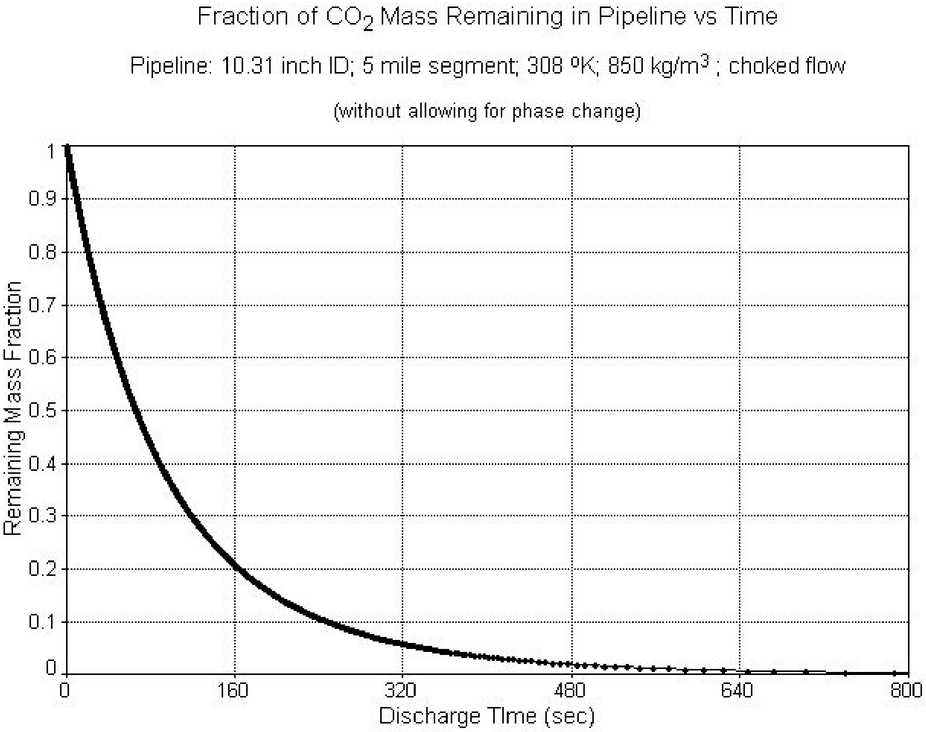

Figure C-2.3. Fraction of CO_2 Mass Remaining in the Pipeline is Plotted as a Function of Time for the Case of Choked Flow Following a Complete Severance of the Pipeline.
(Note that 85% of the initial CO_2 mass is discharged by 200 seconds.)

The SLAB model assumes the CO_2 in the pipeline remains at a constant pressure and temperature during the release simulation. In Figure C-2.4 more than 85% of the CO_2 escapes from the pipeline source in less than 200 seconds. This indicates that the discharge process is rapid and the assumption of constant pressure and temperature may not be very important to the subsequent atmospheric transport processes simulated by SLAB. Several simulations were performed with SLAB to estimate the effect of the variable pressure and temperature during the gas discharge. However, the general conclusions based on a constant temperature and pressure source as currently limited by SLAB would most likely be the same as a future model using a variable pressure and temperature source.

C.2.1 BACKGROUND

The SLAB model is used to simulate the cases where the CO_2 transmission pipeline is either completely severed or where the pipeline is punctured. The atmospheric CO_2 concentrations are then numerically predicted downwind of the discharge point using a constant wind direction, wind-speed, and Pasquill atmospheric stability class. The highest predicted downwind concentrations typically occur when the fluid escapes the pipeline as a horizontal jet. A jet release from a pressurized pipeline can be simulated in SLAB either as an instantaneous source (puff) or as a constant source over a finite period. Releases can consist of both vapor and entrained liquid aerosol phases.

C.2.2 SENSITIVITY SIMULATIONS

Since it was not possible to directly incorporate the effects of variable pressure and temperature in SLAB, a series of sensitivity simulations were made using various extremes in parameter values. A reference case and three other cases are shown below in Table C-2.1. The reference case assumes that all of the CO_2 is discharged in the vapor phase with the pipeline pressure held constant at the initial value of 2,200 psi and at the initial temperature of 308 °K. To examine the sensitivity of the SLAB model to source conditions, three additional cases were examined. The reference case and cases 1, 2, and 3 all have the same total mass released. Case 1 assumes that 50 percent of the discharging fluid is in the liquid phase with the pipeline pressure held constant at 2,200 psi and temperature at 308 °K. Case 2 assumes that 99% of the discharging fluid is in the liquid phase with the pipeline pressure held constant at 2,200 psi and temperature at 308 °K. Case 3 simulates the discharge of 50 percent of the fluid in the liquid phase but the pipeline pressure is held at a constant value of 1,100 psi and the temperature at 200 °K. Concentrations of CO_2 predicted by SLAB are shown in Table C-2.2 for the reference case and the three sensitivity cases.

Table C-2.1. Input Data for Severed Pipeline Simulations of CO_2 Release using SLAB for a 5-Mile Section of 19.3-Inch Inside-Diameter Pipeline. (All runs shown here are simulated with an F2 meteorological condition [2 m/sec wind and Pasquill stability class F].)

Parameter	Reference Case	Case 1	Case 2	Case 3
Pipe pressure (psi)	2,200	2,200	2,200	1,100
Pipe temperature (°K)	308	308	308	200
Discharge Rate (Kg/sec)	7,950	7,950	7,950	4,896
Discharge Duration (sec)	162	162	163	269
% Liquid mass fraction	CMED0 = 0 All CO_2 discharges as a gas	CMED0 = 0.5 ½ the CO_2 discharges as a gas & ½ as a liquid	CMED0 = 0.99 All CO_2 discharges as a liquid	CMED0 = 0.5 ½ the CO_2 discharges as a gas & ½ as a liquid

CMEDO is a SLAB input parameter which sets the gas to liquid ratio at the pipeline discharge point.

Table C-2.2. SLAB Results for the Severed Pipeline Simulations with a 5-Mile Section of 19.3-Inch ID Pipeline (See Table C-2.1). (The distance given here is the maximum downwind distance, measured in meters from the pipeline, to the particular concentration value noted in column 1. It should be noted that these concentrations are time averaged over 15 minutes, to be consistent with health effect standards. See Chapter 3.)

CO_2 Conc Levels (ppmv)	Reference Case (meters)	Case 1 (meters)	Case 2 (meters)	Case 3 (meters)
15,000	562	1884	1728	1808
20,000	281	1614	1475	1552
30,000	193	1256	1184	1240
40,000	158	375	965	578
60,000	107	240	267	368
70,000	65	202	223	309

C.2.3 DISCUSSION

Cases 1, 2, and 3 predict further distances than the reference case, even though they are discharging the same total mass. All cases assume the CO_2 in the pipeline is initially in a supercritical phase. However, once the CO_2 is discharged through the ruptured pipe, and the corresponding pressure and temperature drop, then a portion of the CO_2 may convert to a liquid phase or a solid "snow" phase or both. The current SLAB model does not predict phase changes that can occur within the pipeline and discharge orifice (i.e., the ruptured hole). Instead, SLAB simulations start just outside of the discharge point and the model tracks the subsequent advection and dispersion of gases in the atmosphere. The percent vapor and liquid discharged from the source is set using the SLAB parameter CMEDO. Setting the parameter CMEDO = 0 means that all of the discharging CO_2 is in the vapor phase; setting CMEDO = 0.99 means that virtually all of the discharging fluid is released in a liquid phase.

Case 3 is interesting in that the initial pipeline pressure is one-half that of the reference case but SLAB still predicts longer distances to the same concentrations. This demonstrates the effect of having a lower temperature combined with a portion of the discharging CO_2 in the liquid phase (i.e., as a liquid aerosol). At the lower temperature the liquid aerosol can remain as such for longer distances before vaporizing and thus the CO_2 plume experiences less lateral dispersion.

As the discharging vapor and liquid flow out into the atmosphere, the entrainment of ambient air will dilute the mixture. The transport and dispersal of the liquid phase is simulated by treating the liquid as a mist. This process of discharging mixed phases can result in considerably more CO_2 being transported downwind (Hanna and Drivas 1987, page 25) in comparison to that which would be transported by pure vapor phase releases.

The actual emission process from a pressurized pipeline is more complex. The rapid expansion of CO_2 through a rupture or penetration can be approximated as an adiabatic, constant enthalpy process (a Joule-Thompson expansion). Pressure-enthalpy diagrams for CO_2 can be used to predict phase changes associated with such an expansion (See C-3, Figure C-3.2).

The results described here are similar to those reached in the CO_2CRC report (2005, page 101) for CO_2 sequestration in Australia. The report states "Releases across the range of operating pressures under consideration did not exhibit significantly different plume lengths because choked flow conditions and rapid depressurization of the pipeline limit release rates for the leak cases considered"

Any model that allows for a variable temperature, pressure, or any other thermodynamic variable during the discharge period is still limited by the constraint of having to rapidly discharge the same initial mass of CO_2 from the pipeline. The uncertainties in the dynamics of the release due to temperature and pressure effects are dwarfed by the uncertainty in the dynamics of the accident itself, the subsequent atmospheric transport, and the health effects.

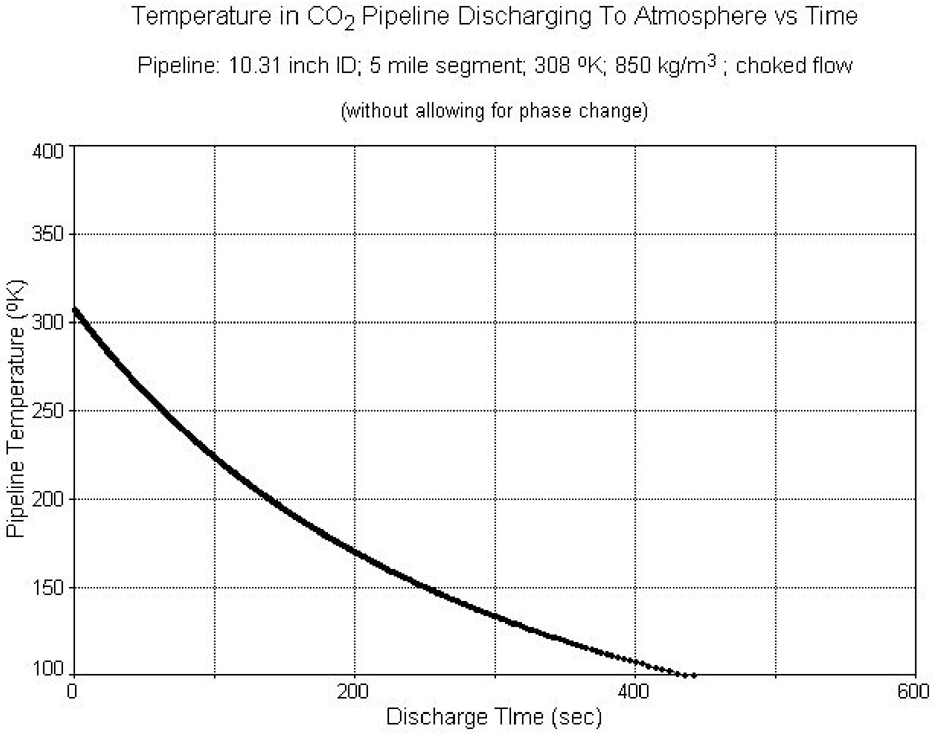

Figure C-2.4. CO_2 Pipeline Temperature Plotted as a Function of Tme for the Case of Choked Flow Following a Complete Severing of the Pipeline.

The theory and equations describing these isentropic expansion relationships for pressure and temperature are given in Part III of Appendix C.

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C.3 Estimation of CO_2 Phases in the Environment after Pipeline Release

Since the hypothetical releases from the pipeline occur quickly, it is assumed that they occur under adiabatic, isenthalpic conditions (Walas, 1985). This is also known as a Joule-Thompson expansion of the fluid. Also assumed is that since the pipeline fluid is 95 percent CO_2, the phase behavior of the fluid mixture can be estimated based upon that of the major component CO_2. Although there are methods for estimating the phase conditions of multicomponent fluid mixtures (for example, the Peng-Robinson equation of state; Walas, 1985), these methods apply best to Vapor-Liquid systems and not as well to a system when solids are present.

Initial conditions in the pipeline are taken as 2,200 psi and 308°K. This pressure and temperature are above the critical point values for CO_2 (1,072 psi and 304.2°K), so the CO_2 in the pipeline is considered a supercritical fluid (dense fluid) rather than a vapor or liquid. At the pipeline pressure and temperature, CO_2 has an enthalpy of 65.5 BTU per pound (Figure C-111.2). The constant enthalpy expansion of the supercritical CO_2 to atmospheric conditions will result in solid and vapor phases as can be seen in Figure C-111, 2. The temperature of the solid-vapor phase mixture will be -78°C as shown by the sublimation line in Figure C-111.1.

The fraction vapor and solid phases can be estimated based upon the original enthalpy at pipeline conditions and the constant quality lines shown in Figure C-111.2. The indicated fraction of the mixture that is vapor — after expansion, is roughly 74 percent. The fraction can be determined more precisely by calculation based upon the enthalpy of the vapor phase (130 BTU/lb), and solid phase (-116 BTU/lb), at atmospheric conditions (Smith and Van Ness, 1987):

1) Let x be the fraction of the released CO_2 that will be solid phase (dry ice snow);

2) Then to preserve constant enthalpy, it follows that (-116 BTU/lb) x + 130 BTU/lb (1-x) = 65.5 BTU/lb; and

3) The above equation can be solved for x, giving x = 0.262, or 26.2 percent of the CO_2 existing as solid following the release.

C.3.1 IMPACTS ON TRACE CONSTITUENTS

The trace constituents present in the CO_2 supercritical fluid will have only minor impacts on the resulting temperature and phases present after expansion into the atmosphere. For example, the very small amount of water present in the pipeline will likely form CO_2 crystal hydrates that could` incorporate minor amounts of other trace constituents. Hydrogen Sulfide is a trace constituent of significant interest due to its toxicity. H_2S has a critical temperature of 100°C; a critical pressure of 89.37 bar (1307 psi); a vapor point of 18 bar at 21°C; a boiling point of -60°C at 1 bar; a melting point of -86°C at 1 bar; and a triple point pressure of 0.28 bar at a triple point temperature of -86°C. Comparison shows the properties of H_2S to be somewhat similar to those of CO_2 (Figure C-111.3). Pure H_2S is a dense fluid at pipeline temperatures and pressures. Expansion of pure H_2S to atmospheric pressure will result in cooling to about -48°C and the formation of two phases (Figure C-111, 4). The H_2S forms vapor (35%) and liquid (65%) phases since the resulting temperature is above the melting point.

Based upon the behavior of pure H_2S and pure CO_2, it is expected that H_2S would be preferentially associated with the solid phase formed by expansion of the supercritical fluid. The vapor phase ratios of pure H_2S and CO_2 suggest that after expansion to the atmosphere the mixture solid phase would contain roughly 200 ppm H_2S and the mixture vapor phase would contain roughly 50 ppm H_2S. Calculations using the Peng-Robinson equation of state (Walas, 1985) also indicate that a trace H_2S (100 ppm)/CO_2

pipeline mixture would yield two phases after expansion to the atmosphere, with the vapor phase containing roughly 50 ppm H_2S.

C.3.2 IMPACTS OF MIXING WITH THE ATMOSPHERE

Upon discharging from the pipeline a portion of the trace H_2S (100 ppm)/CO_2 pipeline fluid would begin mixing with the atmospheric gas, which for simplicity could be considered to contain initially 78 percent nitrogen, 21 percent oxygen, and 1 percent argon. Mixing would alter the gas properties and add heat to the trace H_2S (100 ppm)/CO_2 mixture. Over a period of several days all the solid associated H_2S and the CO_2 would move into the vapor phase. However, this period would be long relative to the duration of the pipeline release. This slow release from the solid phase would not impact the peak vapor phase concentrations associated with the initial discharge. Nor would the slow release cause concentration-time responses that create risk for the non-worker population. Water vapor from the atmosphere would also be present in the resulting post-pipe gas mixture. This would further reduce gas concentrations due to the formation of H_2S and CO_2 hydrates. However, since the amount of water vapor in air is small, this effect would be secondary to the original formation of the dry ice snow.

C.3.3 INPUTS TO RISK ASSESSMENT

The above discussion indicates that perhaps more than a proportional amount of H_2S will be retained with the CO_2 dry ice snow. However, to maintain a conservative (safe) approach in the risk assessment, the amount of H_2S that is initially discharged to the atmosphere following a pipeline release has been taken to be proportional to the initial release of CO_2 to vapor phase, that is 73.8 percent. Correspondingly, the amount of H_2S associated with the dry ice snow has been taken to be 26.2 percent.

C.3.4 REFERENCES

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Smith, J. M. and H. C. Van Ness 1987. *Chemical Engineering Thermodynamics*, McGraw-Hill, New York, New York, 1987.

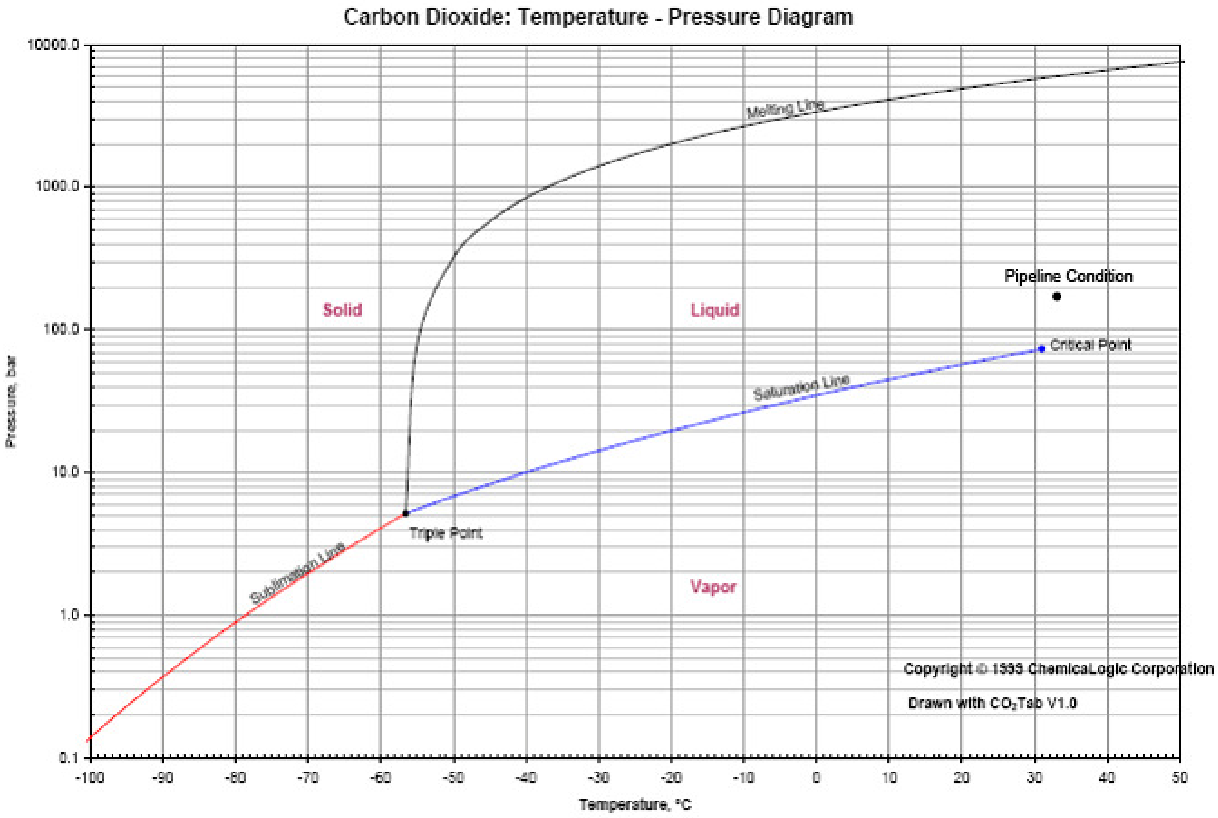
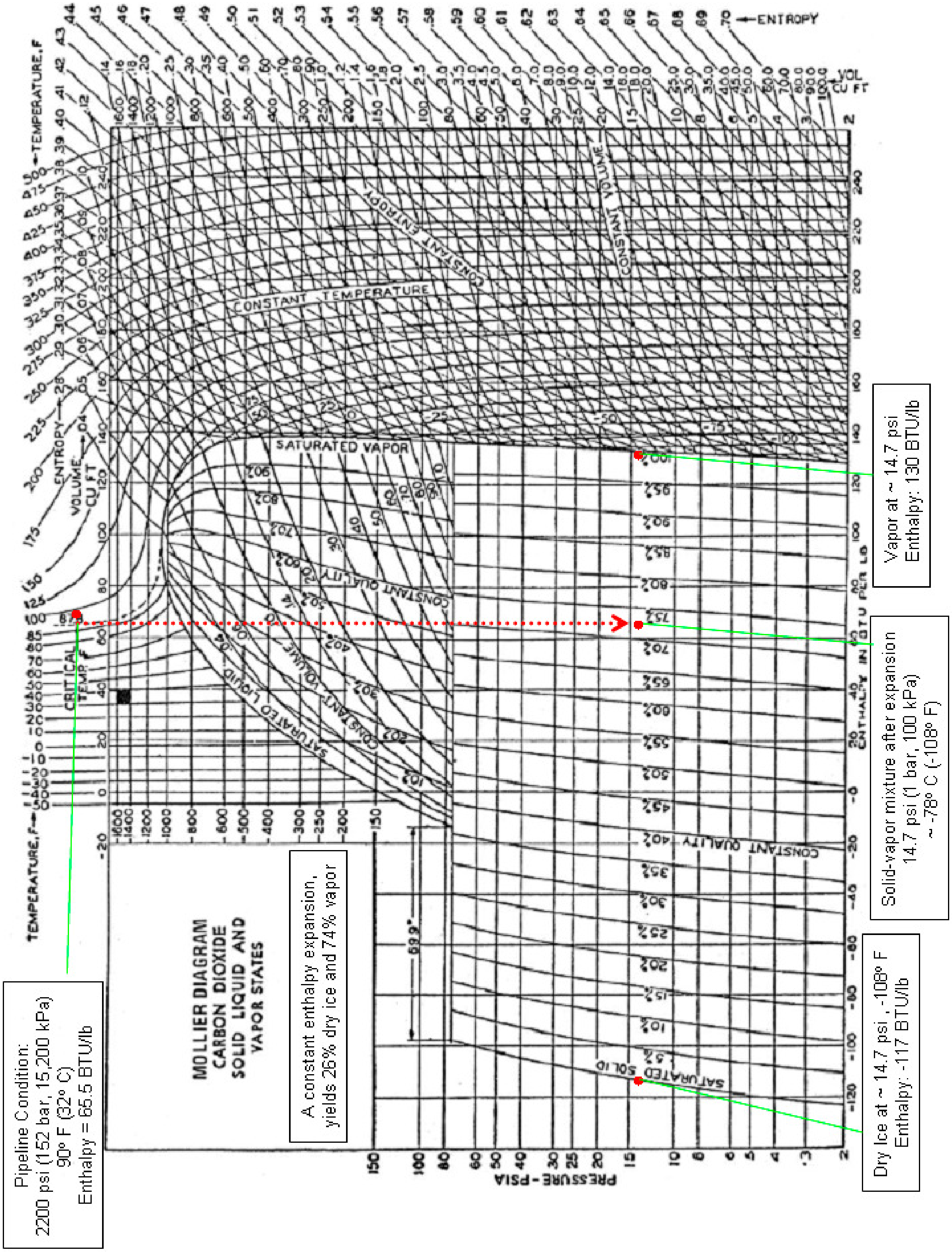


Figure C-3.1. Phase Diagram for Carbon Dioxide



Pipeline Condition:
2200 psi (152 bar, 15,200 kPa)
90° F (32° C)
Enthalpy = 65.5 BTU/lb

A constant enthalpy expansion,
yields 26% dry ice and 74% vapor

Vapor at ~ 14.7 psi
Enthalpy: 130 BTU/lb

Solid-vapor mixture after expansion
14.7 psi (1 bar, 100 kPa)
~ -78° C (-108° F)

Dry Ice at ~ 14.7 psi, -108° F
Enthalpy: -117 BTU/lb

Figure C-3.2. Mollier Diagram for Carbon Phases

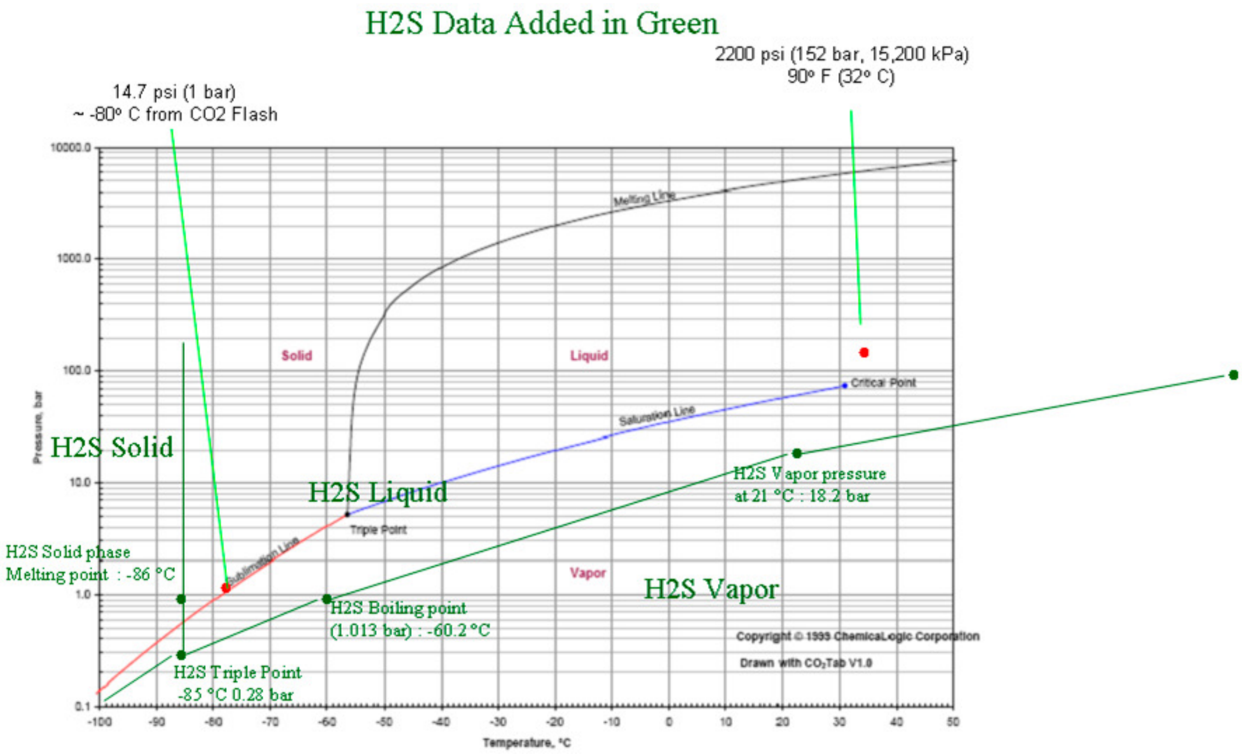
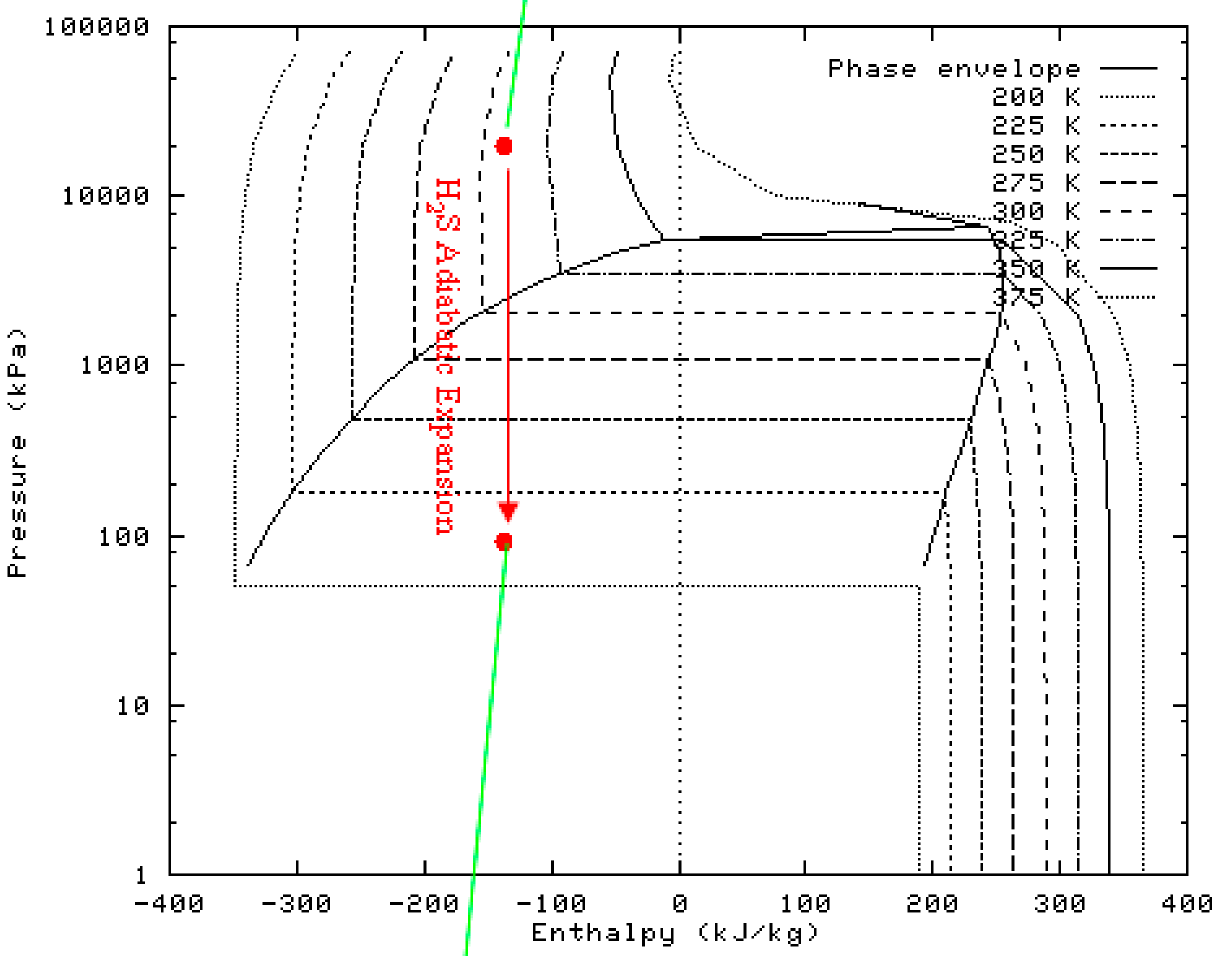


Figure C-3.3. Comparison of Phase Diagrams: Carbon Dioxide Phase Diagram with Hydrogen Sulfide Phase Diagram (superimposed in green). (Point to the far right is the critical point for H2S 1,307 psi, 212 ^{o}F; 90 bar, 100 ^{o}C)

Pipeline conditions: 2200 psi (152 bar, 15,200 kPa)
90° F (32° C)



H_2S is 65% liquid after expansion to 1 bar at a final temperature of 225° K (-48° C)

Figure C-3.4. Mollier Diagram for Hydrogen Sulfide (Isenthalpic expansion from pipeline conditions to atmospheric conditions is shown as red vertical line)

C.4 Risk Calculations: "Pipeline- Walking"

The "Pipeline-Walking" method calculates the number of individuals hypothetically exposed to carbon dioxide and hydrogen sulfide from simulated pipeline ruptures and punctures. The "Pipeline-Walking" approach described here is a tier three analysis, one of the more robust, comprehensive, and computationally intense methods used in risk assessment. The method moves along the pipeline and at points 300 meters apart a series of calculations and simulations are made. First, the total mass of the fluid in the pipe segment is calculated for the specific pipeline properties (inside pipe diameter, length between safety valves, fluid pressure and temperature, etc.) Then a release is simulated. Using an adiabatic, isenthalpic expansion (Joule-Thompson) the CO_2 is partitioned into vapor and solid phases. The H_2S is conservatively assumed to partition like the CO_2 (See C-3). The vapor phase transport is then simulated using the SLAB model (Version 2) for seven different wind-speed/atmospheric Pasquill stability classes. The five main steps in this approach are described below.

Step 1. Summarize Meteorological Conditions that Affect Plume Transport. The meteorological data from the EIVs were used to characterize atmospheric conditions at each site. The proportion of time over a year in each of 112 atmospheric states (combinations of 16 wind directions and 7 stability conditions) was defined. The information for the Jewett site is provided in Table 4-9. The meteorological data for the other sites are presented in C-4.

Step 2. Simulate the Area Potentially Affected by a Pipeline Release. The SLAB model was run to determine the area of the potential impact zone for each of the 112 defined atmospheric states. This step was repeated every 300 m along the length of the pipeline for the release conditions corresponding to both a pipeline puncture and pipeline rupture. 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. For a pipeline puncture, the gaseous impact zone or footprint was determined for five concentration levels corresponding to selected health-effect levels for 8-hour exposure durations: 0.33 ppmv H_2S, 17 ppmv H_2S, 31 ppmv H_2S, 20,000 ppmv CO_2, and 40,000 ppmv CO_2.

Step 3. Estimate Population Affected for Each Atmospheric State. The digital image of each predicted exposure zone defined in Step 2 for each of the 112 atmospheric states was superimposed onto a map containing the digitized census-tract data. The exposure zone was then subdivided into areas having uniform population density. The total affected population in each exposure zone (p_j) was estimated as the sum of the products of the area of each unique sub-portion of the exposure zone (A_k) and the corresponding population density (ρ_k), where k = the index for the census blocks within the area of the plume.

$$p_j = \sum_{k=1}^{m} \rho_k A_k \qquad \text{(Equation 4.1)}$$

where: m= total number of distinct census tracts in impact zone

j = number of defined atmospheric states

= 112

Step 4. Determine the Expected Number of Individuals Potentially Affected at the Specified Release Points. The affected population in each exposure zone (p_j) was next multiplied by the proportion of the time (relative importance) in each atmospheric state (atm_j). Since atm_j for all j = 112 sums to 1, the sum of these products provides the expected number of affected individuals at any selected point (i) along the pipeline (P_i):

$$P_i = \sum_{j=1}^{112} p_j \, atm_j \qquad \text{(Equation 4.2)}$$

or combining Equations 1 and 2:

$$P_i = \sum_{j=1}^{112} atm_j \sum_{k=1}^{m} \rho_k A_k \qquad \text{(Equation 4.3)}$$

Step 5. Characterize the Potential Exposure Along the Entire Pipeline. Tabular and graphical summaries of the expected number of affected individuals (P_i) at all points along the pipeline provide a comprehensive summary of potential health effects from a pipeline release and, as described below, a basis for comparisons between sites. For example, Figure 4-2 shows the results of the analysis of the estimated population exposed to H_2S concentrations (0.51 ppmv) that can result in adverse effects at the Jewett site. Along much of the pipeline (59 km), near zero or less than 10 individuals would be expected to be exposed to H_2S above 0.51 ppmv from a pipeline rupture. At about 62 km along the pipeline, the potentially exposed population increases to greater than 30 and up to 52 individuals.

The expected number of individuals potentially exposed is then plotted versus distance along the pipe. All information is recorded in the state planar system. This entire process is then repeated for the puncture scenarios.

C.4.1 PIPELINE RUPTURES

Maximum population exposure by rupture of the Jewett, Tuscola, Odessa, and Mattoon pipelines is summarized below. Exposures were calculated for five gas concentration levels: three for H_2S, 0.51 ppmv, 27 ppmv, and 50 ppmv; and two for CO_2, 30,000 ppmv and 40,000 ppmv.

Table C-4.1. Expected Population Exposed by Pipeline Rupture at Four Candidate Sites, at Different H_2S and CO_2 Levels

Site	0.51 ppmv H_2S	27 ppmv H_2S	50 ppmv H_2S	30,000 ppmv CO_2	40,000 ppmv CO_2
Jewett	51.8	1.32	1.19	0.47	< 0.5
Tuscola	7.4	0.15	< 0.2	0.089	< 0.1
Odessa	0.19	0.004	< 0.004	0	0
Mattoon	0.12	0.001	< 0.001	0	0

(The rupture released all fluid from five mile segments of the pipeline, except for Mattoon, where the entire 0.5 mile pipeline contents were released. Of the releases, 74 percent initially was emitted directly to the gas phase; the remaining 26 percent formed a solid phase (dry-ice snow) which very slowly sublimated to the vapor phase over time. (See Section C-3). Pipeline characteristics are summarized in Tables C-4.6 and C-4.7. Similar calculations and results are presented for the 3 inch by 1 inch pipeline puncture scenario in a following section).

The probabilities of wind direction and wind-speed/stability classes are listed in the following tables for the Jewett, Tuscola, Odessa, and Mattoon sites (Tables C-4.2, 3, 4, 5). The final population impact for the 0.51 ppmv contour level of H_2S are shown in the following graphs for the Jewett, Tuscola, Odessa, and Mattoon sites (Figures C-4.1, .2, .3, and .4).

Table C-4.2. Wind Rose Data for the Jewett, TX, Site Based on Combined Data from Waco and Huntsville Regional Airports from Jan 1, 2005, through Dec 31, 2005 (EIV, 2007). (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.)

	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	1.125	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

Table C-4.3. Wind Rose for the Tuscola, IL, Site is Based on Data from Champaign/Urbana Willard Airport from Jan 1, 1998, through Dec 31, 2006 (EIV, 2007). (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.)

	F02	**A02**	**B03**	**C05**	**D07**	**D10**	**D12**
From	**Calm (%)**	**1-4 knots (%)**	**4-7 knots (%)**	**7-11 knots (%)**	**11-17 knots (%)**	**17-21 knots (%)**	**>=22 knots (%)**
S	0.29	0.493	3.355	4.342	3.750	0.888	0.395
SSW	0.29	0.197	2.270	2.664	1.974	0.493	0.296
SW	0.29	0.296	1.875	1.776	1.480	0.395	0.099
WSW	0.29	0.296	1.579	1.382	0.888	0.395	0.197
W	0.29	0.592	2.368	2.368	2.171	0.888	0.493
WNW	0.29	0.336	1.678	1.480	1.480	0.592	0.355
NW	0.29	0.257	1.382	1.579	1.421	0.395	0.099
NNW	0.29	0.099	1.184	1.184	0.987	0.257	0.039
N	0.29	0.375	1.776	1.776	1.086	0.296	0.020
NNE	0.29	0.000	1.086	1.421	0.789	0.237	0.020
NE	0.29	0.099	2.053	2.408	1.125	0.395	0.039
ENE	0.29	0.395	2.033	1.776	0.987	0.296	0.039
E	0.29	0.789	2.467	1.579	1.026	0.257	0.000
ESE	0.29	0.276	1.579	0.888	0.553	0.059	0.000
SE	0.29	0.414	1.658	1.263	0.849	0.158	0.000
SSE	0.29	0.237	1.875	1.579	1.184	0.395	0.059

Table C-4.4. Wind Rose for the Odessa, TX, Site is Based on Data from Midland International Airport from Jan 1, 2005, through Dec 31, 2006 (EIV, 2007). (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.)

	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	0.3	0.422	0.422	3.234	2.813	3.938	3.938
SSW	0.3	0.281	0.422	1.969	1.406	1.125	0.703
SW	0.3	0.422	0.281	1.406	0.984	0.703	0.422
WSW	0.3	0.281	0.422	1.125	0.563	0.563	1.266
W	0.3	0.422	0.141	1.125	0.563	0.703	1.688
WNW	0.3	0.000	0.000	0.844	0.422	0.141	0.563
NW	0.3	0.000	0.141	0.984	0.422	0.281	0.281
NNW	0.3	0.056	0.084	0.844	0.422	0.338	0.225
N	0.3	0.422	0.563	1.406	0.563	0.703	0.844
NNE	0.3	0.141	0.338	0.703	0.506	0.844	1.688
NE	0.3	0.000	0.281	1.125	0.984	1.406	1.828
ENE	0.3	0.225	0.338	1.547	1.125	0.984	0.844
E	0.3	0.366	0.338	2.756	1.744	1.688	0.703
ESE	0.3	0.281	0.422	2.109	1.406	1.266	0.703
SE	0.3	0.225	0.563	2.728	1.828	1.969	1.688
SSE	0.3	0.281	0.422	3.938	1.969	3.094	3.516

Table C-4.5. Wind Rose for the Mattoon, IL, Site is Based on Data from Mattoon/Charleston Coles Co. Airport from Jan 1, 1998, through Dec 31, 2006 (EIV, 2007). (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.)

	F02	**A02**	**B03**	**C05**	**D07**	**D10**	**D12**
From	**Calm (%)**	**1-4 knots (%)**	**4-7 knots (%)**	**7-11 knots (%)**	**11-17 knots (%)**	**17-21 knots (%)**	**>=22 knots (%)**
S	0.5088	1.7568	5.9459	6.4865	3.1081	0.2703	0.0000
SSW	0.5088	0.9459	3.5946	3.5135	1.4324	0.1081	0.0000
SW	0.5088	0.4054	2.2973	1.7568	0.6757	0.0000	0.0000
WSW	0.5088	0.3243	2.0270	1.0270	0.4054	0.0000	0.0000
W	0.5088	0.9189	2.1622	1.7568	1.0811	0.2703	0.0270
WNW	0.5088	0.1892	1.4865	1.7568	1.7568	0.6757	0.0811
NW	0.5088	0.0811	1.4595	1.6216	1.8919	0.6757	0.0811
NNW	0.5088	0.0811	1.3514	1.3514	1.2162	0.5135	0.0811
N	0.5088	0.4054	1.8919	2.1622	1.3514	0.4054	0.0000
NNE	0.5088	0.2703	1.3514	1.4865	0.8919	0.3243	0.0000
NE	0.5088	0.2703	1.6216	1.3514	0.6757	0.1351	0.0000
ENE	0.5088	0.2703	1.3514	1.6216	0.2703	0.0000	0.0000
E	0.5088	0.4054	1.3514	1.0811	0.6757	0.0000	0.0000
ESE	0.5088	0.0000	0.9459	0.6757	0.5405	0.0000	0.0000
SE	0.5088	0.4054	1.2162	0.9459	0.4054	0.0000	0.0000
SSE	0.5088	1.3514	2.7027	1.5946	0.8108	0.0270	0.0000

C.4.2 PIPELINE RUPTURE SIMULATIONS

Presented below are analyses of hypothetical pipeline ruptures. In all cases 74 percent of the contents of the pipeline section are released directly to the atmosphere as a gas. The remaining twenty six percent forms a dry-ice snow which sublimates very slowly. Input data used are shown in Tables C-4.6 and C-4.7. Results of the pipeline walk are shown in the figures which follow. Typically very few people are impacted and then only at very low levels.

Table C-4.6. Choked Flow Conditions for Carbon Dioxide Released from a Section of Pipeline under the Rupture Scenario

Site	ID and Orifice Area	Length	Pipeline Temperature (°C)	Absolute Pressure (psi)	CO_2 Mass (kg)	$Q_{choked-CO_2}$ * (kg/sec)	Release Duration (sec)
Jewett	19.312 in. 0.189 m^2	5 mi	35	2,200	954,600	5,880	162
Tuscola	14.438 in. 0.106 m^2	5 mi	35	2,200	535,100	3,290	162
Odessa	12.812 in. 0.0832 m^2	5 mi	35	2,200	420,320	2,590	162
Mattoon	14.438 in. 0.106 m^2	0.5 mi	35	2,200	53,510	3,290	16

* Supercritical density = 850 Kg/m3 at 35°C & 2,200 psi. Choked flow $Q_{choked-CO2}$ is based on carbon dioxide properties. Modeling assumes internal pipeline temperature, pressure, & emission rates remain constant during release. ID = Inner diameter of pipeline. Seventy-four percent of the CO_2 is directly released as a vapor; 26 percent forms dry-ice snow which very slowly sublimates.

Table C-4.7. Simulation Conditions for Hydrogen Sulfide Released from a Section of Pipeline under the Rupture Scenario

Site	ID and Orifice Area	Length	Pipeline Temperature (°C)	Absolute Pressure (psi)	H_2S Mass (kg)	$Q_{choked-H_2S}$ * (kg/sec)	Release Duration (sec)
Jewett	19.312 in. 0.189 m^2	5 mi	35	2,200	95	0.59	162
Tuscola	14.438 in. 0.106 m^2	5 mi	35	2,200	53	0.33	162
Odessa	12.812 in. 0.0832 m^2	5 mi	35	2,200	42	0.26	162
Mattoon	14.438 in. 0.106 m^2	0.5 mi	35	2,200	5.3	0.33	16

* Choked flow $Q_{choked-H2S} = 0.0001{*}Q_{choked-CO2}$ is based on carbon dioxide properties. Modeling assumes internal pipeline temperature, pressure, & emission rates remain constant during release. ID = Inner diameter of pipeline. Unit conversions: 1 psi = 0.06895 bars; 1 psi = 6,895 Newtons/m^2 or Pascals; 1 psi = 0.06805 (atmospheres); 1 atm = 101,325 Newtons/m^2 or Pascals. Seventy-four percent of the H_2S is directly released as a vapor; 26 percent is incorporated into dry-ice snow which very slowly sublimates.

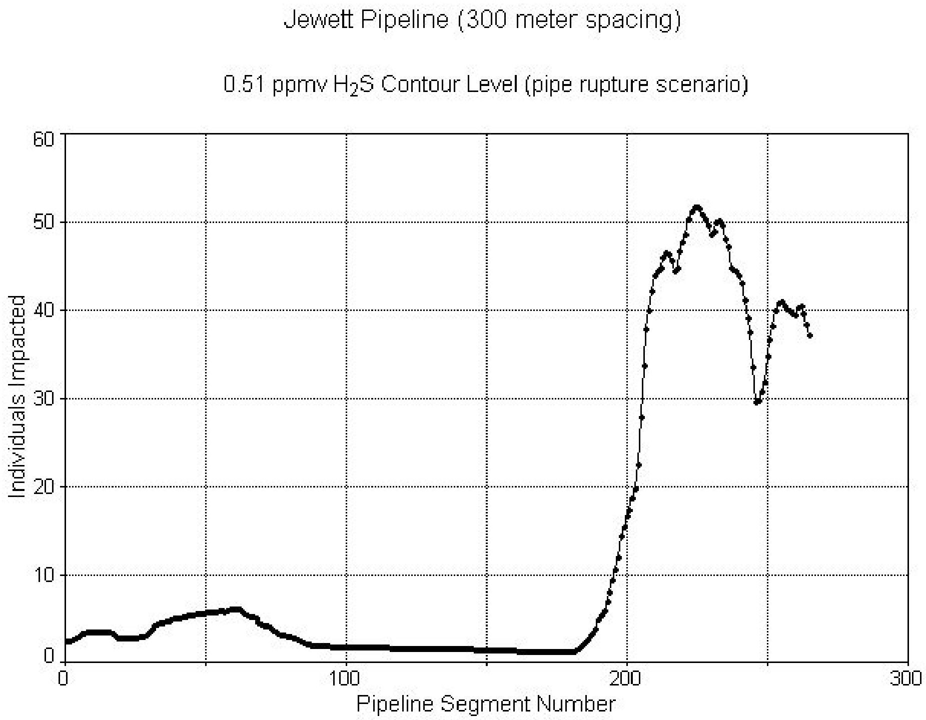


Figure C-4.1. Population Exposure, 0.51 ppmv H_2S Level, from the Pipeline Rupture Scenario at Jewett, TX. (Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection wells.)

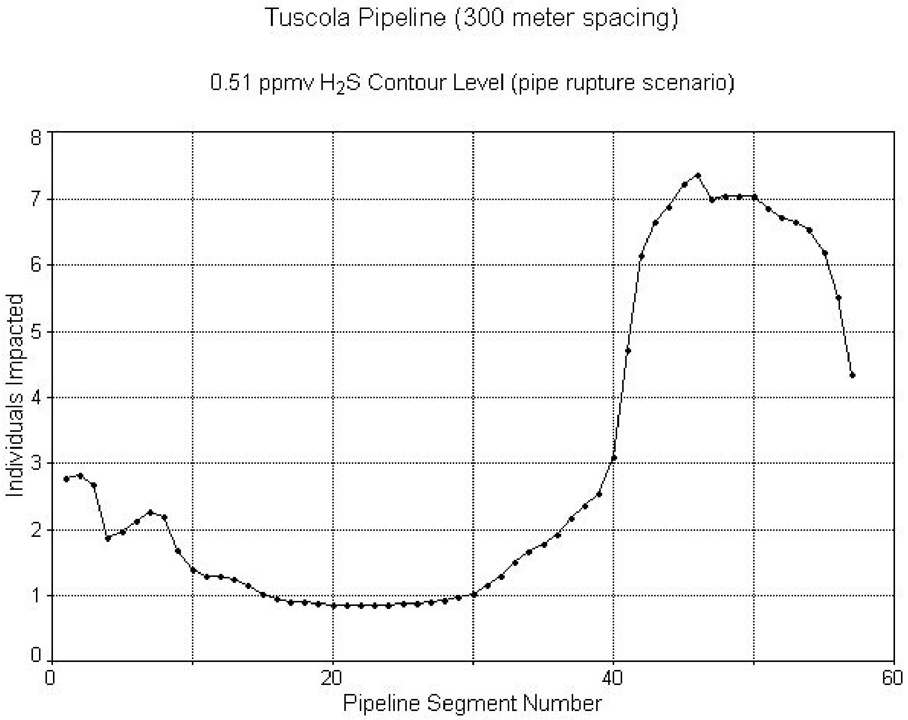


Figure C-4.2. Population Exposure, 0.51 ppmv H_2S Level, from the Pipeline Rupture Scenario at Tuscola, IL. (Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection well.)

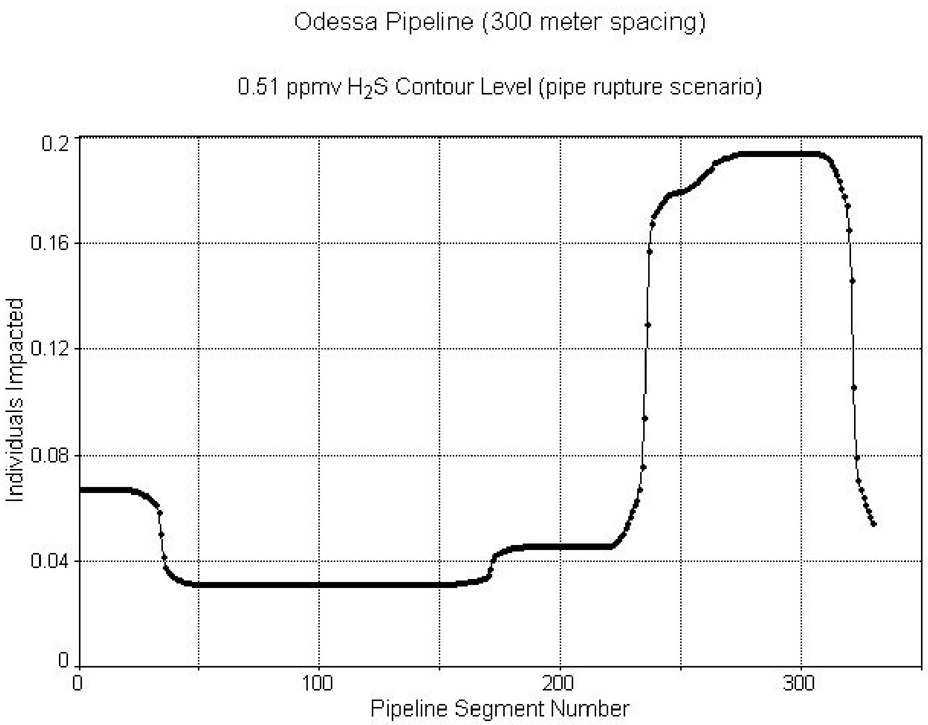


Figure C-4.3. Population Exposure, 0.51 ppmv H_2S Level, from the Pipeline Rupture Scenario at Odessa, TX. (Exposures calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection wells.)

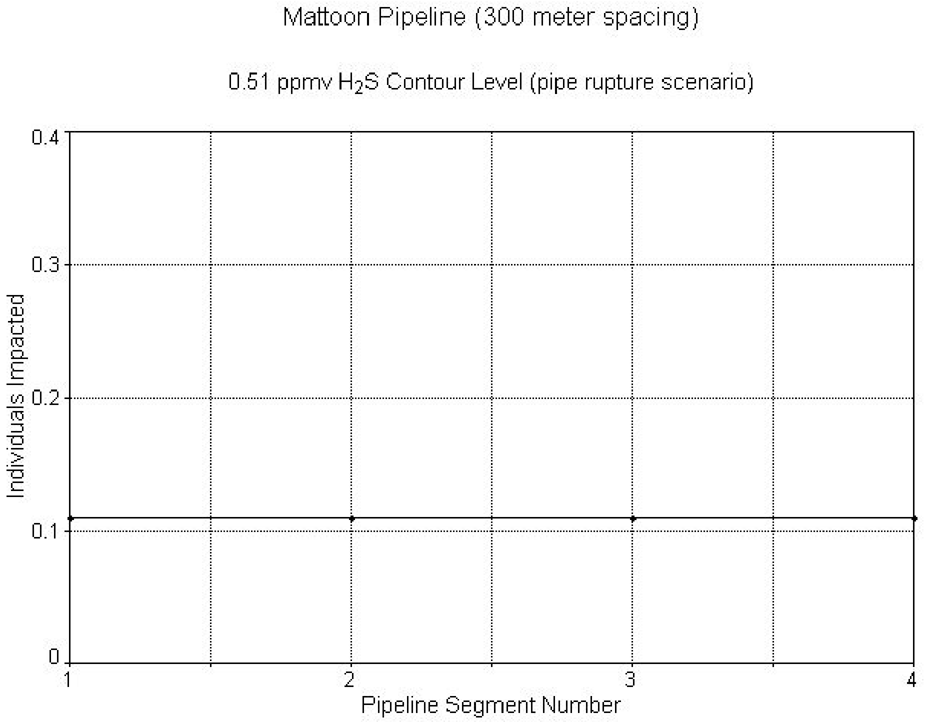


Figure C-4.4. Population Exposure, 0.51 ppmv H_2S Level, from the Pipeline Rupture Scenario at Mattoon, IL. (Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection well.)

C.4.3 PIPELINE PUNCTURE SIMULATIONS

Steps performed here are similar to those for the pipeline rupture simulations, as described previously. The puncture simulations were done separately from those for the rupture. The pipeline puncture is assumed to be a 3 inch by 1 inch hole created by a tooth on the bucket of a 30 to 60 ton tracked excavator.

The expected number of individuals exposed by a pipeline puncture at the Jewett, Tuscola, Odessa, and Mattoon sites are listed in Table C-4.8. Exposures for the puncture scenarios were calculated for five concentration levels: three for H_2S, 0.33 ppmv, 17 ppmv, and 31 ppmv; and two for CO_2, 20,000 ppmv, and 70,000 ppmv. These criteria are different from those for the pipeline rupture because the smaller opening associated with the puncture creates a longer duration plume. Calculations where performed every 300 meters along pipeline.

Table C-4.8. Maximum Population Exposed by Pipeline Puncture at Four Candidate Sites, at Five Different H_2S and CO_2 Levels

Site	0.33 ppmv H_2S	17 ppmv H_2S	31 ppmv H_2S	20,000 ppmv CO_2	70,000 ppmv CO_2
Jewett	6.18	0.076	< 0.08	0.196	< 0.2
Tuscola	1.069	0.015	< 0.02	0.067	< 0.1
Odessa	0.036	0.0005	< 0.0001	< 0.01	< 0.01
Mattoon	0.181	0.002	< 0.002	0.01	< 0.01

*Concentration standards shown here are lower than those shown in Table C-4.1 for the pipeline rupture. This results from exposure durations of one or more hours.

Table C-4.9. Choked Flow Conditions for Carbon Dioxide Released from a 3x1-Inch Puncture in Five-Mile Section of Pipeline using the Puncture Scenario

Site	ID and Orifice Area	Length	Pipeline Temperature (°C)	Absolute Pressure (psi)	CO_2 Mass (kg)	$Q_{choked-CO_2}$ * (kg/sec)	Release Duration (sec)
Jewett	19.312 inch	5 mi	35	2,200	954,600	60.2	15,800
Tuscola	14.438 inch	5 mi	35	2,200	535,000	60.2	8,880
Odessa	12.812 inch	5 mi	35	2,200	420,000	60.2	6,980
Mattoon	14.438 inch	0.5 mi	35	2,200	53,500	60.2	888

* Supercritical density = 850 Kg/m3 at 35°C & 2,200 psi. Choked flow $Q_{choked\text{-}CO2}$ is based on carbon dioxide properties. Modeling assumes internal pipeline temperature, pressure, & emission rates remain constant during release. ID = Inner diameter of pipeline. Seventy-four percent of the CO_2 is directly released as gas; 26 percent forms dry-ice snow which very slowly sublimates.

Table C-4.10. Simulation Conditions for Hydrogen Sulfide Released from a 3x1-Inch Puncture in Five-Mile Section of Pipeline using the Puncture Scenario

Site	ID and Orifice Area	Length	Pipeline Temperature (°C)	Absolute Pressure (psi)	H_2S Mass (kg)	$Q_{choked-H_2S}$ * (kg/sec)	Release Duration (sec)
Jewett	19.312 inch	5 mi	35	2,200.	95.	0.00602	15,800
Tuscola	14.438 inch	5 mi	35	2,200.	53.5	0.00602	8880
Odessa	12.812 inch	5 mi	35	2,200.	42	0.00602	6980.
Mattoon	14.438 inch	0.5 mi	35	2,200.	5.35	0.00602	888

* Choked flow $Q_{choked\text{-} H2S}$ = 0.0001*$Q_{choked\text{-}CO2}$ is based on carbon dioxide properties. Modeling assumes internal pipeline temperature, pressure, & emission rates remain constant during release. ID = Inner diameter of pipeline. Unit conversions: 1 psi = 0.06895 bars; 1 psi = 6,895 Newtons/m^2 or Pascals; 1 psi = 0.06805 (atmospheres); 1 atm = 101,325 Newtons/m^2 or Pascals. Seventy-four percent of the H_2S is directly released as gas; 26 percent is incorporated into dry-ice snow which very slowly sublimates.

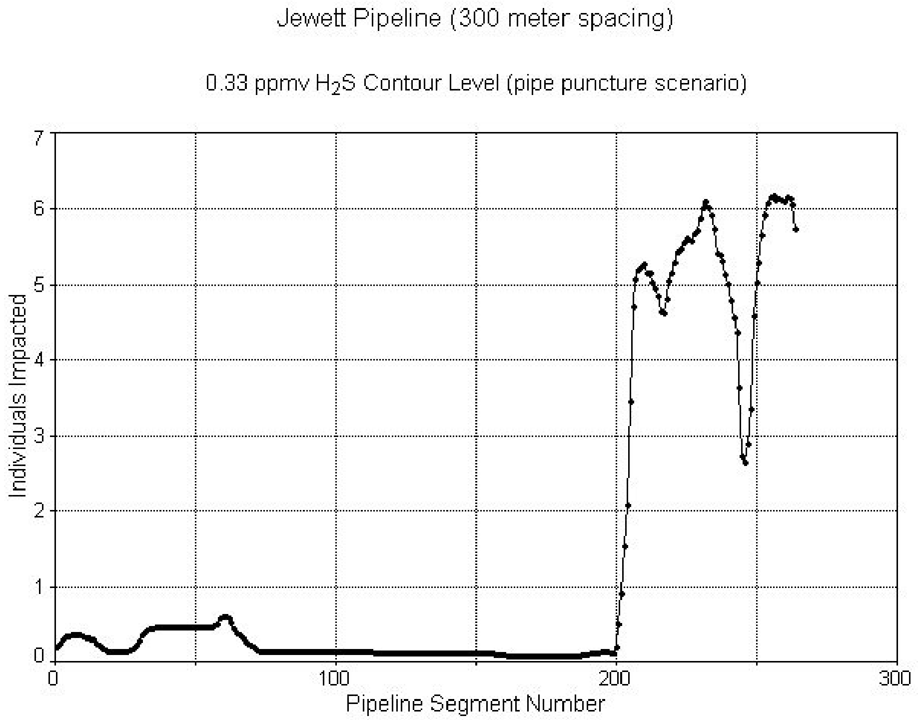


Figure C-4.5. Population Exposure, 0.33 ppmv H_2S Level, from a 3x1-Inch Puncture on the Jewett, TX, Pipeline (Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection wells.)

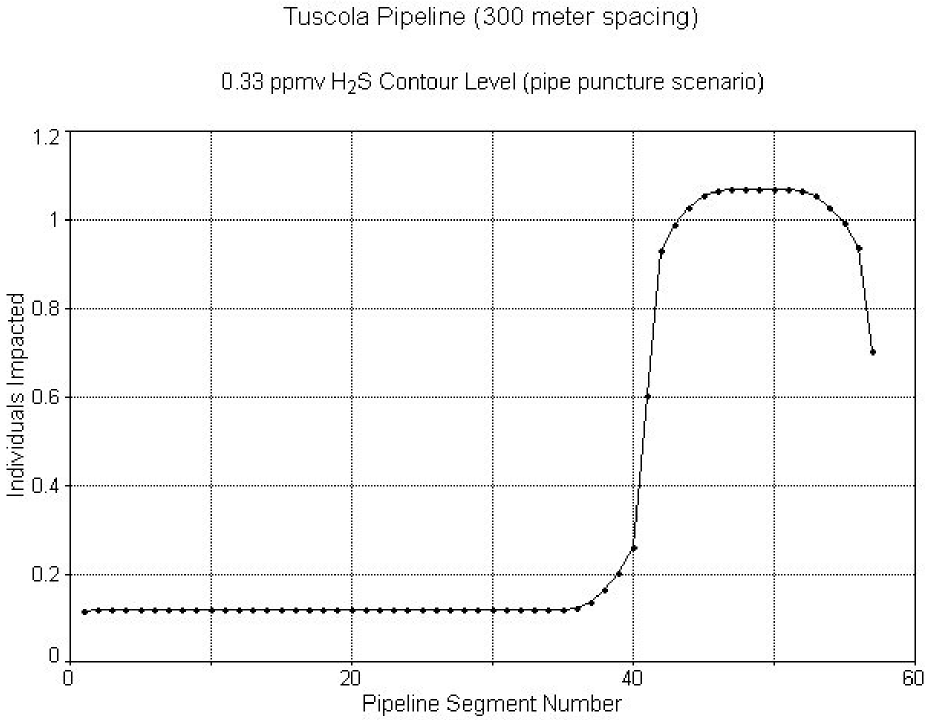


Figure C-4.6. Population Exposure, 0.33 ppmv H_2S Level, from a 3x1-Inch Puncture on the Tuscola, IL, Pipeline (Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection well.)

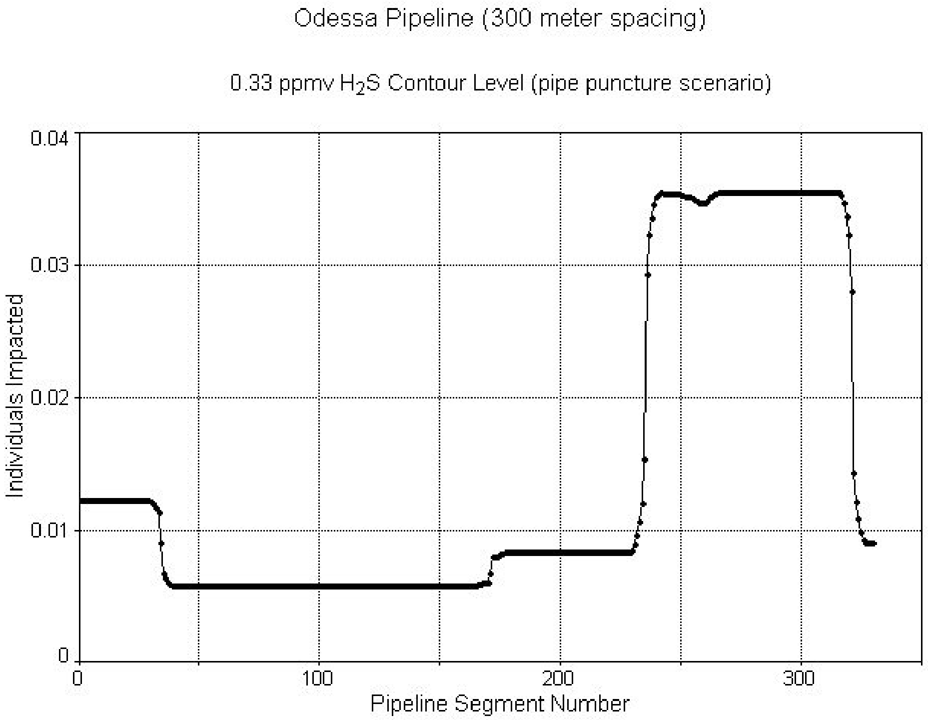


Figure C-4.7. Population Exposure, 0.33 ppmv H_2S Level, from a 3x1-Inch Puncture on the Odessa, TX, pipeline (Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection wells.)

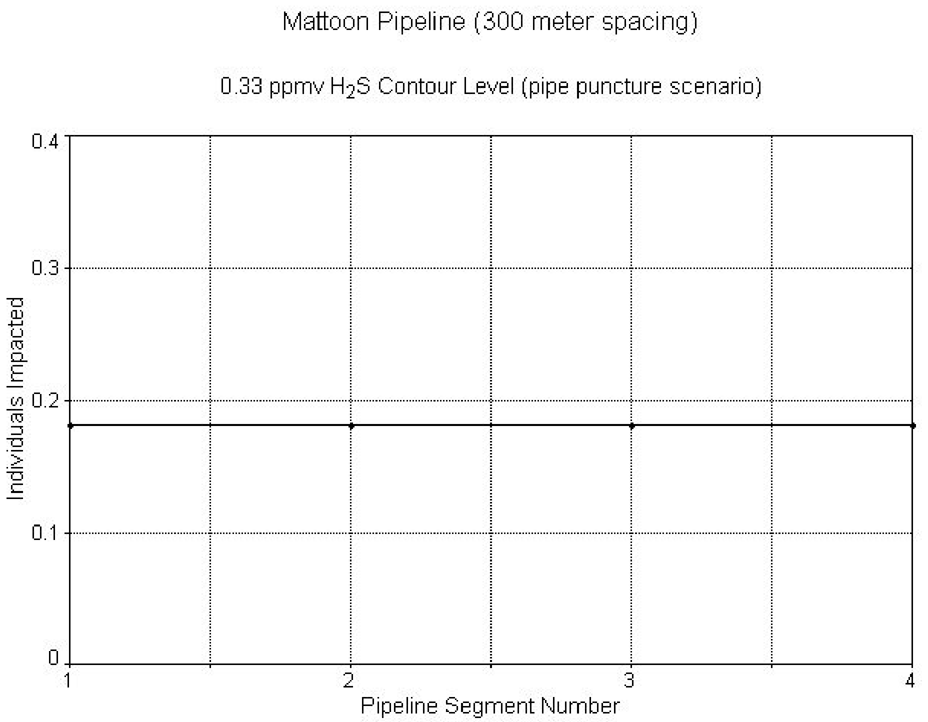


Figure C-4.8. Population Exposure, 0.33 ppmv H_2S Level, from a 3x1-Inch puncture on the Mattoon, IL, pipeline (Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection well.)

C.5 SLAB Modeling Results for Pipeline Rupture and Puncture for 2% H_2S Co-Sequestration Test

C.5.1 ATMOSPHERIC TRANSPORT MODELS USED

The approach used for this modeling effort to simulate the potential effects from a release during a co-sequestration test is the same as used for the original pipeline releases. The results for the original pipeline release scenario are presented in Appendix C.4. The SLAB model (Version 2) was developed for the US Department of Energy to simulate the three-dimensional atmospheric dispersion of gases that are denser than air (Ermak, 1990). The processes of air entrainment and gravity spread associated with dense gases are accounted for by the model. The crosswind-averaged properties of a released gas cloud are calculated as a function of downwind distance. The specified wind velocity is held constant during the simulation. The model simulates finite duration releases and horizontal and vertical jet sources. It can also simulate cloud dispersion of neutrally buoyant releases and cloud lofting for lighter-than-air gases.

C.5.2 CHEMICAL & PHYSICAL PROPERTIES USED IN TRANSPORT MODELING OF PIPELINE RELEASES

The parameters presented here are used in the models to estimate potential risks to plant workers and the general public from any pipeline ruptures and punctures. The basic properties of the fluid in the pipeline as it leaves the plant boundary are presented in Table C.5-1. The volume of gas released to the atmosphere was reduced to 74% to account for the formation of solid phase CO_2 ***(snow). Tables C-5.2 through C-5.4 present pipeline release parameters and properties of carbon dioxide and hydrogen sulfide. Tables C-5.5 and C-5.6 present calculated masses and release durations for*** CO_2 ***and*** H_2S ***from a five mile section of pipe. Five miles is the estimated distance between safety valves in the pipeline, except at Mattoon which would be 0.5 mile. Both the properties shown in Table C-5.1 and the safety valve interval are critical to the model calculations. Tables C-5.9 and C-5.10 present calculated masses and release durations for*** CO_2 ***and*** H_2S ***from a 3 inch by 1 inch pipeline puncture. The puncture scenario is used to represent a hole that a bucket tooth from a 30 to 60 ton excavator might make while digging.***

Table C-5.1. Properties of Supercritical Carbon Dioxide in Pipeline

Parameter	Specified	Reference
CO_2	95 %	EIV
H_2S	1.48%	EIV*
Safety valve interval	5 miles	EIV
Temperature	95°F	EIV
Pressure	2,200 psi	EIV

*74% of 2% for H_2S co-sequestration experiment

Table C-5.2. Modeling Parameters Used for Simulation of Pipeline Rupture with Meteorological Scenarios D5 & F2

Model Parameter	***Value***
Release Parameters	
Release Height	***0 meters***
Release Scenario	***Completely severed; Horizontal jet***
Calculation Height	***1.5 meters***
Meteorological Parameters	
Wind-speed & Pasquill stability class	***D5: 5 m/sec & D-neutral***
	F2: 2 m/sec & F-stable
Ambient temperature	***35°C***
Surface roughness height (z_o)	***0.1 meters***

Table C-5.3. Physical Properties of Carbon Dioxide Used in Modeling Pipeline Rupture (IPCC, 2005; Annex I)

Property	***Value***	***Units***
Carbon Dioxide	***CO_2***	***--***
Molecular weight	***44.01***	***g/mole***
Vapor heat capacity	***873.***	***Joules/(kg °K)***
Boiling point temperature	***194.7***	***°K***
Heat of vaporization	***571,100.***	***Joules/kg***
Liquid heat capacity	***3,048.***	***Joules/(kg °K)***
Supercritical Density	***850 @310°K & 2200 psi***	***Kg/m^3***
	600 @330°K & 2200 psi	***Kg/m^3***
	750 @310°K & 1800 psi	***Kg/m^3***
Specific heat ratio C_{hp}/C_{hv}	***.872/.684=1.31***	***unitless***

Table C-5.4. Physical Properties of Hydrogen Sulfide Used in Modeling Pipeline Rupture (CRC, 1995)

Property	*Value*	*Units*
Hydrogen Sulfide	H_2S	--
Molecular weight	*34.08*	*g/mole*
Vapor heat capacity	*1,004.*	*Joules/(kg °K)*
Boiling point temperature	*213.5*	*°K*
Heat of vaporization	*547,980.*	*Joules/kg*
Liquid heat capacity	*2,010.*	*Joules/(kg °K)*
Liquid density	*960.*	Kg/m^3
Specific heat ratio C_{hp}/C_{hv}	*1.30*	*unitless*

Table C-5.5. Choked Flow Conditions for Carbon Dioxide Released from a Section of Pipeline

Site	*Pipe ID and Orifice Area*	*Section Length*	*Pipeline Temperature (°C)*	*Absolute Pressure (psia)*	CO_2 *Mass (kg)*	$Q_{choked-CO_2}{}^{*}$ *(kg/sec)*	*Release Duration (sec)*
Jewett, TX	*19.312 in.* $0.189\ m^2$	*5 mi*	*35*	*2,200.*	*1,290,000.*	*7,950*	*162*
Tuscola, IL	*14.438 in.* $0.106\ m^2$	*5 mi*	*35*	*2,200.*	*723,100.*	*4,444*	*162*
Odessa, TX	*12.812 in.* $0.0832\ m^2$	*5 mi*	*35*	*2,200.*	*568,000.*	*3,500*	*162*
Mattoon, IL	*14.438 in.* $0.106\ m^2$	*0.5 mi*	*35*	*2,200.*	*72,310.*	*4,444*	*16*

[*] *Supercritical density = 850 Kg/m3 at 35°C & 2,200 psi. Choked flow* $Q_{choked-CO2}$ *is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline.*

Table C-5.6. Simulation Conditions for Hydrogen Sulfide Released from a Section of Pipeline

Site	ID and Orifice Area	Section Length	Pipeline Temperature (°C)	Absolute Pressure (psi)	H_2S Mass (kg)	$Q_{choked-H_2S}{}^{*}$ (kg/sec)	Release Duration (sec)
Jewett, TX	19.312 in. 0.189 m^2	5 mi	35	2,200.	19,100.	117.	162
Tuscola, IL	14.438 in. 0.106 m^2	5 mi	35	2,200.	10,700.	65.1	162
Odessa, TX	12.812 in. 0.0832 m^2	5 mi	35	2,200.	8,400.	51.8	162
Mattoon, IL	14.438 in. 0.106 m^2	0.5 mi	35	2,200.	1,070.	65.1	16

* *Choked flow $Q_{choked\text{-}H2S}$ = 0.0148*$Q_{choked\text{-}CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline. Unit Conversions: 1 psi = 0.06895 bars; 1 psi = 6,895 (Newtons/m^2 or Pascals); 1 psi = 0.06805 (atmospheres); 1 atm = 101,325 (Newtons/m^2 or Pascals).*

Table C-5.7. Maximum Distance to Different Levels of Hydrogen Sulfide Released from a Rupture of a Section of Pipeline under F2 Meteorology

Site	ID and Orifice Area	Section Length	Radius (m) To H_2S 0.51 ppmv	Radius (m) To H_2S 27 ppmv	Radius (m) To H_2S 50 ppmv	Radius (m) To H_2S 100 ppmv
Jewett, TX	19.312 in. 0.189 m^2	5 mi	136,995	14,410	10,200	6,890
Tuscola, IL	14.438 in. 0.106 m^2	5 mi	95,225	10,491	7,448	4,940
Odessa, TX	12.812 in. 0.0832 m^2	5 mi	82,256	9,415	6,580	4,280
Mattoon, IL	14.438 in. 0.106 m^2	0.5 mi	25,966	2,745	1,878	1,180

* *Choked flow $Q_{choked\text{-}H2S}$ = 0.0148*$Q_{choked\text{-}CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline. Unit Conversions: 1 psi = 0.06895 bars; 1 psi = 6,895 (Newtons/m^2 or Pascals); 1 psi = 0.06805 (atmospheres); 1 atm = 101,325 (Newtons/m^2 or Pascals).*

Table C-5.8. Maximum Population Potentially Exposed by Pipeline Rupture at Four Candidate Sites, at Different Levels of Hydrogen Sulfide (Results are taken from the Pipe-walk Routine)

Site	ID and Orifice Area	Section Length	Maximum Individuals Potentially Affected From H_2S 0.51 ppmv	Maximum Individuals Potentially Affected From H_2S 27 ppmv	Maximum Individuals Potentially Affected From H_2S 50 ppmv	Maximum Individuals Potentially Affected From H_2S 100 ppmv
Jewett, TX	19.312 in. 0.189 m^2	5 mi	1,415.	177.	125.	77.
Tuscola, IL	14.438 in. 0.106 m^2	5 mi	542.	27.	16.	9.5
Odessa, TX	12.812 in. 0.0832 m^2	5 mi	55.	0.92	0.50	0.25
Mattoon, IL	14.438 in. 0.106 m^2	0.5 mi	123.	0.61	0.29	0.15

[*] *Choked flow $Q_{choked\text{-}H2S} = 0.0148 * Q_{choked\text{-}CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline. Unit Conversions: 1 psi = 0.06895 bars; 1 psi = 6,895 (Newtons/m^2 or Pascals); 1 psi = 0.06805 (atmospheres); 1 atm = 101,325 (Newtons/m^2 or Pascals).*

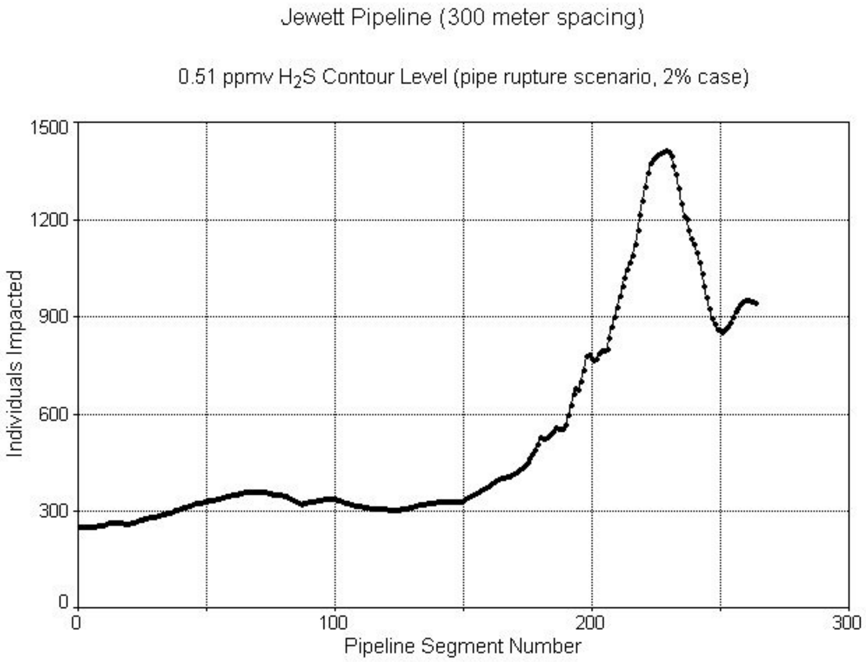


Figure C-5.1. Population exposure, 0.51 ppmv H_2S level, from the pipeline rupture scenario at Jewett, TX. Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection wells.

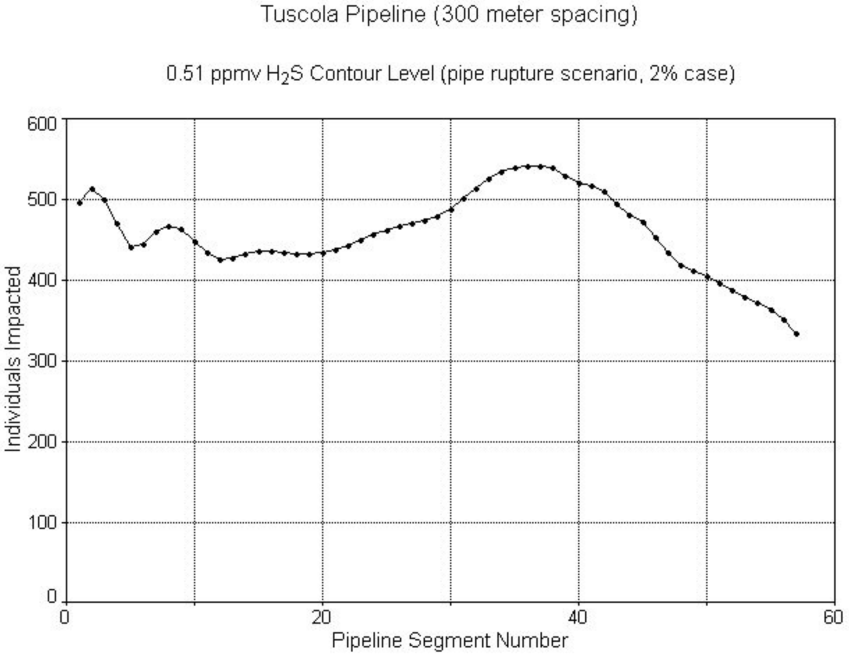


Figure C-5.2. Population exposure, 0.51 ppmv H_2S level, from the pipeline rupture scenario at Tuscola, IL. Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection well.

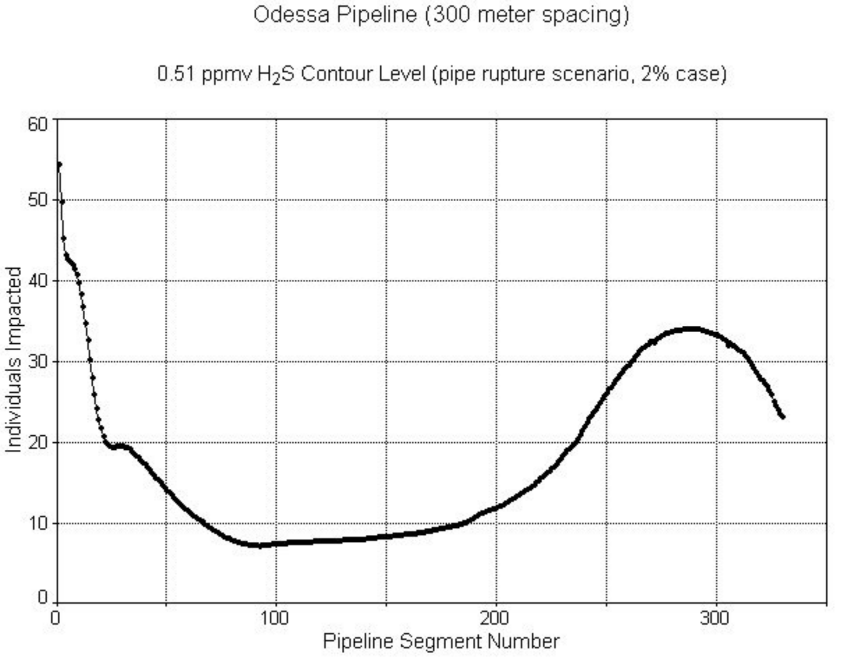


Figure C-5.3. Population exposure, 0.51 ppmv H_2S level, from the pipeline rupture scenario at Odessa, TX. Exposures calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection wells.

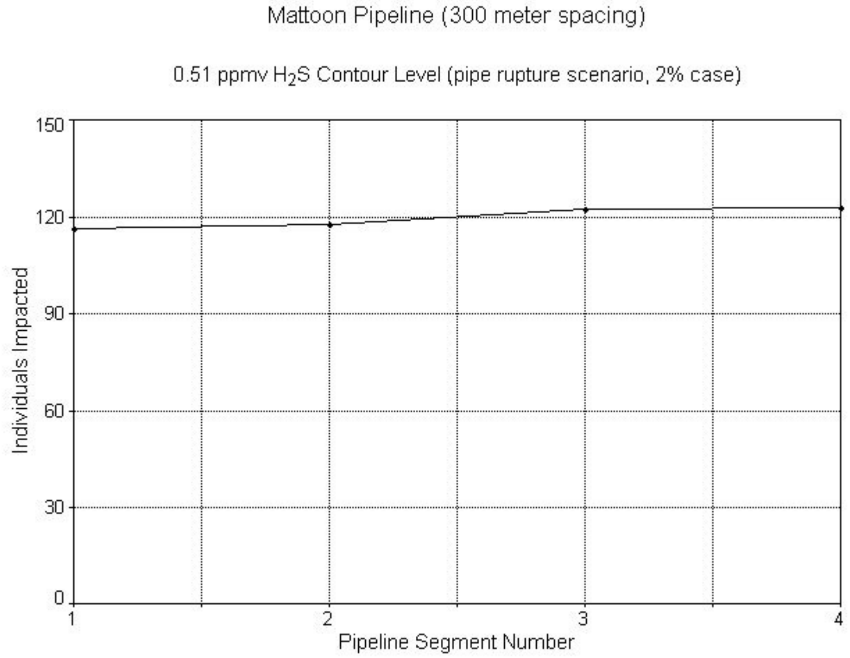


Figure C-5.4. Population exposure, 0.51 ppmv H_2S level, from the pipeline rupture scenario at Mattoon, IL. Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection well.

C.5.3 PIPELINE PUNCTURE SIMULATIONS

Steps performed here are similar to those for the pipeline rupture simulations, as described previously. The puncture simulations were done separately from those for the rupture. The pipeline puncture is assumed to be a 3 inch by 1 inch hole created by a tooth on the bucket of a 30 to 60 ton tracked excavator.

The expected numbers of individuals potentially exposed by a pipeline puncture at the Jewett, Tuscola, Odessa, and Mattoon sites are listed in Table C-5.12. Exposures for the puncture scenarios were calculated for five concentration levels: three for H_2S, 0.33 ppmv, 17 ppmv, and 31 ppmv; and two for CO_2, 20,000 ppmv, and 70,000 ppmv. These criteria are different from those for the pipeline rupture because the smaller opening associated with the puncture creates a longer duration plume. Calculations where performed every 300 meters along pipeline.

Table C-5.9. Simulation Conditions for Carbon Dioxide Released from a 3x1 inch Puncture (an area of 0.00194 m^2) in a Section of Pipeline

Site	Pipeline ID	Section Length	Pipeline Temperature (℃)	Absolute Pressure (psi)	CO_2 Mass (kg)	$Q_{choked-CO_2}{}^*$ (kg/sec)	Release Duration (sec)
Jewett, TX	19.312 inch	5 mi	35	2,200.	1,290,000.	81.4	15,800
Tuscola, IL	14.438 inch	5 mi	35	2,200.	723,100.	81.4	8880
Odessa, TX	12.812 inch	5 mi	35	2,200.	568,000.	81.4	6980.
Mattoon, IL	14.438 inch	0.5 mi	35	2,200.	72,310.	81.4	888

* Supercritical density = 850 Kg/m3 at 35℃ & 2,200 psi. Choked flow $Q_{choked-CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline.

Table C.5-10. Simulation Conditions for Hydrogen Sulfide Released from a 3x1 inch Puncture (an area of 0.00194 m^2) in a Section of Pipeline

Site	Pipeline ID	Section Length	Pipeline Temperature (℃)	Absolute Pressure (psi)	H_2S Mass (kg)	$Q_{choked-H_2S}{}^*$ (kg/sec)	Release Duration (sec)
Jewett, TX	19.312 inch	5 mi	35	2,200.	19,100.	1.21	15,800
Tuscola, IL	14.438 inch	5 mi	35	2,200.	10,700.	1.21	8880
Odessa, TX	12.812 inch	5 mi	35	2,200.	8,400.	1.21	6980.
Mattoon, IL	14.438 inch	0.5 mi	35	2,200.	1,070.	1.21	888

* Choked flow $Q_{choked-H2S} = 0.0128 * Q_{choked-CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline. Unit Conversions: 1 psi = 0.06895 bars; 1 psi = 6,895 (Newtons/m^2 or Pascals); 1 psi = 0.06805 (atmospheres); 1 atm = 101,325 (Newtons/m^2 or Pascals).

Table C-5.11. Maximum Distance to Different Levels of Hydrogen Sulfide Released from a 3x1 inch Puncture (an area of 0.00194 m^2) in a Section of Pipeline under F2 Meteorology.

Site	*Pipeline ID*	*Section Length*	*Radius (m) To H_2S 0.33 ppmv*	*Radius (m) To H_2S 17 ppmv*	*Radius (m) To H_2S 31 ppmv*
Jewett, TX	*19.312 inch*	*5 mi*	*61,400*	*3,536*	*2,420*
Tuscola, IL	*14.438 inch*	*5 mi*	*59,779*	*3,536*	*2,420*
Odessa, TX	*12.812 inch*	*5 mi*	*56,184*	*3,536*	*2,420*
Mattoon, IL	*14.438 inch*	*0.5 mi*	*18,555*	*1,669*	*1,188*

*[*] Choked flow $Q_{choked-H2S}$ = 0.0128*$Q_{choked-CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline. Unit Conversions: 1 psi = 0.06895 bars; 1 psi = 6,895 (Newtons/m^2 or Pascals); 1 psi = 0.06805 (atmospheres); 1 atm = 101,325 (Newtons/m^2 or Pascals).*

Table C-5.12. Maximum Population Potentially Exposed by Pipeline Puncture at Four Candidate Sites, at Different Levels of Hydrogen Sulfide (Results are taken from the pipe-walk routine)

Site	Pipeline ID	Section Length	Maximum Individuals Potentially Affected From H_2S 0.33 ppmv	Maximum Individuals Potentially Affected From H_2S 17 ppmv	Maximum Individuals Potentially Affected From H_2S 31 ppmv
Jewett, TX	19.312 inch	5 mi	447.	25.	14.
Tuscola, IL	14.438 inch	5 mi	178.	4.9	2.5
Odessa, TX	12.812 inch	5 mi	9.48	0.16	0.085
Mattoon, IL	14.438 inch	0.5 mi	52.	0.2	0.11

* Choked flow $Q_{choked\text{-}H2S} = 0.0128 * Q_{choked\text{-}CO2}$ is based on carbon dioxide properties. Modeling assumes emission rates remain constant during release. ID = Inner diameter of pipeline. Unit Conversions: 1 psi = 0.06895 bars; 1 psi = 6,895 (Newtons/m^2 or Pascals); 1 psi = 0.06805 (atmospheres); 1 atm = 101,325 (Newtons/m^2 or Pascals).

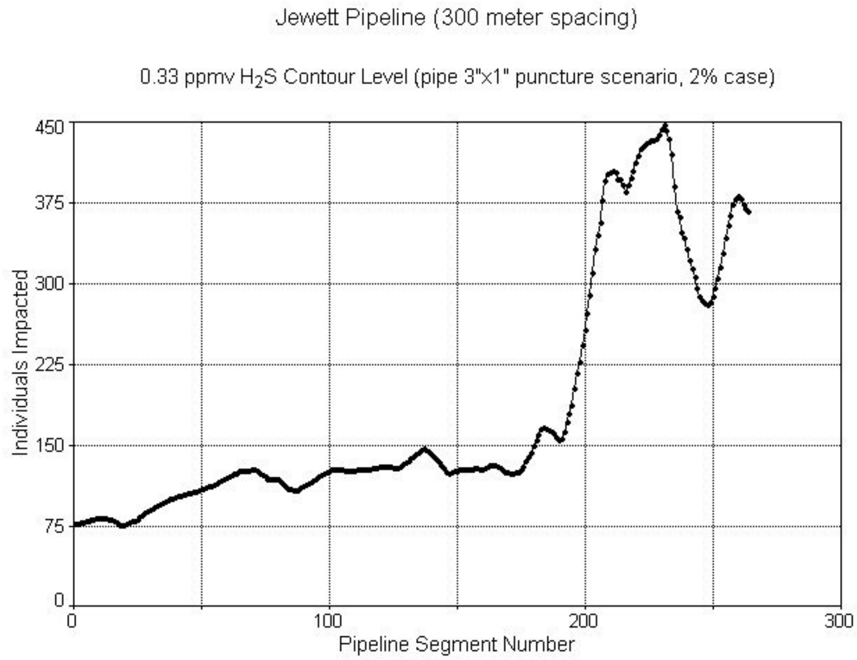


Figure C.5-5. Population exposure, 0.33 ppmv H_2S level, from a 3"x1" puncture on the Jewett, TX pipeline. Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection wells.

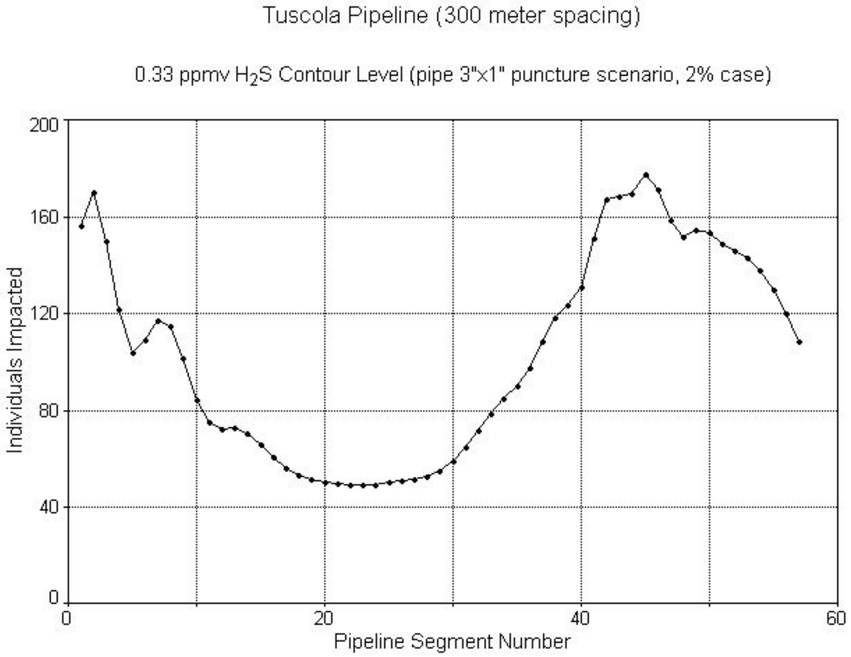


Figure C.5-6. Population exposure, 0.33 ppmv H_2S level, from a 3"x1" puncture on the Tuscola, IL pipeline. Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection well.

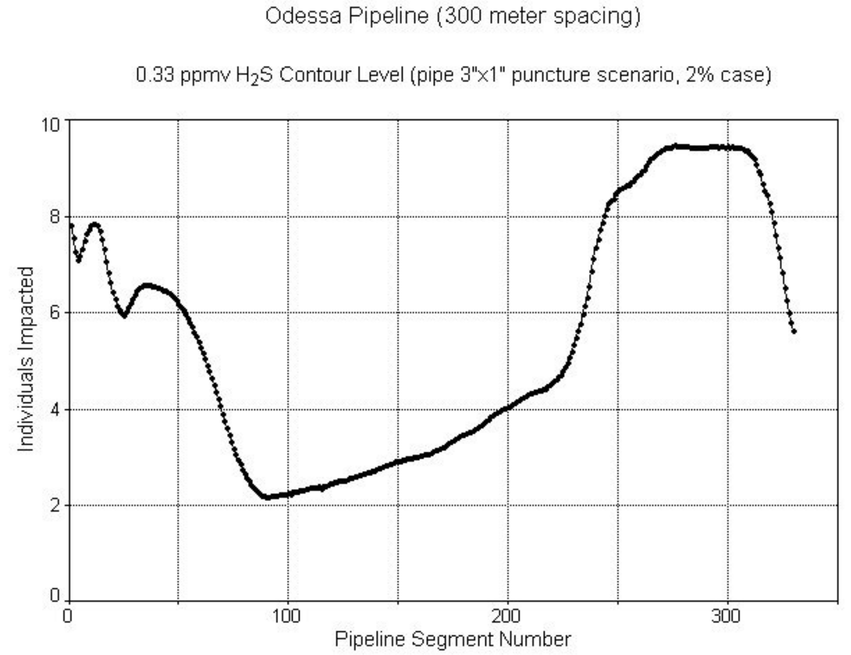


Figure C.5-7. Population exposure, 0.33 ppmv H_2S level, from a 3"x1" puncture on the Odessa, TX pipeline. Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection wells.

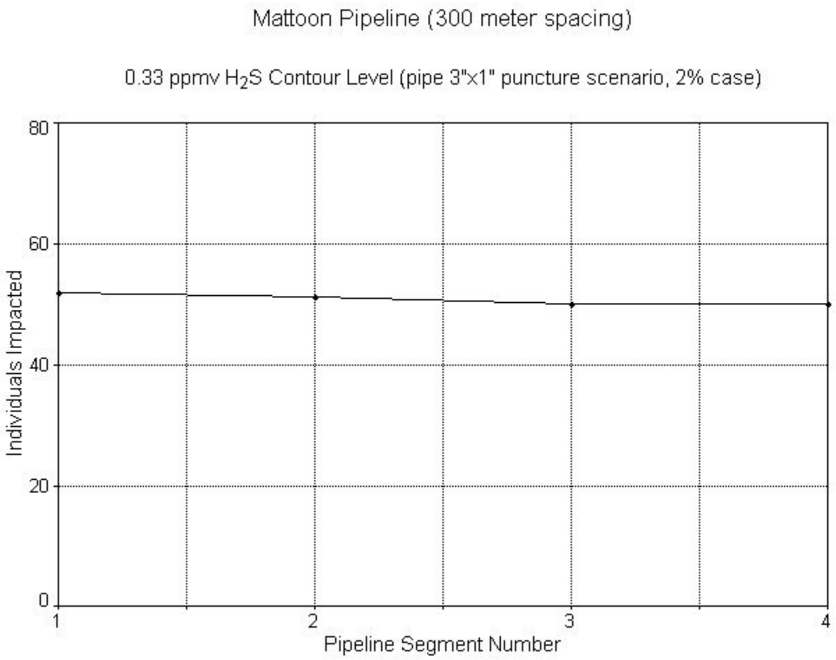


Figure C.5-8 Population exposure, 0.33 ppmv H_2S level, from a 3"x1" puncture on the Mattoon, IL pipeline. Exposures are calculated at every 300 meter point along the pipeline. Pipeline segments are numbered from left-to-right, starting at the plant site and proceeding toward the injection well.

C.6 Sensitivity of the Time-Averaged Concentration Distance Calculation to Meteorological Parameters for the 2% H_2S Case

The sensitivity of the computed maximum time-averaged concentration distances by the SLAB program to meteorological parameters at different hydrogen sulfide (H_2S) concentration criteria was examined for the co-sequestration experiment using 2% H_2S for a seven day period using site specific data from the four proposed sites.

C.6.1 PIPE RUPTURE SCENARIOS

First, consider the pipe rupture scenario in which the pipeline transporting carbon dioxide to the injection wells is completely severed. The H_2S content of the pipeline is assumed to be 2% of the total mass in the pipeline. During the resultant discharge to the atmosphere, 26% of the discharging H_2S is assumed to be associated with the solid dry ice phase of the CO_2, which means that only 74% of the discharging H_2S is in a gaseous phase. The H_2S associated with the solid dry ice phase is assumed to sublimate at a much slower rate and is not included in the SLAB simulation of atmospheric transport. The net effect is that the gaseous component of the discharging H_2S represents 1.48% of the total mass being discharged from the pipe. The computed distance to time-averaged concentration contours are listed below for the H_2S time-averaged concentration criteria of 0.51, 27, 50, and 100 ppmv (averaged over a 900 second period 15 minutes, the shortest time period that pertains to the above criteria) for seven different meteorological conditions called F2, A1, A2, B3, B4, C6, and D8. The letter symbol represents the Pasquill stability class and the numerical symbol indicates the representative wind speed condition in meters per second. The selection of the meteorological parameters comes from those conditions classified in the wind rose charts provided in the EIV (2007) for each of the four sites. The distances predicted by SLAB for pipeline rupture simulations of Jewett, TX are listed in Table C-6.1, in Table C-6.2 for Odessa, TX, in Table C-6.3 for Tuscola, IL, and in Table C-6.4 for Mattoon, IL. The data and predictions shown in these four tables are the same data used with the pipe-walk analysis of potential population impacts, which is discussed in Appendix C.4. The SLAB program generates during each simulation a file containing all of the (X,Y) coordinates of every CO_2 and H_2S time-averaged concentration contour "footprint", whereas only the maximum downwind distance of a given contour is listed in Tables C-6.1 to C-6.4. The pipe-walk routine uses the entire contour footprint to predict the impact of a chemical release.

The following tables show that the maximum predicted time-averaged concentration distances are dependent upon the particular meteorological conditions used. Classes D & F of the Pasquill stability categories are used to represent the most neutral wind conditions; classes A & B of the Pasquill stability categories represent the most unstable wind conditions. The farthest distance to the specified time-averaged concentration criteria is predicted by SLAB for F2 meteorological conditions (i.e., class F wind stability and a 2 m/sec wind speed). The shortest distance to the specified time-averaged concentration criteria is predicted by SLAB for A2 meteorological conditions (i.e., class A wind stability and a 2 m/sec wind speed).

It should be noted that the time-averaged concentration distances are predicted by SLAB under the assumption that the wind speed and wind stability conditions remain constant over the entire rupture simulation. For example, if the time-averaged concentration distance is predicted as 5 kilometers under F2 conditions, then the wind is assumed to remain constant over a 2,500 second interval, which is about seven-tenths of an hour. Furthermore, if the time-averaged concentration distance is predicted as 140 kilometers under F2 conditions, then the wind is assumed to remain constant over a 70,000 second interval, which is more than nineteen hours long. It is unrealistic to assume the wind

conditions remain constant for such long periods of time. As a result, the maximum predicted distance, such as the 140 kilometer distance for the 0.51 ppmv H_2S contour, is an over-prediction. SLAB predicts time-averaged concentrations at an elevation of 2 meters above ground at down-wind locations along the direction of wind flow so the distances predicted are not very sensitive to variations in wind direction with time but SLAB is much more sensitive to changes in either the wind speed or the stability class of the atmosphere with time. There is no readily available methodology to account for actual time-varying meteorological conditions unless substantially more data are collected at each site, such as obtaining meteorological data every 15 minutes over a period of at least one year and preferably 5 years at each site. Typically, wind speed and sky condition (stability) data published by the NOAA National Climatic Data Centers for airports are based on data collected once an hour using a 3 to 5 minute averaging period at the top of every hour throughout the day. Only graphs of the annually averaged wind rose data were provided in the EIV (2007). Information from the wind rose has been summarized and listed on the third line of the following tables to indicate the probability of occurrence, on an annual basis, for each of the site's seven meteorological conditions.

The simulation results in the tables given below can be used to obtain a rough sense of the potential sensitivity of the predicted distances. Typically, the farthest time-averaged concentration distance is about 9 times greater than that of the shortest time-averaged concentration distance for the 0.51 ppmv criteria for H_2S and at least 7 times greater than that of the shortest time-averaged concentration distance for the 100 ppmv criteria for H_2S. It should also be pointed out that SLAB predicts the distances based on a 900 second time-averaged calculation of the H_2S concentrations that evolve over time during the simulation. Hence, the instantaneous concentration of H_2S at any given location varies over many orders of magnitude as the discharged plume of H_2S is transported downwind.

C.6.2 ADDITIONAL LIMITATIONS OF THE PIPEWALK MODELING

The pipewalk routine is used to probabilistically estimate the impact of a pipeline release to the surrounding community by taking into account the effect due to the variable direction of wind and the effect of different wind speed/wind stability conditions. The probability-of-occurrence for each of sixteen wind directions and seven wind speed/wind stability class combinations is obtained from the annually averaged wind rose data provided in the EIV (2007) for each of the four sites. SLAB is run for each site separately using site specific information and data for the seven wind speed/wind stability class combinations but with a single wind direction (e.g., wind from the north). SLAB generates the resultant time-averaged concentration footprints for each of the four H_2S criteria of 0.51, 27, 50, and 100 ppmv. The coordinate orientation of each time-averaged concentration footprint is mathematically rotated to correspond to the sixteen wind directions of the wind rose. The rotated footprints are superimposed onto a geographical information system map containing the boundaries of census count tracts for each site. Census data were originally obtained for approximately a 25 kilometer radius about the proposed pipeline transportation corridors given in the EIV (2007). This proved to be more than adequate for the 0.01% H_2S case presented in the risk assessment since the maximum footprint distances were less than 25 kilometers. However, for the present 2% H_2S case several of the H_2S footprints for the 0.51 ppmv criteria extended more than 100 kilometers. For these extreme cases, the Pipe-walk routine under-predicted the total impact since census tract data coverage did not go beyond 25 km for some segments of the pipeline, although wind conditions are unlikely to remain stable long enough for a plume to reach these long distances. Census tract data coverage was complete for the 27, 50, and 100 ppmv contours.

C.6.3 PIPE PUNCTURE SCENARIOS

The discussion given above pertains to the pipe rupture scenario (complete severing of the pipeline). In addition to this, a pipe puncture scenario involving a 3 inch by 1 inch hole in the pipeline was performed. The computed distance to time-averaged concentration contours are estimated for the H_2S time-averaged concentration criteria of 0.33, 17, and 31 ppmv (averaged over a 3,600 second period) at seven different meteorological conditions called F2, A1, A2, B3, B4, C6, and D8. However, the same problem of over-prediction for the distance to the smallest criteria of 0.33 ppmv occurs. Results for the puncture scenario are listed in Tables C.6-5 to C.6-8 for Jewett, TX.

Table C-6.1. Predicted distances of four time-averaged H2S concentration criteria subject to seven different meteorological conditions during a pipeline rupture simulation in Jewett, TX ***A rupture scenario is simulated by SLAB assuming 2% of the mass in a 5 mile segment of pipeline is H_2S. The simulations also assumed that 74% of the released H_2S was in a gaseous phase and that the remaining 26% was associated with the dry ice phase of CO_2. The simulations assumed a 162 second duration discharge of gaseous phase H_2S at the rate of 117 kg/sec. Time-averaged H_2S concentrations are based on a 900 sec average. Pipeline parameters are described in Appendix C-I. The wind rose line indicates the percent of time the wind blows with a particular wind speed/wind stability.***

Stability Class	F	A	A	B	B	C	D
Wind Speed	2 m/sec	1 m/sec	2 m/sec	3 m/sec	4 m/sec	6 m/sec	8 m/sec
Wind Rose	20.8 %	6.5 %	8.7 %	27.9 %	14.3 %	13.4 %	8.4 %
H_2S Criteria: 0.51 ppmv	140 km	16 km	13 km	21 km	18 km	29 km	35 km
H_2S Criteria: 27 ppmv	14 km	2.1 km	1.5 km	2.1 km	1.8 km	2.6 km	2.8 km
H_2S Criteria: 50 ppmv	10 km	1.5 km	1.1 km	1.5 km	1.3 km	1.8 km	2.0 km
H_2S Criteria: 100 ppmv	6.9 km	1.0 km	0.76 km	1.0 km	0.9 km	1.3 km	1.4 km

Table C-6.2. Predicted distances of four time-averaged H_2S concentration criteria subject to seven different meteorological conditions during a pipeline rupture simulation in Odessa, TX ***A rupture scenario is simulated by SLAB assuming 2% of the mass in a 5 mile segment of pipeline is H_2S. The simulations also assumed that 74% of the released H_2S was in a gaseous phase and that the remaining 26% was associated with the dry ice phase of CO_2. The simulations assumed a 162 second duration discharge of gaseous phase H_2S at the rate of 51.8 kg/sec. Time-averaged H_2S concentrations are based on a 900 sec average. Pipeline parameters are described in Appendix C-I. The wind rose line indicates the percent of time the wind blows with a particular wind speed/wind stability.***

Stability Class	F	A	A	B	B	C	D
Wind Speed	2 m/sec	1 m/sec	2 m/sec	3 m/sec	4 m/sec	6 m/sec	8 m/sec
Wind Rose	4.8 %	3.8 %	5.2 %	27.8 %	17.7 %	19.7 %	20.9 %
H_2S Criteria: 0.51 ppmv	82 km	11 km	8.5 km	13 km	11 km	17 km	23 km
H_2S Criteria: 27 ppmv	9.4 km	1.4 km	1 km	1.3 km	1.2 km	1.6 km	2 km
H_2S Criteria: 50 ppmv	6.6 km	0.99 km	0.72 km	0.97 km	0.83 km	1.2 km	1.5 km
H_2S Criteria: 100 ppmv	4.3 km	0.68 km	0.5 km	0.66 km	0.59 km	0.81 km	0.98 km

***Table C-6.3. Predicted distances of four time-averaged H_2S concentration criteria subject to seven different meteorological conditions during a pipeline rupture simulation in Tuscola, IL** A rupture scenario is simulated by SLAB assuming 2% of the mass in a 5 mile segment of pipeline is H_2S. The simulations also assumed that 74% of the released H_2S was in a gaseous phase and that the remaining 26% was associated with the dry ice phase of CO_2. The simulations assumed a 162 second duration discharge of gaseous phase H_2S at the rate of 65.1 kg/sec. Time-averaged H_2S concentrations are based on a 900 sec average. Pipeline parameters are described in Appendix C-I. The wind rose line indicates the percent of time the wind blows with a particular wind speed/wind stability.*

Stability Class	F	A	B	C	D	D	D
Wind Speed	2 m/sec	2 m/sec	3 m/sec	5 m/sec	7 m/sec	10 m/sec	12 m/sec
Wind Rose	4.6 %	5.2 %	30.2 %	29.5 %	21.8 %	6.4 %	2.2 %
H_2S Criteria: 0.51 ppmv	95 km	9.8 km	15 km	21 km	29 km	23 km	21 km
H_2S Criteria: 27 ppmv	10 km	1.1 km	1.5 km	2.0 km	2.5 km	2. km	1.9 km
H_2S Criteria: 50 ppmv	7.4 km	0.81 km	1.1 km	1.5 km	1.7 km	1.5 km	1.3 km
H_2S Criteria: 100 ppmv	4.9 km	0.56 km	0.76 km	1 km	1.2 km	0.99 km	0.9 km

***Table C-6.4. Predicted distances of four time-averaged H_2S concentration criteria subject to seven different meteorological conditions during a pipeline rupture simulation in Mattoon, IL** A rupture scenario is simulated by SLAB assuming 2% of the mass in a 0.5 mile segment of pipeline is H_2S. The simulations also assumed that 74% of the released H_2S was in a gaseous phase and that the remaining 26% was associated with the dry ice phase of CO_2. The simulations assumed a 16 second duration discharge of gaseous phase H_2S at the rate of 65.1 kg/sec. Time-averaged H_2S concentrations are based on a 900 sec average. Pipeline parameters are described in Appendix C-I. The wind rose line indicates the percent of time the wind blows with a particular wind speed/wind stability.*

Stability Class	F	A	B	C	D	D	D
Wind Speed	2 m/sec	2 m/sec	3 m/sec	5 m/sec	7 m/sec	10 m/sec	12 m/sec
Wind Rose	8.1 %	8.1 %	32.8 %	30.2 %	17.2 %	3.4 %	0.25 %
H_2S Criteria: 0.51 ppmv	26 km	2.7 km	3.8 km	5.4 km	6.7 km	5.6 km	5.1 km
H_2S Criteria: 27 ppmv	2.7 km	0.35 km	0.45 km	0.6 km	0.7 km	0.6 km	0.55 km
H_2S Criteria: 50 ppmv	1.9 km	0.25 km	0.33 km	0.42 km	0.49 km	0.43 km	0.39 km
H_2S Criteria: 100 ppmv	1.2 km	0.17 km	0.22 km	0.28 km	0.32 km	0.28 km	0.26 km

***Table C-6.5. Predicted distances of three time-averaged H_2S concentration criteria subject to seven different meteorological conditions during a pipeline puncture simulation in Jewett, TX** A 3 inch-by-1 inch puncture is simulated by SLAB assuming 2% of the mass in a 5 mile segment of pipeline is H_2S. The simulations also assumed that 74% of the released H_2S was in a gaseous phase and that the remaining 26% was associated with the dry ice phase of CO_2. The simulations assumed a 15,800 second duration discharge of gaseous phase H_2S at the rate of 1.21 kg/sec. Time-averaged H_2S concentrations are based on a 3,600 sec average. Pipeline parameters are described in Appendix C-I. The wind rose line indicates the percent of time the wind blows with a particular wind speed/wind stability.*

Stability Class	*F*	*A*	*A*	*B*	*B*	*C*	*D*
Wind Speed	*2 m/sec*	*1 m/sec*	*2 m/sec*	*3 m/sec*	*4 m/sec*	*6 m/sec*	*8 m/sec*
Wind Rose	*20.8 %*	*6.5 %*	*8.7 %*	*27.9 %*	*14.3 %*	*13.4 %*	*8.4 %*
H_2S Criteria: 0.33 ppmv	*61 km*	*4 km*	*2.7km*	*3.8 km*	*3.1 km*	*4.7 km*	*5.9 km*
H_2S Criteria: 17 ppmv	*3.5 km*	*0.48 km*	*0.33 km*	*0.44 km*	*0.37 km*	*0.5 km*	*0.61 km*
H_2S Criteria: 31 ppmv	*2.4 km*	*0.36 km*	*0.25 km*	*0.32 km*	*0.28 km*	*0.37 km*	*0.44 km*

***Table C-6.6. Predicted distances of three time-averaged H_2S concentration criteria subject to seven different meteorological conditions during a pipeline puncture simulation in Odessa TX** A 3 inch-by-1 inch puncture is simulated by SLAB assuming 2% of the mass in a 5 mile segment of pipeline is H_2S. The simulations also assumed that 74% of the released H_2S was in a gaseous phase and that the remaining 26% was associated with the dry ice phase of CO_2. The simulations assumed a 6,980 second duration discharge of gaseous phase H_2S at the rate of 1.21 kg/sec. Time-averaged H_2S concentrations are based on a 3,600 sec average. Pipeline parameters are described in Appendix C-I. The wind rose line indicates the percent of time the wind blows with a particular wind speed/wind stability.*

Stability Class	F	A	A	B	B	C	D
Wind Speed	2 m/sec	1 m/sec	2 m/sec	3 m/sec	4 m/sec	6 m/sec	8 m/sec
Wind Rose	4.8 %	3.8 %	5.2 %	27.8 %	17.7 %	19.7 %	20.9 %
H_2S Criteria: 0.33 ppmv	56 km	4 km	2.7km	3.8 km	3.1 km	4.7 km	5.9 km
H_2S Criteria: 17 ppmv	3.5 km	0.48 km	0.33 km	0.44 km	0.37 km	0.5 km	0.61 km
H_2S Criteria: 31 ppmv	2.4 km	0.36 km	0.25 km	0.32 km	0.28 km	0.37 km	0.44 km

Table C-6.7. Predicted distances of three time-averaged H_2S concentration criteria subject to seven different meteorological conditions during a pipeline puncture simulation in Tuscola, IL ***A 3 inch-by-1 inch puncture is simulated by SLAB assuming 2% of the mass in a 5 mile segment of pipeline is H_2S. The simulations also assumed that 74% of the released H_2S was in a gaseous phase and that the remaining 26% was associated with the dry ice phase of CO_2. The simulations assumed a 8,880 second duration discharge of gaseous phase H_2S at the rate of 1.21 kg/sec. Time-averaged H_2S concentrations are based on a 3,600 sec average. Pipeline parameters are described in Appendix C-I. The wind rose line indicates the percent of time the wind blows with a particular wind speed/wind stability.***

Stability Class	*F*	*A*	*B*	*C*	*D*	*D*	*D*
Wind Speed	*2 m/sec*	*2 m/sec*	*3 m/sec*	*5 m/sec*	*7 m/sec*	*10 m/sec*	*12 m/sec*
Wind Rose	*4.6 %*	*5.2 %*	*30.2 %*	*29.5 %*	*21.8 %*	*6.4 %*	*2.2 %*
H_2S Criteria: 0.33 ppmv	*60 km*	*2.7 km*	*3.8km*	*5.2 km*	*6.4 km*	*5.1 km*	*4.6 km*
H_2S Criteria: 17 ppmv	*3.5 km*	*0.33 km*	*0.44 km*	*0.57 km*	*0.65 km*	*0.54 km*	*0.49 km*
H_2S Criteria: 31 ppmv	*2.4 km*	*0.25 km*	*0.32 km*	*0.41 km*	*0.47 km*	*0.39 km*	*0.35 km*

***Table C-6.8. Predicted distances of three time-averaged H_2S concentration criteria subject to seven different meteorological conditions during a pipeline puncture simulation in Mattoon, IL** A 3 inch-by-1 inch puncture is simulated by SLAB assuming 2% of the mass in a 5 mile segment of pipeline is H_2S. The simulations also assumed that 74% of the released H_2S was in a gaseous phase and that the remaining 26% was associated with the dry ice phase of CO_2. The simulations assumed a 888 second duration discharge of gaseous phase H_2S at the rate of 1.21 kg/sec. Time-averaged H_2S concentrations are based on a 3,600 sec average. Pipeline parameters are described in Appendix C-I. The wind rose line indicates the percent of time the wind blows with a particular wind speed/wind stability.*

Stability Class	F	A	B	C	D	D	D
Wind Speed	2 m/sec	2 m/sec	3 m/sec	5 m/sec	7 m/sec	10 m/sec	12 m/sec
Wind Rose	8.1 %	8.1 %	32.8 %	30.2 %	17.2 %	3.4 %	0.25 %
H_2S Criteria: 0.33 ppmv	19 km	1.4 km	2.0km	2.7 km	3.3 km	2.6 km	2.3 km
H_2S Criteria: 17 ppmv	1.7 km	0.19 km	0.24 km	0.31 km	0.36 km	0.29 km	0.26 km
H_2S Criteria: 31 ppmv	1.2 km	0.14 km	0.18 km	0.23 km	0.26 km	0.21 km	0.19 km

APPENDIX D

Table D-1.1 Jewett, TX

Geologic Carbon Sequestration HSE Screening and Ranking Framework Version 1.0

9/24/2004 **C.M. Oldenburg (LBNL)** **Last update: 9/20/2005**

Basis...	Funded by...	Contact: Curt Oldenburg cmoldenburg@lbl.gov
Instructions...	Reference...	
Disclaimer...	Copyright...	Acknowledgments

Site: Jewett, TX

Operator: FutureGen

Evaluator (name): Bob Johns
Affiliation: Tetra Tech
Date: 11/21/2006
Revision: 2.0

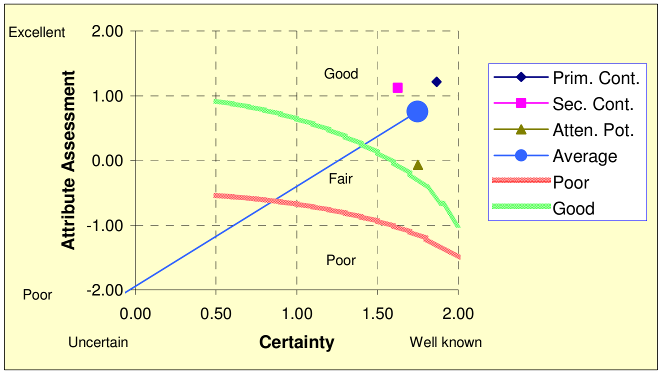


Chart Details

Total Average Certainty:	1.75
Total Average Attribute:	0.76
Magnitude of Total Average:	3.26
Prim. Cont. Weighting factor:	1
Sec. Cont. Weighting factor:	1
Atten. Pot. Weighting factor:	1

	Primary Containment		Secondary Containment		Attenuation Potential	
Average of attributes:	1.22	(2 = excellent site; -2 = poor	1.12	(2 = excellent site; -2 = poor	-0.07	(2 = excellent site; -2 = poor site)
Average certainty:	1.87	(2 = well known; 0.1 = poorly	1.63	(2 = well known; 0.1 = poorly	1.75	(2 = well known; 0.1 = poorly known)
Overall score:	2.35	(4 = excellent site; -4 = poor	1.62	(4 = excellent site; -4 = poor	-0.22	(4 = excellent site; -4 = poor site)

Summary comments:

This site has good primary containment, fair to good secondary containment, and fair attenuation potential. The site is well characterized.

Sources:

FutureGen EIV for Jewett, TX Site
Response to FutureGen Alliance Geohydrologic Conceptual Model Data Request Package, Heart of Brazos Site, Texas Version 2, September 15, 2006 Bureau of Economic Geology, UT-A

Table D-1.2 Jewett, TX

Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk 2 = excellent (positive attribute) 0 = neutral (fair attribute) -2 = poor (negative attribute)	Weighted Assessment of Attribute	Certainty Factor 2.0 = Very well known 1.0 = Generally accepted 0.1 = Poorly known
	Description				
0.48	122 m		0	0.00	2
0.24	Shale (Eagle Ford)		2	0.48	2
0.24	Main seal for large E TX oilfields		2	0.48	2
0.05	Large areal extent in E TX		2	0.10	2
1.00		Average:	1.50	1.05	2.00
	Description				
1.00	about 4800 ft		2	2.00	2
1.00		Average:	2.00	2.00	2.00
	Description				
0.07	tone (woodbine and Travis Peak)		2	0.13	2
0.13	5-3000 mD, 5-30%		2	0.27	2
0.07	257 m		2	0.13	2
0.07	Primary		2	0.13	2
0.07	DS from 85,000 to 120,000		-1	-0.07	1
0.07	Hydrostatic at 0.465 psi/ft		0	0.00	1
0.13	stress regime, small normal faults but		0	0.00	2
0.13	Slow flow		0	0.00	1
0.13	2 deep wells (Woodbine)		0	0.00	2
0.13	aults low k due to low offset		0	0.00	1
1.00		Average:	0.70	0.60	1.60

Table D-1.3 Jewett, TX

11/21/2006 **Jewett, TX** **Revision: 2.0**

Overall score for this sheet	Average of weighted assessments of attribute
1.62	1.12

Secondary Containment

Attribute	Weight 10 = most importa 1 = least	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk 2 = excellent (positive attribute) 0 = neutral (fair attribute) -2 = poor (negative attribute)
Secondary Seal			**Description**		
Thickness	10	0.38	122 m (Austin Chalk)		0
Lithology	5	0.19	Chalk		0
Demonstrated sealing	1	0.04	Not known		0
Lateral continuity	5	0.19	Laterally continuous		1
Depth	5	0.19	Austin Chalk ~1,219 m		2
	26	1.00		Average:	0.60

Attribute	Weight	Normalized Weight	Property/Value		Assessment
Shallower Seals			**Description**		
Thickness	10	0.33	ana, Taylor, Pecan Gap > 550 m		2
Lithology	5	0.17	Shale		2
Lateral continuity	5	0.17	Fair		0
Evidence of seepage	10	0.33	None		2
	30	1.00		Average:	1.50

Table D-1.4 Jewett, TX

Attribute	Weight	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk	Weighted Assessment of Attribute	Certainty Factor
	10 = most import 1 = least				**2 = excellent (positive attribute)** **0 = neutral (fair attribute)** **-2 = poor (negative attribute)**		**2.0 = Very well known** **1.0 = Generally accepted** **0.1 = Poorly known**
Surface Characteristics			**Description**				
Topography	5	0.15	Flat		2	0.30	2
Wind	10	0.30	Seasonally windy		0	0.00	2
Climate	2	0.06	Sub-humid		-2	-0.12	2
Land use	4	0.12	Farmland/wetlands		1	0.12	2
Population	10	0.30	Rural		1	0.30	2
Surface water	2	0.06	Perennial wetlands exist		-2	-0.12	2
	33	1.00		Average:	0.00	0.48	2.00
Groundwater Hydrology			**Description**				
Regional flow	6	0.32	Carrizo-Wilcox, 9 to 90 ft/yr		1	0.32	2
Pressure	7	0.37	Hydrostatic		0	0.00	2
Geochemistry	2	0.11	near neutral		0	0.00	1
Salinity	4	0.21	Low TDS <500		1	0.21	1
	19	1.00		Average:	0.50	0.53	1.50
Existing Wells			**Description**				
Deep wells	5	0.25	2 deep wells		0	0.00	2
Shallow wells	4	0.20	Numerous shallow wells		-2	-0.40	2
Abandoned wells	10	0.50	Many abandoned wells.		-2	-1.00	2
Disposal wells	1	0.05	None present		0	0.00	2
	20	1.00		Average:	-1.00	-1.40	2.00
Faults			**Description**				
Tectonic faults	10	0.59	Minor faults		0	0.00	2
Normal faults	1	0.06	Some normal faults		0	0.00	2
Strike-slip faults	1	0.06	Few strike-slip faults		2	0.12	1
Fault permeability	5	0.29	faults are low k		0	0.00	1
	17	1.00		Average:	0.50	0.12	1.50

Table D-1.5 Jewett, TX

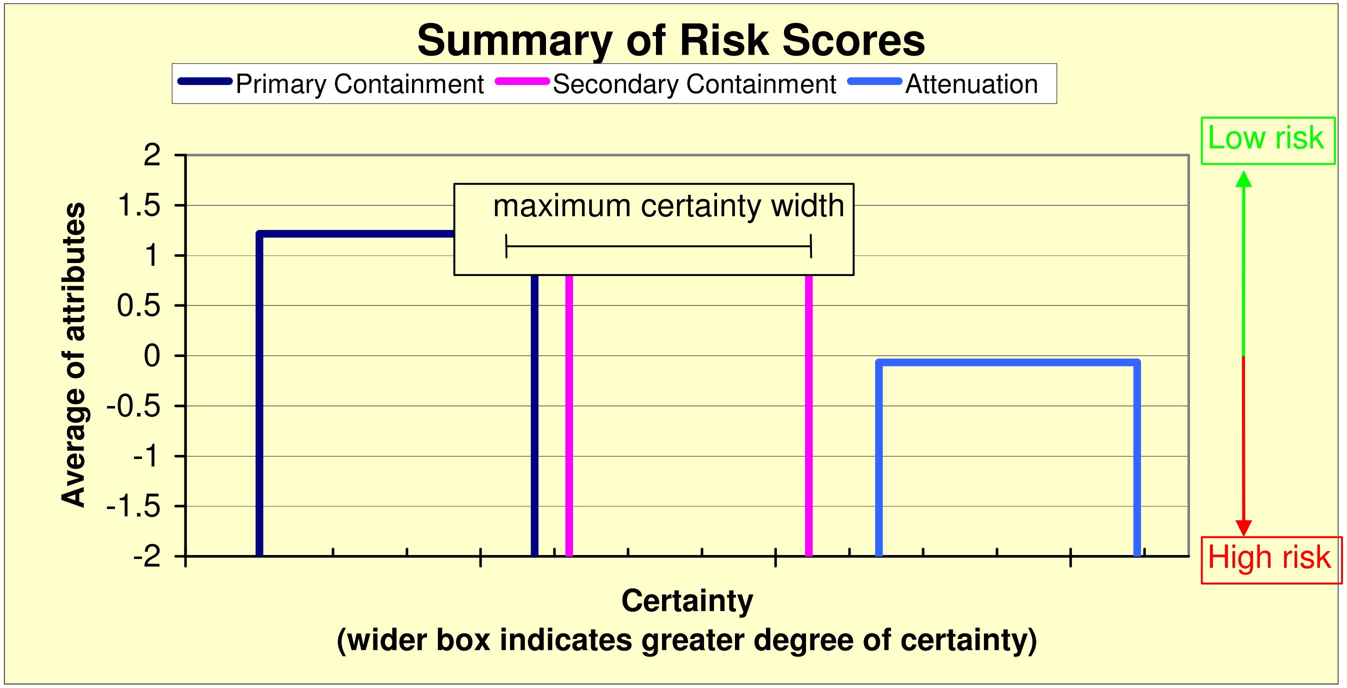
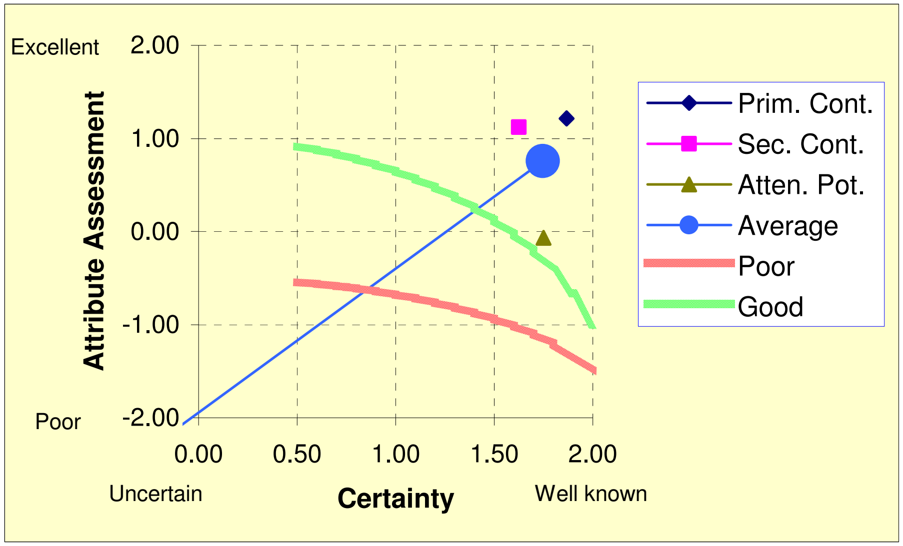


Table D-1.6 Jewett, TX



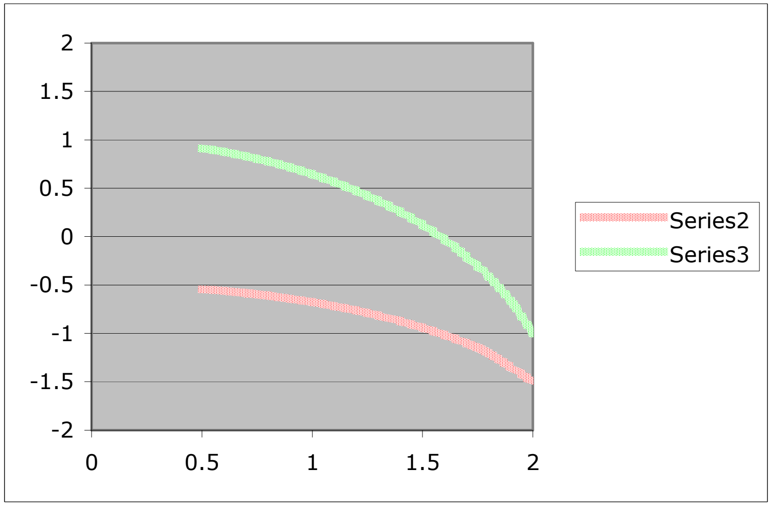
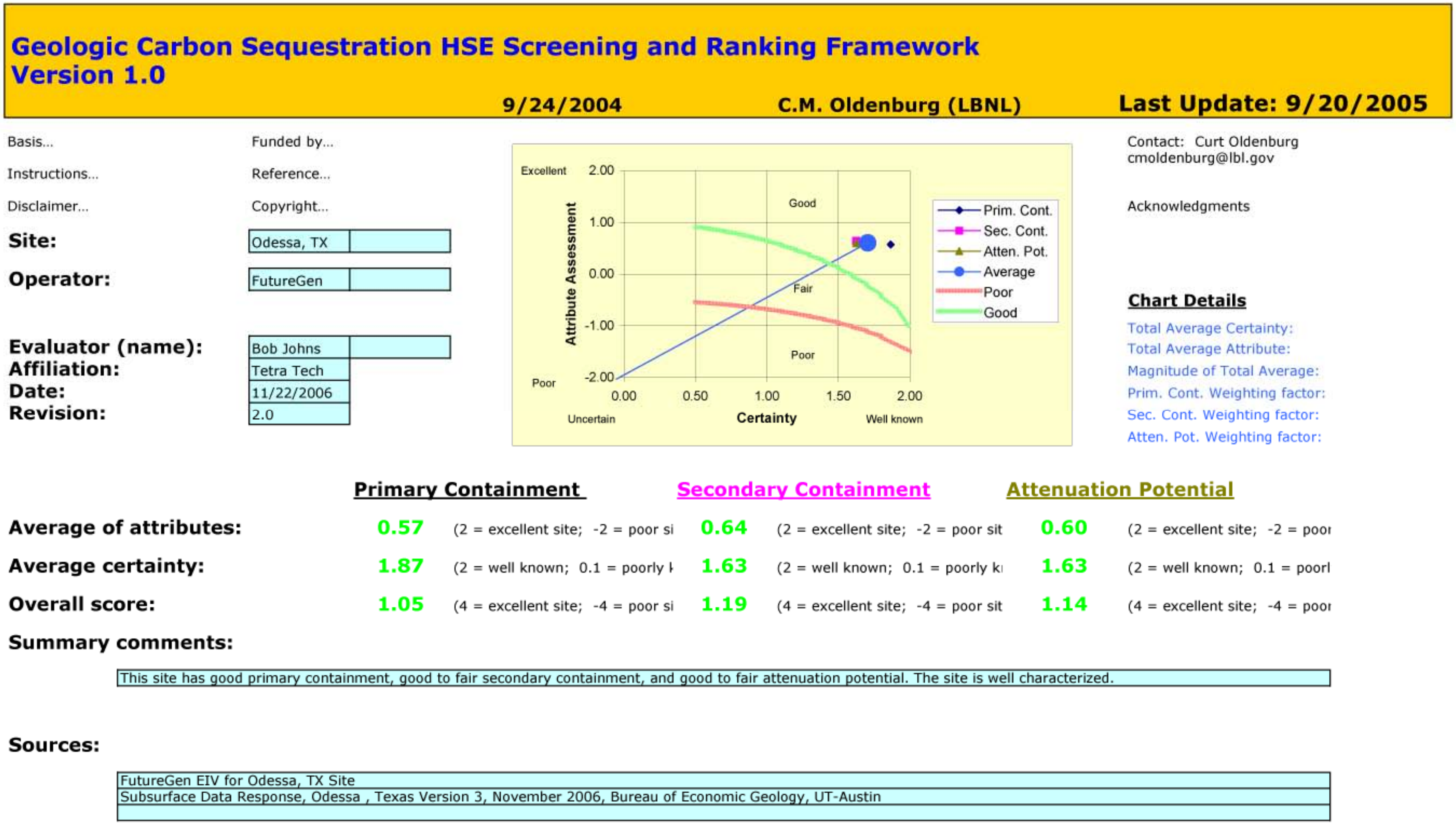


Table D-2.1 Odessa, TX



Geologic Carbon Sequestration HSE Screening and Ranking Framework
Version 1.0

9/24/2004 **C.M. Oldenburg (LBNL)** **Last Update: 9/20/2005**

Basis... Funded by...

Instructions... Reference...

Disclaimer... Copyright...

Contact: Curt Oldenburg
cmoldenburg@lbl.gov

Acknowledgments

Site:	Odessa, TX
Operator:	FutureGen
Evaluator (name):	Bob Johns
Affiliation:	Tetra Tech
Date:	11/22/2006
Revision:	2.0

Chart Details

Total Average Certainty:
Total Average Attribute:
Magnitude of Total Average:
Prim. Cont. Weighting factor:
Sec. Cont. Weighting factor:
Atten. Pot. Weighting factor:

	Primary Containment		**Secondary Containment**		**Attenuation Potential**	
Average of attributes:	0.57	(2 = excellent site; -2 = poor si	0.64	(2 = excellent site; -2 = poor sit	0.60	(2 = excellent site; -2 = poor
Average certainty:	1.87	(2 = well known; 0.1 = poorly k	1.63	(2 = well known; 0.1 = poorly k	1.63	(2 = well known; 0.1 = poorl
Overall score:	1.05	(4 = excellent site; -4 = poor si	1.19	(4 = excellent site; -4 = poor sit	1.14	(4 = excellent site; -4 = poor

Summary comments:

This site has good primary containment, good to fair secondary containment, and good to fair attenuation potential. The site is well characterized.

Sources:

FutureGen EIV for Odessa, TX Site
Subsurface Data Response, Odessa , Texas Version 3, November 2006, Bureau of Economic Geology, UT-Austin

Table D-2.2 Odessa, TX

Odessa, TX **Revision: 2.0**

Overall score for this sheet **1.05**

Average of the weighted assessments of attributes **0.57**

Primary Containment

Attribute	Weight	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk	Weighted Assessment of Attribute
	10 = most import 1 = least				2 = excellent (positive attribute) 0 = neutral (fair attribute) -2 = poor (negative attribute)	
Primary Seal			**Description**			
Thickness	10	0.48	146 m		0	0.00
Lithology	5	0.24	anhydrite w minor carbonate/halite (S		2	0.48
Demonstrated sealing	5	0.24	seals O&G accumulations		2	0.48
Lateral continuity	1	0.05	seals across several counties		2	0.10
	21	1.00		Average:	1.50	1.05
Depth			**Description**			
Distance below ground	10	1.00	about 2700 ft		0	0.00
	10	1.00		Average:	0.00	0.00
Reservoir			**Description**			
Lithology	1	0.07	dstone (Queen/Delaware Mtn)		2	0.13
Perm., poros.	2	0.13	5-25 mD, 6-10%		-1	-0.13
Thickness	1	0.07	732 m		2	0.13
Fracture or primary poros.	1	0.07	Primary		2	0.13
Pores filled with…	1	0.07	TDS ~100,000		0	0.00
Pressure	1	0.07	ydrostatic at 0.45-0.46 psi/ft		0	0.00
Tectonics	2	0.13	normal (tensional) and strike-slip		2	0.27
Hydrology	2	0.13	Nearly stagnant		2	0.27
Deep wells	2	0.13	many deep O&G expl wells		-2	-0.27
Fault permeability	2	0.13	fault traps present		1	0.13
	15	1.00		Average:	0.80	0.67

Table D-2.3 Odessa, TX

Odessa, TX **Revision: 2.0**

Secondary Containment

Overall score for this sheet	Average of weighted assessments of attributes
1.19	0.64

Attribute	Weight 10 = most import 1 = least	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk 2 = excellent (positive attribute) 0 = neutral (fair attribute) -2 = poor (negative attribute)	Weighted Assessment of Attribute
Secondary Seal			**Description**			
Thickness	10	0.38	172 m (Salado/Transill)		1	0.38
Lithology	5	0.19	hydrite and anhydrite/halite		2	0.38
Demonstrated sealing	1	0.04	Seal for WIPP site		2	0.08
Lateral continuity	5	0.19	Laterally continuous		2	0.38
Depth	5	0.19	ado ~447 m/Transill ~594 m		-1	-0.19
	26	1.00		Average:	1.20	1.04
Shallower Seals			**Description**			
Thickness	10	0.33	ewey Lake/Rustler = 40 m		-1	-0.33
Lithology	5	0.17	Mudstone/Siltstone		-0.5	-0.08
Lateral continuity	5	0.17	Fair		0	0.00
Evidence of seepage	10	0.33	None		2	0.67
	30	1.00		Average:	0.13	0.25

Table D-2.4 Odessa, TX

Odessa, TX **Revision: 2.0**

Attenuation Potential

Overall score for this sheet	Average of weighted assessments attributes	Average certainty
1.14	0.60	1.63

Attribute	Weight 10 = most import 1 = least	Normalized Weight	Property/Value	Assessment of Attribute Property Relative to HSE Risk 2 = excellent (positive attribute) 0 = neutral (fair attribute) -2 = poor (negative attribute)	Weighted Assessment of Attribute	Certainty Factor 2.0 = Very well known 1.0 = Generally accepted 0.1 = Poorly known
Surface Characteristics			**Description**			
Topography	5	0.15	Flat	2	0.30	2
Wind	10	0.30	windy	2	0.61	2
Climate	2	0.06	Arid	1	0.06	2
Land use	4	0.12	Range	2	0.24	2
Population	10	0.30	Sparsely populated	2	0.61	2
Surface water	2	0.06	y except intermittent streams	2	0.12	2
	33	1.00	Average:	1.83	1.94	2.00
Groundwater Hydrology			**Description**			
Regional flow	6	0.32	wards-Trinity, 50 to 250 ft/yr	2	0.63	2
Pressure	7	0.37	Hydrostatic	0	0.00	2
Geochemistry	2	0.11	near neutral	0	0.00	1
Salinity	4	0.21	Low TDS, 300-500	1	0.21	1
	19	1.00	Average:	0.75	0.84	1.50
Existing Wells			**Description**			
Deep wells	5	0.25	many deep wells	-2	-0.50	2
Shallow wells	4	0.20	Numerous shallow wells	-2	-0.40	2
Abandoned wells	10	0.50	Many abandoned wells.	-2	-1.00	1
Disposal wells	1	0.05	None present	2	0.10	1
	20	1.00	Average:	-1.00	-1.80	1.50
Faults			**Description**			
Tectonic faults	10	0.59	ts at Reservoir or shallower depths	2	1.18	2
Normal faults	1	0.06	Few normal faults	2	0.12	2
Strike-slip faults	1	0.06	Few strike-slip faults	2	0.12	1
Fault permeability	5	0.29	No fault traps	0	0.00	1
	17	1.00	Average:	1.50	1.41	1.50

Table D-2.5 Odessa, TX

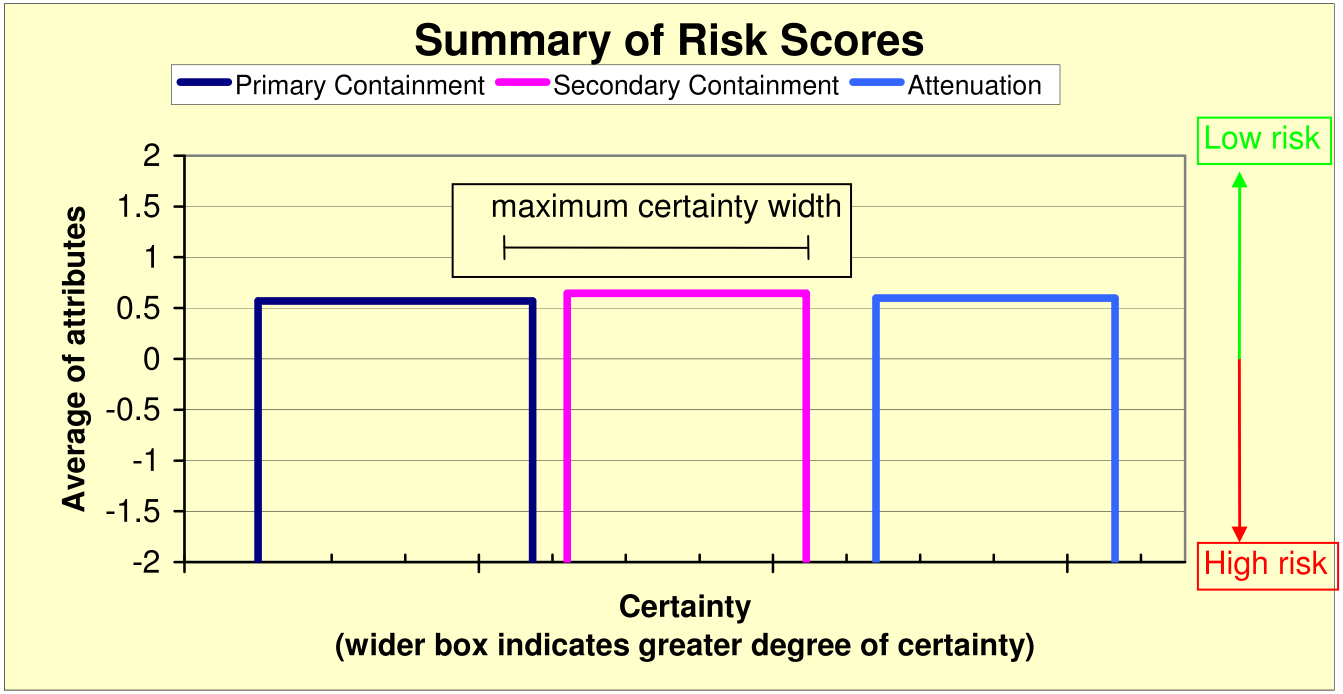
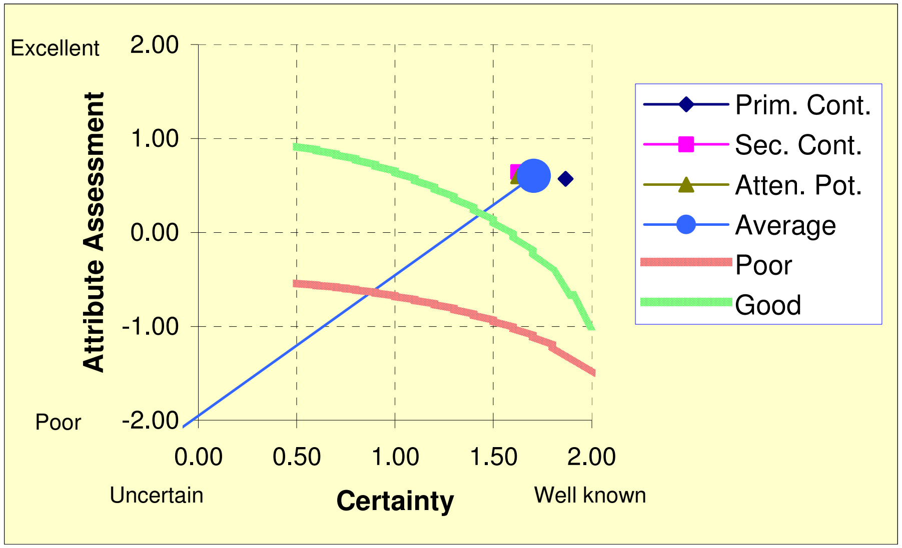


Table D-2.6 Odessa, TX



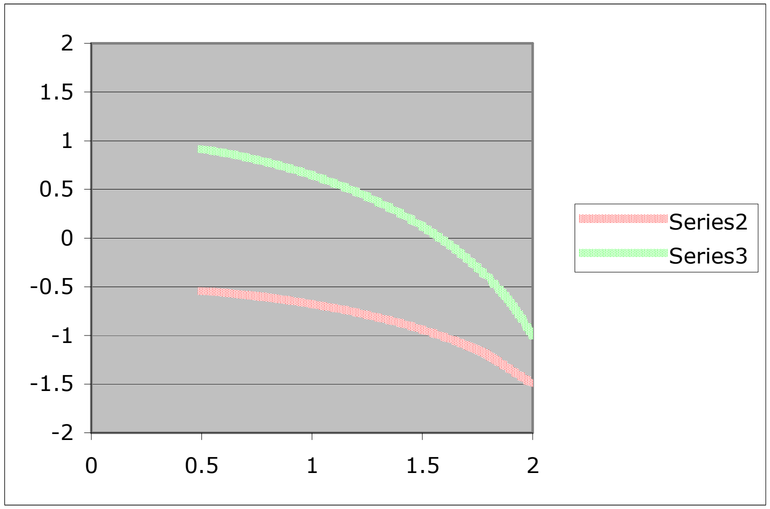


Table D-3.1 Mattoon, IL

Geologic Carbon Sequestration HSE Screening and Ranking Framework Version 1.0

9/24/2004 **C.M. Oldenburg (LBNL)** **Last update: 9/20/2005**

Basis... Funded by...

Instructions... Reference...

Disclaimer... Copyright...

Contact: Curt Oldenburg
cmoldenburg@lbl.gov

Acknowledgments

Site:	Mattoon, IL
Operator:	FutureGen
Evaluator (name):	Bob Johns
Affiliation:	Tetra Tech
Date:	11/24/2006
Revision:	2.0

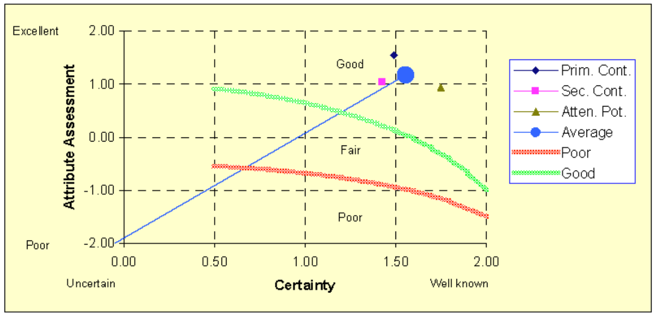


Chart Details

Total Average Certainty:	1.56
Total Average Attribute:	1.17
Magnitude of Total Average:	3.53
Prim. Cont. Weighting factor:	1
Sec. Cont. Weighting factor:	1
Atten. Pot. Weighting factor:	1

	Primary Containment		**Secondary Containment**		**Attenuation Potential**	
Average of attributes:	**1.55**	(2 = excellent site; -2 = poor site)	**1.04**	(2 = excellent site; -2 = poor site)	**0.93**	(2 = excellent site; -2 = poor site)
Average certainty:	**1.49**	(2 = well known; 0.1 = poorly know	**1.43**	(2 = well known; 0.1 = poorly knowr	**1.75**	(2 = well known; 0.1 = poorly known)
Overall score:	**2.26**	(4 = excellent site; -4 = poor site)	**1.49**	(4 = excellent site; -4 = poor site)	**1.60**	(4 = excellent site; -4 = poor site)

Summary comments:

This site has good primary containment, good secondary containment, and good attenuation potential. The site is reasonably characterized.

Sources:

FutureGen EIV for Mattoon, IL Site

Table D-3.2 Mattoon, IL

Attribute	Weight	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk	Weighted Assessment of Attribute	Certainty Factor
	10 = most import 1 = least				2 = excellent (positive attribute) 0 = neutral (fair attribute) -2 = poor (negative attribute)		2.0 = Very well known 1.0 = Generally accepted 0.1 = Poorly known
Primary Seal			**Description**				
Thickness	10	0.48	168 m		0.68	0.32	1.5
Lithology	5	0.24	shale and siltstone (Eau Clare)		2	0.48	2
Demonstrated sealing	5	0.24	seal for 38 Gas Storage sites		2	0.48	2
Lateral continuity	1	0.05	high - seal for NGS ~58 miles N		2	0.10	2
	21	1.00		Average:	1.67	1.37	1.88
Depth			**Description**				
Distance below ground	10	1.00	about 6400 ft (1,951 m)		2	2.00	1.25
	10	1.00		Average:	2.00	2.00	1.25
Reservoir			**Description**				
Lithology	1	0.07	Sandstone (Mt Simon)		2	0.13	2
Perm., poros.	2	0.13	00 mD, 5-15% (12% avg)		0	0.00	0.5
Thickness	1	0.07	732 m		2	0.13	1
Fracture or primary poros.	1	0.07	Primary		2	0.13	2
Pores filled with…	1	0.07	TDS ~120,000		-1	-0.07	1
Pressure	1	0.07	ydrostatic at 0.43-0.45 psi/ft		0	0.00	1
Tectonics	2	0.13	nal (mixed thrust and strike-slip faults)		2	0.27	2
Hydrology	2	0.13	Nearly stagnant		2	0.27	1
Deep wells	2	0.13	no wells in Mt Simon		2	0.27	2
Fault permeability	2	0.13	fault traps present		1	0.13	1
	15	1.00		Average:	1.20	1.27	1.35

Table D-3.3 Mattoon, IL

Mattoon, IL **Revision: 2.0**

	Overall score for this sheet	Average of weighted assessments of attributes	Average certainty
Secondary Containment	1.49	1.04	1.43

Attribute	**Weight** 10 = most import 1 = least	**Normalized Weight**	**Property/Value**		**Assessment of Attribute Property Relative to HSE Risk** **2 = excellent (positive attribute)** **0 = neutral (fair attribute)** **-2 = poor (negative attribute)**	**Weighted Assessment of Attribute**	**Certainty Factor** **2.0 = Very well known** **1.0 = Generally accepted** **0.1 = Poorly known**
Secondary Seal			**Description**				
Thickness	10	0.38	53 to 61 m (Maquoketa)		-0.4	-0.15	1
Lithology	5	0.19	marine shale		2	0.38	2
Demonstrated sealing	1	0.04	w Albany seal for O&G fields		2	0.08	2
Lateral continuity	5	0.19	Laterally continuous		2	0.38	2
Depth	5	0.19	1143		2	0.38	1
	26	1.00		Average:	1.52	1.08	1.6
Shallower Seals			**Description**				
Thickness	10	0.33	New Albany = 61 m		-1	-0.33	1
Lithology	5	0.17	marine shale		2	0.33	1
Lateral continuity	5	0.17	Regional seal		2	0.33	1
Evidence of seepage	10	0.33	None		2	0.67	2
	30	1.00		Average:	1.25	1.00	1.25

Table D-3.4 Mattoon, IL

Attribute	Weight	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk	Weighted Assessment of Attribute
	10 = most import				**2 = excellent (positive attribute)**	
	1 = least				**0 = neutral (fair attribute)**	
Surface Characteristics			**Description**		**-2 = poor (negative attribute)**	
Topography	5	0.15	Flat		2	0.30
Wind	10	0.30	seaonally windy		0	0.00
Climate	2	0.06	sub-humid		-1	-0.06
Land use	4	0.12	Farmland		1	0.12
Population	10	0.30	Rural		1	0.30
Surface water	2	0.06	some streams/wetlands		-1	-0.06
	33	1.00		Average:	0.33	0.61
Groundwater Hydrology			**Description**			
Regional flow	6	0.32	Sand-Gravel, ~>0.1 f/day		1	0.32
Pressure	7	0.37	Hydrostatic		0	0.00
Geochemistry	2	0.11	High alkaliinty		1	0.11
Salinity	4	0.21	TDS marginal (500-1000)		0	0.00
	19	1.00		Average:	0.50	0.42
Existing Wells			**Description**			
Deep wells	5	0.25	no deep wells		2	0.50
Shallow wells	4	0.20	few shallow wells		2	0.40
Abandoned wells	10	0.50	Few abandoned wells.		0	0.00
Disposal wells	1	0.05	None present		2	0.10
	20	1.00		Average:	1.50	1.00
Faults			**Description**			
Tectonic faults	10	0.59	faults (basement faults only)		2	1.18
Normal faults	1	0.06	Few normal faults		2	0.12
Strike-slip faults	1	0.06	Few strike-slip faults		2	0.12
Fault permeability	5	0.29	fault traps present		1	0.29
	17	1.00		Average:	1.75	1.71

Table D-3.5 Mattoon, IL

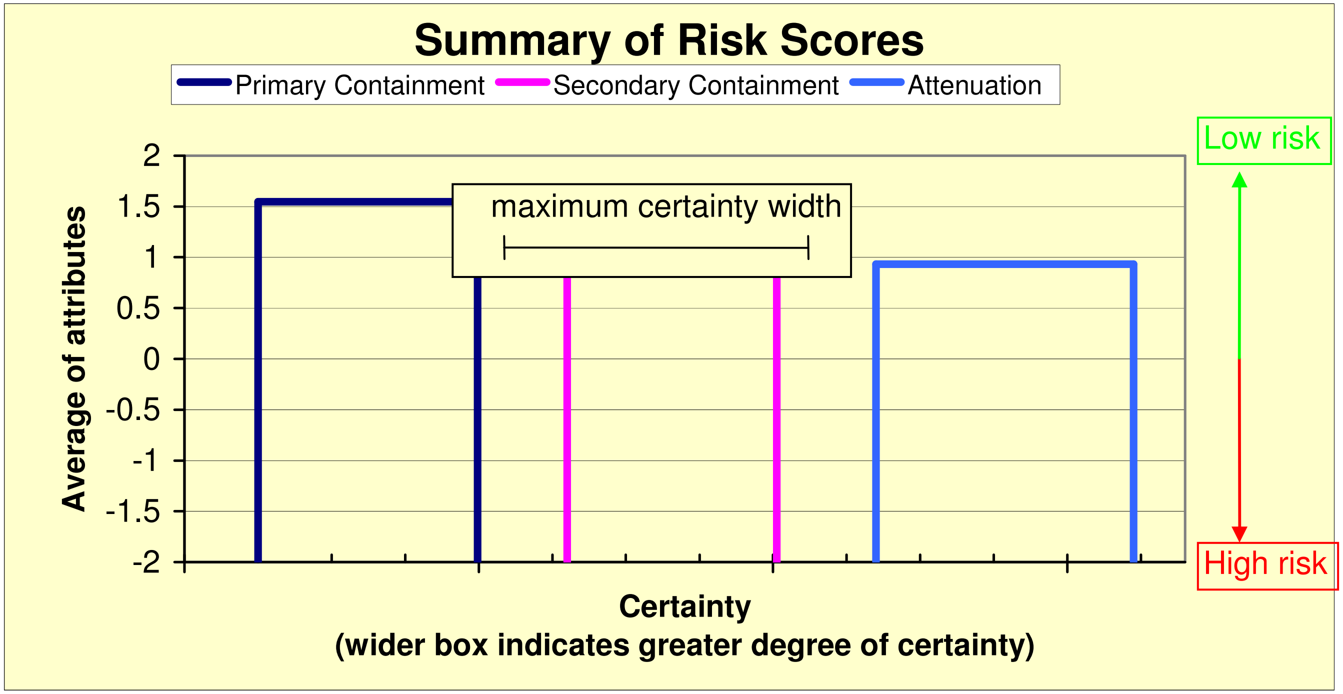
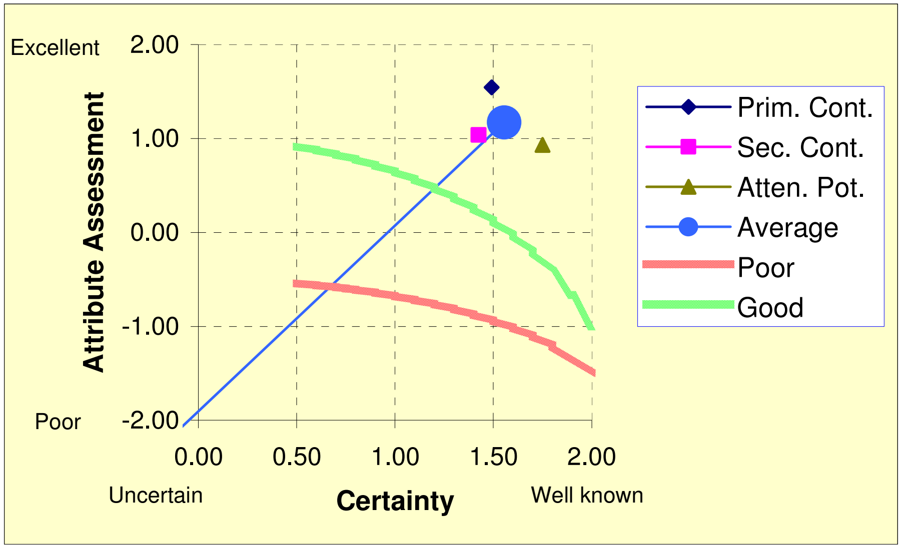


Table D-3.6 Mattoon, IL



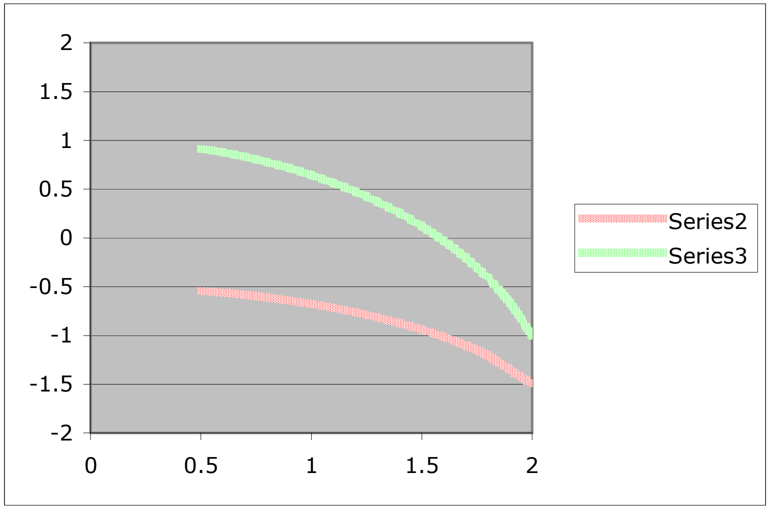
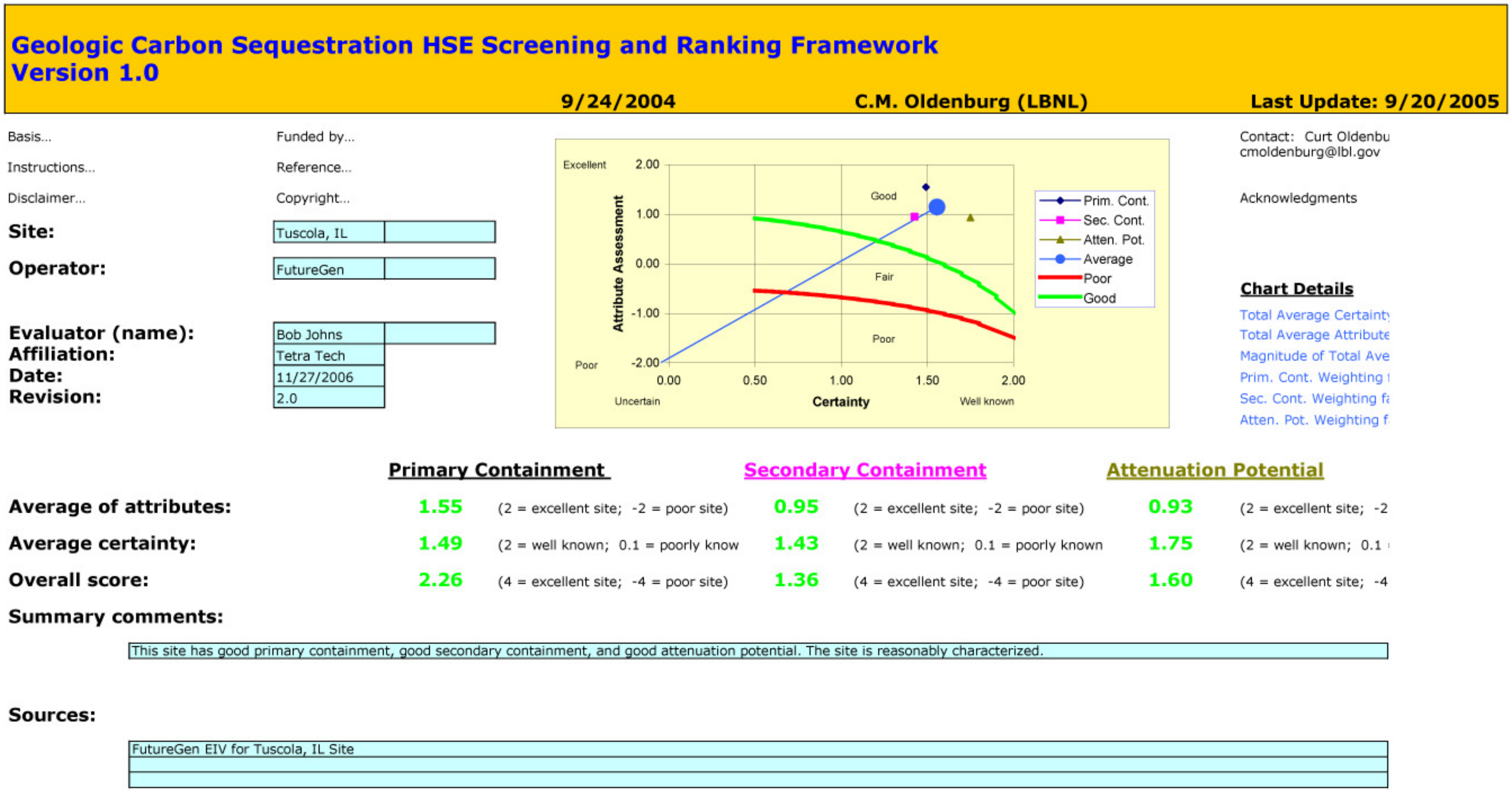


Table D-4.1 Tuscola, IL



Geologic Carbon Sequestration HSE Screening and Ranking Framework
Version 1.0

9/24/2004 **C.M. Oldenburg (LBNL)** **Last Update: 9/20/2005**

Basis... Funded by...

Instructions... Reference...

Disclaimer... Copyright...

Contact: Curt Oldenbu
cmoldenburg@lbl.gov

Acknowledgments

Site: Tuscola, IL

Operator: FutureGen

Evaluator (name): Bob Johns
Affiliation: Tetra Tech
Date: 11/27/2006
Revision: 2.0

Chart Details

Total Average Certaint
Total Average Attribute
Magnitude of Total Ave
Prim. Cont. Weighting
Sec. Cont. Weighting f
Atten. Pot. Weighting f

	Primary Containment		**Secondary Containment**		**Attenuation Potential**	
Average of attributes:	1.55	(2 = excellent site; -2 = poor site)	0.95	(2 = excellent site; -2 = poor site)	0.93	(2 = excellent site; -2
Average certainty:	1.49	(2 = well known; 0.1 = poorly know	1.43	(2 = well known; 0.1 = poorly known	1.75	(2 = well known; 0.1
Overall score:	2.26	(4 = excellent site; -4 = poor site)	1.36	(4 = excellent site; -4 = poor site)	1.60	(4 = excellent site; -4

Summary comments:

This site has good primary containment, good secondary containment, and good attenuation potential. The site is reasonably characterized.

Sources:

FutureGen EIV for Tuscola, IL Site

Table D-4.2 Tuscola, IL

Attribute	Weight	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk	Weighted Assessment of Attribute	Certainty Factor
	10 = most importa				2 = excellent (positive attribute)		2.0 = Very well known
	1 = least				0 = neutral (fair attribute)		1.0 = Generally accepted
Primary Seal			**Description**		-2 = poor (negative attribute)		0.1 = Poorly known
Thickness	10	0.48	168 m		0.68	0.32	1.5
Lithology	5	0.24	shale and siltstone (Eau Clare)		2	0.48	2
Demonstrated sealing	5	0.24	seal for 38 Gas Storage sites		2	0.48	2
Lateral continuity	1	0.05	high - seal for NGS ~58 miles N		2	0.10	2
	21	1.00		Average:	1.67	1.37	1.88

Attribute	Weight	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk	Weighted Assessment of Attribute	Certainty Factor
Depth			**Description**				
Distance below ground	10	1.00	about 6150 ft (1,875 m)		2	2.00	1.25
	10	1.00		Average:	2.00	2.00	1.25

Attribute	Weight	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk	Weighted Assessment of Attribute	Certainty Factor
Reservoir			**Description**				
Lithology	1	0.07	Sandstone (Mt Simon)		2	0.13	2
Perm., poros.	2	0.13	00 mD, 5-15% (12% avg)		0	0.00	0.5
Thickness	1	0.07	488 m		2	0.13	1
Fracture or primary poros.	1	0.07	Primary		2	0.13	2
Pores filled with…	1	0.07	TDS ~130,000		-1	-0.07	1
Pressure	1	0.07	ydrostatic at 0.43-0.45 psi/ft		0	0.00	1
Tectonics	2	0.13	nal (mixed thrust and strike-slip faults)		2	0.27	2
Hydrology	2	0.13	Nearly stagnant		2	0.27	1
Deep wells	2	0.13	no wells in Mt Simon		2	0.27	2
Fault permeability	2	0.13	fault traps present		1	0.13	1
	15	1.00		Average:	1.20	1.27	1.35

Table D-4.3 Tuscola, IL

Tuscola, IL **Revision: 2.0**

Secondary Containment

Overall score for this sheet	Average of weighted assessments of attributes	Average certainty
1.36	0.95	1.43

Attribute	**Weight** 10 = most import 1 = least	**Normalized Weight**	**Property/Value**		**Assessment of Attribute Property Relative to HSE Risk** **2 = excellent (positive attribute)** **0 = neutral (fair attribute)** **-2 = poor (negative attribute)**	**Weighted Assessment of Attribute**	**Certainty Factor** **2.0 = Very well known** **1.0 = Generally accepted** **0.1 = Poorly known**
Secondary Seal			**Description**				
Thickness	10	0.38	61 m (Maquoketa)		-0.4	-0.15	1
Lithology	5	0.19	marine shale		2	0.38	2
Demonstrated sealing	1	0.04	w Albany seal for O&G fields		2	0.08	2
Lateral continuity	5	0.19	Laterally continuous		2	0.38	2
Depth	5	0.19	937		1.6	0.31	1
	26	1.00		Average:	1.44	1.00	1.6
Shallower Seals			**Description**				
Thickness	10	0.33	New Albany = 23 m		-1.3	-0.43	1
Lithology	5	0.17	marine shale		2	0.33	1
Lateral continuity	5	0.17	Regional seal		2	0.33	1
Evidence of seepage	10	0.33	None		2	0.67	2
	30	1.00		Average:	1.18	0.90	1.25

Table D-4.4 Tuscola, IL

Attribute	**Weight**	**Normalized Weight**	**Property/Value**		**Property Relative to HSE Risk**	**Assessment of Attribute**	**Certainty Factor**
	10 = most import				**2 = excellent (positive attribute)**		**2.0 = Very well known**
	1 = least				**0 = neutral (fair attribute)**		**1.0 = Generally accepted**
Surface Characteristics			**Description**		**-2 = poor (negative attribute)**		**0.1 = Poorly known**
Topography	5	0.15	Flat		2	0.30	2
Wind	10	0.30	seaonally windy		0	0.00	2
Climate	2	0.06	sub-humid		-1	-0.06	2
Land use	4	0.12	Farmland		1	0.12	2
Population	10	0.30	Rural		1	0.30	2
Surface water	2	0.06	some streams/wetlands		-1	-0.06	2
	33	1.00		Average:	0.33	0.61	2.00
Groundwater Hydrology			**Description**				
Regional flow	6	0.32	glacial till ~>0.03 ft/day		0	0.00	2
Pressure	7	0.37	Hydrostatic		0	0.00	2
Geochemistry	2	0.11	high alkalinity		2	0.21	1
Salinity	4	0.21	Low TDS 100-500		1	0.21	1
	19	1.00		Average:	0.75	0.42	1.50
Existing Wells			**Description**				
Deep wells	5	0.25	no deep wells		2	0.50	2
Shallow wells	4	0.20	few shallow wells		2	0.40	2
Abandoned wells	10	0.50	Few abandoned wells.		0	0.00	2
Disposal wells	1	0.05	None present		2	0.10	2
	20	1.00		Average:	1.50	1.00	2.00
Faults			**Description**				
Tectonic faults	10	0.59	faults (basement faults only)		2	1.18	2
Normal faults	1	0.06	Few normal faults		2	0.12	2
Strike-slip faults	1	0.06	Few strike-slip faults		2	0.12	1
Fault permeability	5	0.29	fault traps present		1	0.29	1
	17	1.00		Average:	1.75	1.71	1.50

Table D-4.5 Tuscola, IL

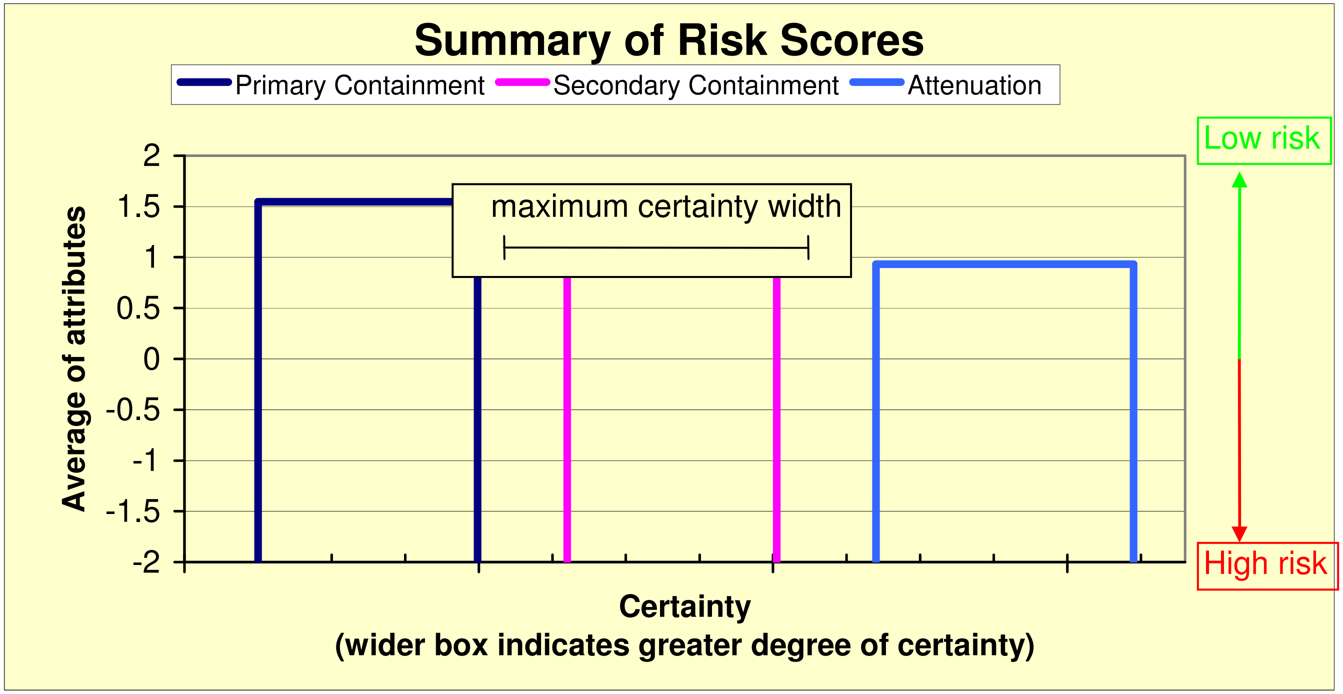


Table D-4.6 Tuscola, IL