APPENDIX G

HUMAN HEALTH AND SAFETY IMPACTS FROM POTENTIAL CO_2 RELEASES

for the

American Electric Power
Mountaineer Commercial Scale
Carbon Capture and Storage Project
Mason County, West Virginia

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G.1 INTRODUCTION

This appendix describes the potential human health and safety impacts associated with potential releases of carbon dioxide (CO_2) from the potential pipelines and injection wells during the operational period. In addition, the potential for post-injection releases from the subsurface storage formations are evaluated. The health and safety impacts are evaluated in terms of the potential risks to workers and the public. The level of risk is estimated based on the current conceptual design of the project, applicable safety and spill prevention regulations, and expected operating procedures.

Federal, state, and local health and safety regulations, as well as industrial codes and standards, would govern work activities during construction and operation of the project to protect the health and safety of workers and the public.

G.2 METHOD OF ANALYSIS

The methods used to analyze the potential health and safety impacts of the construction and operation of the Mountaineer Carbon Capture and Storage (CCS) II Project are similar to those developed in consultation with United States (U.S.) Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA) and used for the Environmental Impact Statement (EIS) for a previous CCS project (DOE, 2007a) and the risk assessment for the four candidate sites (DOE, 2007b). Data from the U.S. Census Bureau for the year 2000 were used to approximate the number of people near the plant and associated facilities that could be affected by any accidents or releases.

DOE analyzed the potential health effects for workers and the public who may be exposed to releases of captured gases during pipeline transport, at the injection well sites, or during subsurface storage. Based on DOE’s review, each incident was classified into one the following categories and frequency ranges:

- **Possible:** Accidents estimated to occur one or more times in 100 years of facility operations (frequency $\geq 1 \times 10^{-2}$ per year)
- **Unlikely:** Accidents estimated to occur between once in 100 years and once in 10,000 years of facility operations (frequency from 1×10^{-2} to 1×10^{-4} per year)
- **Extremely Unlikely:** Accidents estimated to occur between once in 10,000 years and once in 1 million years of facility operations (frequency from 1×10^{-4} to 1×10^{-6} per year)
- **Incredible:** Accidents estimated to occur less than one time in 1 million years of facility operations (frequency $< 1 \times 10^{-6}$ per year)

The transport of the released gases was estimated through atmospheric dispersion modeling. The predicted concentrations in air are then used to estimate the potential for exposure and any resulting potential impacts on human receptors. The effects of the releases to the atmosphere from the pipelines and injection wells during operation were simulated using the SLAB model (Ermak, 1990) and the pipeline-walk methodology developed for and used in a previous DOE project (DOE, 2007b). The pipeline-walk method was used to evaluate the effects of thermodynamically determined gas phase releases along the entire length of a pipeline and to calculate the number of individuals hypothetically exposed to CO_2 and other substances from simulated pipeline ruptures and punctures. The method moves along the pipeline at points 300 meters apart where a series of calculations are made using the SLAB model results for the range of meteorological conditions likely to occur at a site. The five main steps in the pipeline-walk method for pipeline rupture and puncture release scenarios are described below:

- **Step 1. Summarize meteorological conditions that affect plume transport.** The meteorological data are used to estimate the proportion of time over a year that each atmospheric state occurs (combinations of wind directions and stability conditions).
- **Step 2. Simulate the area potentially affected by a pipeline release.** The SLAB model is run to determine the area of the potential impact zone for each of the defined atmospheric states. Separate runs are performed for CO_2 and other gases for each health-effect level and exposure period for the rupture and puncture scenarios.
- **Step 3. Estimate population affected for each atmospheric state.** The areal extent of each predicted exposure zone for each gas is superimposed onto a map of the population density data along the pipeline route.
- **Step 4. Determine the expected number of individuals potentially affected at the specified release points.** The affected population in each exposure zone is next multiplied by the proportion of the time (relative importance) in each of the defined atmospheric states. Since all the stability classes sum to 1, the sum of these products provides the expected number of affected individuals at any selected point along the pipeline.
- **Step 5. Characterize the potential exposure along the entire pipeline.** Tabular and graphical summaries of the expected number of affected individuals at all points along the pipeline provide a comprehensive summary of potential health effects from a pipeline release.

G.3 TOXICITY OF CO_2 AND OTHER CONSTITUENTS OF CAPTURED GAS

The captured gas from the proposed plant could contain not only CO_2, but also potentially trace amounts of co-constituents such as ammonia, and other gases (e.g., oxygen, nitrogen, and water vapor) (see Table G-3). Potential health effects from CO_2 and co-constituents would be dependent on the concentration and length of exposure to each gas. The evaluation considered gaseous releases that may occur rapidly for only a short time (e.g., rupture of a pipeline) or more slowly over a longer period of time (e.g., leakage from a pipeline puncture or subsurface reservoir).

Potential health effects from inhalation of high concentrations of CO_2 gas can range from headache, dizziness, sweating, and vague feelings of discomfort, to breathing difficulties, increased heart rate, convulsions, coma, and possibly death. Potential health effects from exposure to ammonia can range from skin, eye, throat, and lung irritation to coughing, burns, lung damage, and possibly death at high concentrations. Table G-1 provides health risk criteria for workers and the public for exposure to CO_2 and ammonia. In general, health protective criteria concentrations for CO_2 and co-constituents are lower for longer lengths of exposure. Table G-2 provides the concentrations of these chemicals that are not likely to cause an appreciable risk of deleterious effects to humans (including sensitive subgroups) for longer exposure periods up to a lifetime.

Table G-1. Potential Health Effects from Exposure to CO_2 and Ammonia

Gas	Potential Health Effects	Health Protective Criteria Concentrations – Public[a] (ppm)	Health Protective Criteria Concentrations – Workers[b] (ppm)
CO_2	No health effects	Less than 5,000 (1 hour)	PEL: 5,000 (8 hours)
	Adverse (e.g., headache, dizziness, sweating, vague feelings of discomfort)	Between 5,000 and 30,000 (1 hour)	
	Irreversible adverse (e.g., breathing difficulties, increased heart rate, convulsions, coma)	Above 30,000 (1 hour)	IDLH: 40,000 (30 minutes)
	Life threatening	Above 40,000 (1 hour)	
Ammonia	No health effects	Less than 30	PEL: 50 (8 hours)
	Adverse (e.g., skin, eye, throat irritation)	Above 30 (1 hour and 8 hours)	
	Irreversible adverse (e.g., coughing, burns, lung damage)	Above 160 (1 hour) Above 110 (8 hours)	IDLH: 300
	Life threatening	Above 1100 (1 hour) Above 390 (8 hours)	

[a] Based on Protective Action Criteria (PAC) for exposure time of 1 hour or less established by DOE's Subcommittee on Consequence Actions and Protective Assessments (SCAPA, 2010) and EPA's Acute Exposure Guideline Levels (AEGL) for multiple time periods varying from 10 minutes up to 8 hours (EPA, 2010d).

PAC-1, AEGL-1: The airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience discomfort, irritation, or certain asymptomatic, non-sensory effects; however, these effects are not disabling and are transient and reversible upon cessation of exposure (DOE, 2010 and EPA, 2010d).

PAC-2, AEGL-2: The airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals could experience irreversible or other serious, long-lasting, adverse health effects or an impaired ability to escape (DOE, 2010 and EPA, 2010d).

PAC-3, AEGL-3: The airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death (DOE, 2010 and EPA, 2010d).

[b] "Permissible exposure levels are legally enforceable standards established by the U.S. Occupational Safety and Health Administration (OSHA, 2010). Immediately dangerous to life and health (IDLH) levels are recommended criteria established by the National Institute of Safety and Health (NIOSH, 2005), designed to allow a worker to escape within 30 minutes.

CO_2 = carbon dioxide; IDLH = immediately dangerous to life and health; PEL = permissible exposure level; ppm = parts per million

Table G-2. Longer Duration Criteria for CO_2 and Ammonia Not Likely to Cause Appreciable Health Risks to Humans

Gas	RfC (ppm)	Acute MRL (ppm)	Intermediate MRL (ppm)	Chronic MRL (ppm)
CO_2	None established	None established	None established	None established
Ammonia	0.14	1.7	None established	0.1

Sources: EPA, 2010a,b (acute and chronic MRLs); ATSDR, 2009 (NH3 MRLs); EPA, 2010e (NH_3 RfC)

CO_2 = carbon dioxide; MRL = minimal risk levels (estimates of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse non-cancer health effects for three different exposure periods: acute MRL for 1-14 days, intermediate; MRL for >14 to 365 days, and a chronic MRL for 365 days and longer); ppm = parts per million; RfC = reference concentration (estimates of daily inhalation exposure likely to cause no appreciable risk of deleterious effects to humans, including sensitive subgroups, during a lifetime)

G.4 POTENTIAL IMPACTS OF THE PROPOSED ACTION

G.4.1 Potential Effects Related to Accidental Releases from Pipelines

The U.S. Department of Transportation (DOT), Pipeline and Hazardous Materials Safety Administration, Office of Pipeline Safety (OPS), governs CO_2 pipeline safety. Pipelines and their operators are subject to numerous safety requirements and regulations. Operator requirements include routine maintenance and inspection, integrity testing, installation and monitoring of automatic leak detection systems and alarms, establishing written emergency preparedness and response plans, and ensuring that their employees are fully trained and qualified.

DOT's OPS administers and enforces the rules and regulations regarding natural gas and CO_2 pipeline transport. States also may regulate pipelines under partnership agreements with the OPS. The Public Service Commission of West Virginia is the designated agency that oversees gas pipeline safety in the state (WVPSC, 2010). West Virginia does not currently have regulations specifically pertaining to CO_2 pipelines. The rules are designed to protect the public and the environment by ensuring safety in gas pipeline design, construction, testing, operation, and maintenance.

When characterizing the potential for impacts related to accidents, DOE considered the expected frequency for which such accidents may occur. The expected frequency of an accident is the chance that the accident might occur for certain types of activities or operations. Accident frequency is typically discussed in terms of the number of occurrences over a period of time. For example, the frequency of occurrence for an accident that can be expected to happen once every 50 years is, 1 accident divided by the 50-year period (0.02 per year or $2x10^{-2}$ per year). An annual frequency estimate can be converted to a probability estimate by considering the time period of the operation. To characterize the annual frequency of certain events, DOE used the terms possible, unlikely, extremely unlikely, and incredible. Although pipeline punctures or ruptures would be unlikely, DOE analyzed the potential risks from CO_2 pipeline releases using the SLAB model (Ermak, 1990) and the pipeline-walk methodology (DOE, 2007b).

The transported gases are expected to be 99.5 percent CO_2, with other constituents possibly present in the pipeline as shown in Table G-3. The constituent of interest from a health perspective is ammonia, because the concentrations of this compound could be high compared to relevant health-related criteria. Under normal conditions, there may be low amounts of ammonia in the captured gas; however, it is possible for the captured gas to contain up to 50 parts per million (ppm) of this compound. DOE assessed the potential pipeline release risks using the maximum concentration of ammonia and the expected CO_2 concentration shown in Table G-3.

Table G-3. Estimated Captured Gas Composition for Mountaineer Plant

Compound	Quantity[a]
Carbon Dioxide	> 99.5 vol%
Water	< 3,000 ppmv
Nitrogen	< 100 ppmv
Ammonia	< 50 ppmv

[a] Values for compounds were provided by AEP.
ppmv = parts per million by volume; vol% = percentage by volume

Two accidental release scenarios (pipeline rupture and puncture) represent the most likely cause of pipeline releases at larger volumes. A pipeline rupture release would occur if the pipeline was completely severed, for example by heavy equipment during excavation activities. A rupture could also result from a longitudinal running fracture of a pipe section or a seam-weld failure. In these cases, the entire contents of the pipeline between the two nearest control valve stations could be discharged from the severed pipeline within minutes.

A pipeline puncture release is defined here as a 3-inch by 1-inch hole that could be made by a tooth of an excavator. In such a case, all of the contents in the pipeline between the two nearest control valve stations would discharge into the atmosphere, but the release would occur over a period of several hours, as the opening is small relative to the total volume and the pressure declines as the fluid escapes.

Captured CO_2 may be transported as a supercritical fluid, such that its density resembles a liquid but it expands to fill space like a gas. When mixed with water, the CO_2 can form carbonic acid, which is highly corrosive. For this reason, the moisture content of the CO_2 would be maintained at a low level. If CO_2 is released from a pipe, it expands rapidly as a gas and can include both liquid and solid (i.e., dry ice) phases, depending on temperature and pressure. Supercritical CO_2 has a very low viscosity, but is denser than air. A potential release of CO_2 through an open orifice in the pipeline as a gas moving at the speed of sound is referred to as choked or critical flow (Bird et al., 2002). In the rupture scenario, the escaping gas from the pipeline is assumed to escape as a horizontal jet at ground level, which is typically the worst-case event for heavier-than-air gases (Hanna and Drivas, 1987).

Potential releases to the atmosphere represent the primary exposure pathway considered in the exposure analysis. The receptor groups likely to be exposed by releases from pipelines or aboveground equipment at the plant or injection well site are onsite workers and offsite populations. In addition to the potential health effects of a release, which would be dependent on the exposure concentrations and local meteorological conditions at the time of a release, workers near a ruptured or punctured pipeline or wellhead are likely to also be affected by the physical forces from the accident itself, including the release of gases at high flow rates and at very high speeds. Workers involved at the location of an accidental release would be potentially affected, possibly due to a combination of effects, such as physical trauma, asphyxiation (displacement of oxygen in a small confined place), or frostbite from the rapid expansion of CO_2 (e.g., 3,000 pounds per square inch (psi) to 15 psi).

The SLAB model was used to simulate rupture and puncture of the pipelines. There are three scenarios involving multiple pipeline route options between the plant and the injection wells (see Figure 2-7 for a map showing pipeline routes). Each of these scenarios is described below.

Scenario A (Lower Bound) would use two pipeline routes to transport the captured gas to the injection wells:

- The Plant Route, a 0.13 mile-long, 8-inch inner diameter pipe to two injection wells located on the plant property
- The Borrow Area Route, a 2.24 mile-long, 8-inch inner diameter pipe to two injection wells located on Borrow Area No. 8

Scenario B would use three pipeline routes to transport the captured gas to the injection wells:

- The Borrow Area Route, a 2.24 mile-long, 12-inch inner diameter pipe to carry all the captured gas prior to reaching the two injection wells located on Borrow Area No. 8
- One of four Eastern Sporn Routes, a 4.99 to 8.21 mile-long[1], 8-inch inner diameter pipe to two of the three injection wells located on the Eastern Sporn Tract
- One of four Jordan Routes, an 8.39 to 9.66 mile-long[1], 8-inch inner diameter pipe to two injection wells located on the Jordan Tract

Scenario C (Upper Bound) would use four pipeline routes to transport the captured gas to the injection wells:

- The first leg (North Segment A) of the Borrow Area Route, a 0.85 mile-long, 12-inch inner diameter pipe to carry all the captured gas prior to splitting the flow into two parts
- The remainder of the Borrow Area Route, a 1.39 mile-long, 12-inch inner diameter pipe to carry most of the captured gas prior to reaching the two injection wells located on Borrow Area No. 8
- One of four Eastern Sporn Routes, a total of 4.99 to 8.21 mile-long[1], 8-inch inner diameter pipe to two of the three injection wells located on the Eastern Sporn Tract
- One of four Jordan Routes, a total of 8.39 to 9.66 mile-long[1], 8-inch inner diameter pipe to two injection wells located on the Jordan Tract
- The Western Sporn Route, a total of 5.68 mile-long[1], 8-inch inner diameter pipe to two injection wells located on the Western Sporn Tract

Because of the number of options, every individual route was not simulated with SLAB or the pipeline-walk methodology. Both routes of Scenario A, the lower bond, were simulated. Two other routes were also simulated, the Jordan Route, since it is the longest, and the Western Sporn Route, since it has higher population densities along part of its route. The SLAB results for these cases were then used to estimate the potential impacts to nearby populations using the pipeline-walk methodology. The pipeline-walk method was also used for the last part of the Eastern Sporn Route, which had a similar length to the Borrow Area Route.

The pipeline inner diameter was set as 11.875 inches for 100 percent of the flow and 8.063 inches for 50 percent of the flow or less. The base case conditions for both the large and small pipelines were a pressure of 1,500 psi at approximately 88 degrees Fahrenheit (°F) (31.1 degrees Celsius [°C]), which means the CO_2 would be transported in a supercritical state. A higher temperature of up to 110°F (43.3°C) may be used in the pipelines at a pressure of 1,500 psi, which would result in a lower density for the CO_2. This case was not simulated, because the volume released would be less than for the base case. In addition, an alternate set of conditions was simulated with a pressure of 3,000 psi at approximately

[1] Note: The lengths given here are the total trunk distances from the CO_2 capture facility to the injection wells or start of the pipeline spurs to the injection wells, unless noted.

120°F, where the CO_2 would also move in a supercritical state. If a pipeline release occurs, part of the supercritical fluid is converted to a dry-ice snow form, which then slowly sublimates. The percent of CO_2 released as a vapor is estimated to be 73 percent for the lower pressure case and 75 percent for the higher pressure case. The transport of the vapor phase in the atmosphere is then simulated using SLAB and the results compared to appropriate health criteria.

Seven meteorological stability classes, as defined in Table G-4, and all 16 different wind directions were used for the simulations based on local data from the Huntington Tri-State Airport National Weather Service Station between 1991 and 1995 (NCDC, 2009). As shown in the wind rose diagram (see Figure 3.1-2 in Section 3.1, Air Quality and Climate), calm conditions occurred about 5.6 percent of the time. The predominant wind direction is from the southwest (11.2 percent of the time), with significant winds also from the west and west-southwest (8.31 and 10.24 percent of the time, respectively).

Table G-4. Meteorological Conditions Used in SLAB Simulations

Condition	F1	A1	B3	C5	D7	D10	D11
Pasquill[a] Category	F	A	B	C	D	D	D
Average Wind Speed (m/sec)	1	1	3	5	7	10	11

[a] Pasquill Meteorological Stability Classes (Turner, 1994):
A – Extremely unstable conditions
B – Moderately unstable conditions
C – Slightly unstable conditions
D – Neutral conditions
E – Slightly stable conditions
F – Calm, stable conditions
G – Extremely stable conditions
Note: Classes E and G are not used for the Mountaineer Plant.
m/sec = meters per second

Simulations were conducted to determine the impact zone where workers and the public could be exposed to concentrations from pipe ruptures equal to the pertinent short-duration health criteria for CO_2 and ammonia using Protective Action Criteria (PAC-0 to PAC-3; see Table G-1). An exposure period of 15 minutes was used for the pipe ruptures. The pipe puncture releases would be longer in duration, so the longer-duration health criteria, the EPA Acute Exposure Guideline Levels (AEGL) for 8 hours (AEGL-1 to AEGL-3; see Table G-1) were used for assessing the potential effects related to this release type. For workers, a simulation was also made to determine the impact zone for 40,000 ppm CO_2 for a 30-minute exposure period. For ammonia, only the PAC-1 or AEGL-1 of 30 ppm was simulated, since the maximum estimated concentration in the captured gas is 50 ppm, which is less than the concentrations that could cause adverse or serious effects (see Table G-1).

The potential plume from a given pipe rupture scenario would be small in areal extent and its position would depend on the wind direction, speed, and stability conditions at the time of the release. Figure G-1 shows the pipeline route options and the population densities from the 2000 U.S. Census. The 2000 U.S. Census was used because it provided data for smaller tracts versus larger block data sets, which would provide population density for an overly large area. The land surrounding the potential injection well sites and the plant is owned by American Electric Power Service Corporation (AEP), as shown in Figure G-1.

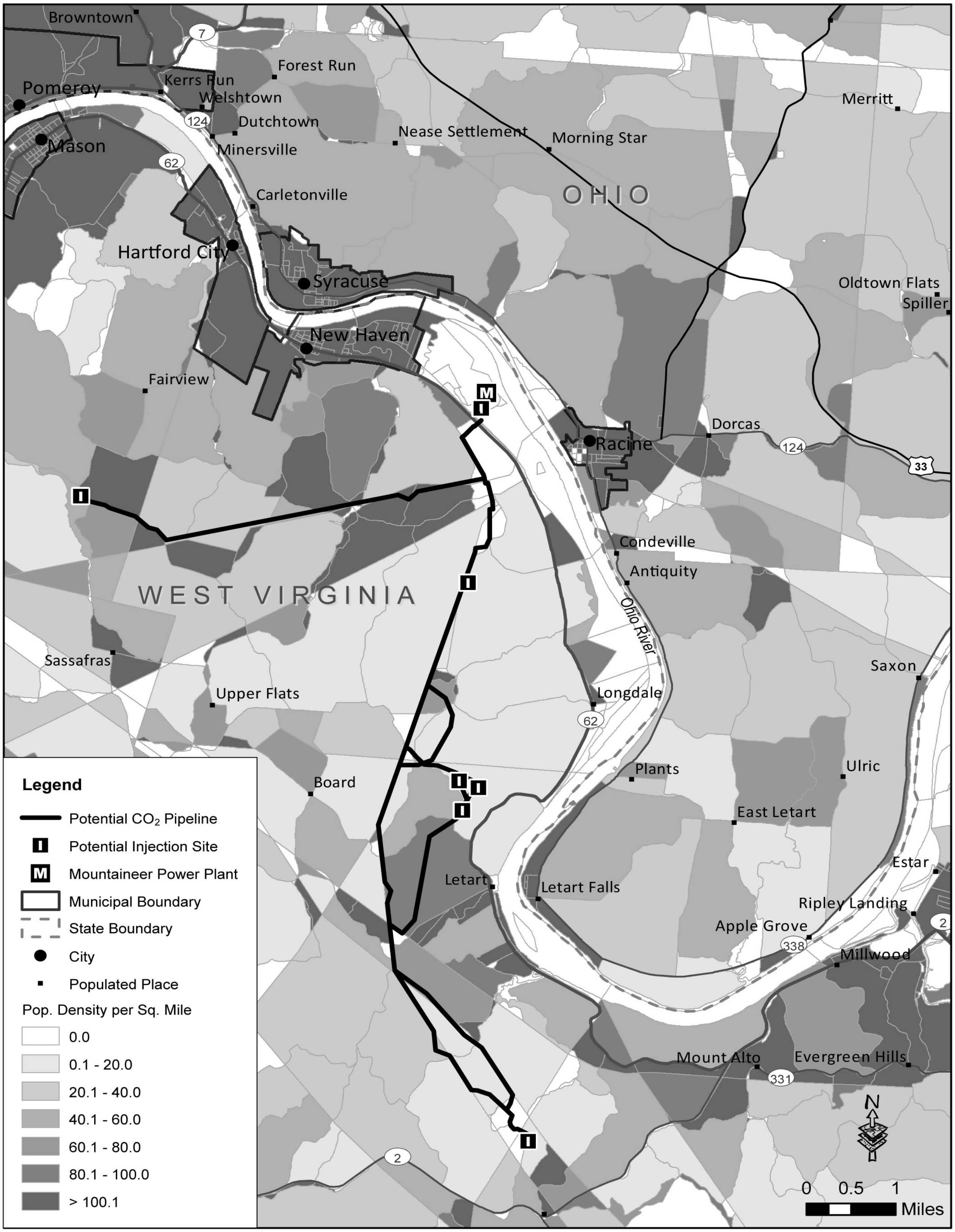

Figure G-1. Potential Population in Vicinity of Potential Pipeline Routes (2000 U.S. Census)

G.4.1.1 Scenario A Pipeline Routes

Table G-5 shows the estimated distances that a given exposure concentration plume could extend out from a hypothetical pipeline release due to a rupture or puncture for the pipeline routes included in Scenario A (the 0.13 mile Plant pipeline and the 2.24-mile 8-inch pipeline to the Borrow Area). The results shown in this table are for the base case conditions, pressure at 1,500 psi and temperature at 88°F. The results for conditions with pressure of 3,000 psi and temperature of 120°F indicated that the plume distances would be at most 15 percent longer, since the release volume would be greater, but the duration of the release would be less due to the higher pressure.

Table G-5. Simulated Plume Transport Distances for the Hypothetical Pipeline Releases for Scenario A

Release Type	Exposure Duration	Criteria (ppm)	Distance (m)	Meteorological Condition[a]	Distance (m)	Meteorological Condition[a]
Due to CO_2			**8-Inch Plant Route Pipeline**		**8-Inch Borrow Area Route Pipeline**	
Rupture	15 minutes	40,000	<1	All	17.41	D11
	15 minutes	30,000	<1	All	26.14	D11
	15 minutes	5,000	4.66	D10 and D11	997.29	F1
Puncture	8 hours	40,000	<1	All	1.55	A1,B3,C5,D10,D11
	8 hours	20,000	<1	All	2.37	A1,B3,D10,D11
	8 hours	5,000	1.02	All	7.27	F1
Due to Ammonia			**8-Inch Plant Route Pipeline**		**8-Inch Borrow Area Route Pipeline**	
Rupture	15 minutes	30	6.09	A1	37.3	A1
Puncture	8 hours	30	1.96	A1	5.31	A1

[a] Meteorological Condition for Longest Distance Case (see Table G-4 for description.)
CO_2 = carbon dioxide; m = meter; ppm = parts per million

Table G-5 shows that the furthest distance along the pipeline route that a CO_2 concentration of 5,000 ppm (PAC-0 criteria) could extend from a hypothetical pipeline rupture along the Plant Route was 4.66 meters (15 feet). This distance would be within the AEP-owned property. The furthest distance along the pipeline route that an ammonia concentration of 30 ppm could extend from a hypothetical pipeline rupture was about 6.09 meters (20 feet). This distance would also be within the AEP-owned property. Thus, the public would not be exposed to a hypothetical release along the Plant Route. For the longer route to the Borrow Area, the furthest distance that a CO_2 concentration of 5,000 ppm could extend from a rupture was 997.3 meters (0.62 mile) under calm conditions, but only 211.6 meters (0.13 mile) under windier conditions (Pasquill stability class D7 with an average wind speed of 7 meters per second). Most of the property along the Borrow Area Route is AEP-owned property, except for one area, which is about 0.25 mile from the pipe centerline. Thus, the general public is unlikely to be exposed to CO_2 under this hypothetical scenario except from a rupture that occurred under calm conditions when they could potentially experience only temporary, transient effects. The furthest distance from a puncture was much less, as seen in Table G-5. The furthest distance that an ammonia concentration of 30 ppm (PAC-1 criteria) could extend from a rupture was 37.3 meters (0.02 mile) under calm conditions, or even less from a puncture, so the public would not be exposed to such releases. The levels of CO_2 and ammonia would need to exceed the PAC-2 criteria in order for the general population to have the potential to experience serious, adverse, or irreversible effects.

The pipeline-walk method and the population density data were used to estimate the expected numbers of people that could be affected by hypothetical ruptures or punctures of CO_2 or ammonia along the route options of Scenario A based on the percent of time that a plume would be transported by the wind in the different directions and speeds. Tables G-6 and G-7 present the estimated number of people potentially affected by exposure to CO_2 and ammonia at various criteria concentrations, resulting from a hypothetical pipeline release for both a rupture and puncture for the Plant and Borrow Area Routes for the base case pipe conditions (Scenario A). The estimated number of people is a calculated number based on the population density within each hypothetical plume given the full range of meteorological conditions that could occur multiplied by the percent of time that each of those conditions could occur. For each scenario, a pipeline rupture or puncture would statistically affect none or less than one person in all cases, not considering workers located nearby at the time of the release. Based on the distances provided in Table G-5, offsite receptors would not be affected by potential pipeline releases from ruptures or punctures along the Plant Route. For the Borrow Area Route, offsite receptors would not be affected unless a rupture occurred under calm conditions, if the pipeline pressure was 1,500 psi or 3,000 psi.

Table G-6. Estimated Number of People Affected by CO_2 from the Hypothetical Pipeline Releases for Scenario A

Release Type	Exposure Duration	CO_2 Criteria, ppm [Exposure Level]	Number of People Potentially Affected (Plant/Borrow Area Routes)
Rupture	15 minutes	40,000 [PAC-3]	0/<1
	15 minutes	30,000 [PAC-2]	0/<1
	15 minutes	5,000 [PAC-0]	0/<1
Puncture	8 hours	40,000 [EPA, 2000]	0/0
	8 hours	20,000 [EPA, 2000]	0/0
	8 hours	5,000 [PEL]	0/0

CO_2 = carbon dioxide; EPA = U.S. Environmental Protection Agency; PAC = Protective Action Criteria; PEL = permissible exposure level; ppm = parts per million

Table G-7. Estimated Number of People Affected by Ammonia from the Hypothetical Pipeline Releases for Scenario A

Release Type	Exposure Duration	Ammonia Criteria, ppm [Exposure Level]	Number of People Potentially Affected (Plant/Borrow Area Routes)
Rupture	15 minutes	30 [PAC-1]	0/0
Puncture	8 hours	30 [AEGL-1]	0/0

AEGL = Acute Exposure Guideline Level; PAC = Protective Action Criteria; ppm = parts per million

Estimated Frequencies and Probabilities of Pipeline Releases

Table G-8 shows safety incidents between 1988 and 2008 involving natural gas and CO_2 pipelines in the U.S. (OPS, 2009). As shown in Table G-8, incidents involving CO_2 pipelines have not resulted in any fatalities and the annual incident frequency is 0.23 per 1,000 kilometers or 1.33 per 100 miles (OPS, 2009). The major cause of pipeline failure is damage (puncture or rupture) during excavation (OPS, 2010) for repairs or replacement or third-parties working on new pipelines. DOE used the OPS data to estimate CO_2 pipeline failure rates and the probabilities of pipeline release incidents for the project. Incident data between 1988 and 2008 from the on-line library of the OPS were used to calculate the frequency and probability of pipeline ruptures and punctures.

Table G-8. Pipeline Safety Record in United States (1988 – 2008)

Pipelines[a]	Natural Gas	CO_2
Length (km/miles)	494,477 / 307,254	5,581 / 3,468
Incidents	2,038	26
Fatalities	59	0
Injuries	224	1
Property Damage (in $M)	1,221.7	1.25
Incidents/1000 km per year (Incidents/100 miles per year)	0.21 (1.51)	0.23 (1.33)

[a] Based on Office of Pipeline Safety Data through 4/2009.

CO_2 = carbon dioxide; km = kilometer; $M = millions of dollars

Four of the 26 incidents that occurred between 1988 and 2008 with the largest CO_2 releases (greater than 4,000 barrels) were designated as rupture-type releases. Using the total length of CO_2 pipelines involved of 5,581 kilometers (3,468 miles), the annual rupture failure frequency was calculated to be 3.41×10^{-5} (kilometer-year)$^{-1}$, which is the same as (0.0000341 per kilometer-year). The next seven largest releases from the existing CO_2 pipelines had losses of CO_2 between 300 and 3,600 barrels. The remaining incidents had releases of less than 100 barrels. The annual rupture failure frequency was calculated to be 5.97×10^{-5} (kilometer-year)$^{-1}$, which is the same as (0.0000597 per kilometer-year). The annual pipeline failure frequencies and the probability of at least one failure over a 20-year lifetime of the pipelines were calculated assuming the probability of failure to be exponentially distributed with the hazard rate equal to the product of the failure frequency and the pipeline length.

The annual frequency of a rupture on the potential pipeline would vary from 7.16×10^{-6} per year (0.0000716 per year) for the shortest pipeline, the Plant Route pipe, to 1.23×10^{-4} per year (0.000123 per year) for the longer pipe route to the Borrow Area. The probability of at least one rupture over a 20-year operating period is estimated to be 1.43×10^{-4} (0.000143) and 2.45×10^{-3} (0.00245) for these two routes. The annual frequency of a puncture on the potential pipeline would vary from 1.25×10^{-5} per year (0.000125 per year) for the Plant Route pipe to 2.15×10^{-4} per year (0.000215 per year) for the pipe route to the Borrow Area. The probability of a puncture over a 20-year operating period is estimated to be 2.51 $\times 10^{-4}$ (0.000251) and 4.29×10^{-3} (0.00429) for these two routes. Based on the estimated frequencies of pipeline punctures or ruptures, both releases on the Plant Route are considered extremely unlikely (1×10^{-4} per year to 1×10^{-6} per year or between 0.0001 per year and 0.00001 per year) and unlikely on the Borrow Area Route (1×10^{-2} per year to 1×10^{-4} per year or between 0.01 per year and 0.0001 per year).

G.4.1.2 Scenario B Pipeline Routes

Scenario B includes a 12-inch pipeline along the Borrow Area Route, and 8-inch trunk lines to the Jordan Tract and to the Eastern Sporn Tract. As mentioned previously, there are four alternate configurations for both the Jordan Tract and Eastern Sporn Routes. The longest route was the Jordan Route 3, so this route was simulated using an 8-inch pipe. The length of the Jordan Tract pipeline would vary, depending on which route was selected for the Eastern Sporn Route. The longest route to the Eastern Sporn Tract was Route 2, which used part of the Jordan Tract until splitting off at the start of the Eastern Sporn Corridor. This part of the route was simulated using the pipeline-walk method and results for the 8-inch Borrow Area Route pipeline, which had a similar distance.

Table G-9 shows the estimated distances that a given exposure concentration plume could extend out from a hypothetical pipeline release due to a rupture or puncture. The results shown in this table are for the base case conditions, pressure at 1500 psi and temperature at 88°F. The furthest distance along the pipeline route that a CO_2 concentration of 5,000 ppm, which can result in transient, reversible effects could extend from a hypothetical pipeline rupture was estimated to be 0.96 mile for the 12-inch pipeline to the Borrow Area, 1.27 miles for the Jordan Route, and 0.62 mile for the Eastern Sporn Corridor of the Eastern Sporn Route. This distance would extend outside the AEP-owned property, along part of the Borrow Area Route on the west side of the pipeline. These simulations are for calm conditions when the SLAB model showed that the CO_2 plume could extend further than for windy conditions by a factor of up to 3.

The SLAB results indicated that CO_2 concentrations over 30,000 ppm averaged over a 15 minute period, which can potentially cause irreversible adverse effects, would not extend beyond the AEP property along the Borrow Area Route. The furthest distance that an ammonia concentration of 30 ppm could extend from a hypothetical pipeline rupture of the 12-inch pipeline along the Borrow Area Route would also not extend beyond the AEP-owned property. The levels of CO_2 and ammonia would need to exceed the PAC-2 criteria in order for the general population to potentially experience serious, adverse, or irreversible effects. Table G-9 shows that for the pipelines to the Jordan Tract and Eastern Sporn Tract, CO_2 concentrations of 30,000 ppm averaged over a 15-minute period could extend beyond the permanent pipeline right-of-way of 50 feet.

Table G-10 shows the expected number of people that could be affected by a hypothetical rupture of CO_2 from each of the major pipeline routes for Scenario B. The estimated number of people potentially affected by a release of CO_2 at a concentration over 30,000 ppm, which could cause irreversible adverse effects, was less than 1 for all cases. These estimates are conservative in that the entire distance of a given route was used, since a hypothetical release could occur at the junction of two pipelines. The public could potentially be exposed to transient, reversible effects of CO_2 concentrations between 5,000 ppm and 30,000 ppm, if a rupture occurred along the Jordan Route or the Eastern Sporn Routes. The estimated number of people affected by a hypothetical release was less than 1 up to a maximum of 4 people for the Jordan Tract and up to 5 people for the last segment of the Eastern Sporn Route. Table G-11 shows that the expected number of people potentially affected by a release of ammonia is less than 1 for all cases and routes.

The results for conditions with pressure of 3,000 psi and temperature of 120°F indicated that the distances for the 12-inch pipeline to the Borrow Area were up to 12 percent longer, since the volume is greater, but the duration of the release would be less. The furthest distance that a concentration over 5,000 ppm could occur from a rupture was 1.07 miles, which indicates that if a rupture occurred along the first part of this route, offsite receptors could be potentially affected by transient, reversible affects. Thus, the estimated number of people could increase to 1 that could be affected by a CO_2 concentration of 5,000 ppm, but all the other cases for CO_2 and ammonia were still less than 1. The estimated number of people that could be affected by higher CO_2 concentrations that could potentially cause adverse effects would be less than 1, since the estimated extent of the plume would be within the AEP property. For an 8-inch pipeline for the higher pressure conditions to the Jordan Tract, the furthest distance that a CO_2 concentration of 5,000 ppm could increase by about 8 percent. The estimated number of people that could be affected for this rupture was up to 3 people. The estimated number of people that could be affected at higher CO_2 or ammonia concentrations was still less than 1 for the other cases, although the distances would be up to 5 percent further. For the pipeline from the Jordan Tract to the Eastern Sporn Tract wells, the estimated number of people was up to 4 people, for the case where people could potentially be affected by CO_2 concentrations of 5,000 ppm. For higher concentrations, the estimated numbers of people affected were less than 1 for the other cases.

There are some places along these pipeline routes where a stream valley is crossed, where a plume could spread along the valley rather than radially out from the release. An example of such a place occurs along the southern part of the Jordan Tract. Detailed information on stream crossings is provided for all the pipeline routes in Section 3.6, Surface Water. Because CO_2 is a dense gas, it would tend to remain in the low areas, rather than move upward following the topography. The predicted plume concentrations developed using the SLAB model, do not account for these local topographic features.

Table G-9. Simulated Plume Transport Distances for the Hypothetical Pipeline Releases for Scenario B

Release Type	Exposure Duration	Criteria (ppm)	Distance (m)	Meteorological Condition[a]	Distance (m)	Meteorological Condition[a]	Distance (m)	Meteorological Condition[a]
Due to CO_2			**12-Inch Borrow Area Route**		**8-Inch Jordan Route**		**8-Inch Eastern Sporn Route[a]**	
Rupture	15 minutes	40,000	29.28	D11	116.9	F1	17.41	D11
	15 minutes	30,000	42.61	D11	175.49	F1	26.14	D11
	15 minutes	5,000	1,540	F1	2,051	F1	997.29	F1
Puncture	8 hours	40,000	2.50	D11	<5	All	1.55	A1,B3,C5, D10,D11
	8 hours	20,000	4.30	D11	8.08	A1	2.37	A1,B3,D10, D11
	8 hours	5,000	24.19	F1	59.41	F1	7.27	F1
Due to Ammonia			**12-Inch Borrow Area Route**		**8-Inch Jordan Route**		**8-Inch Eastern Sporn Route[a]**	
Rupture	15 minutes	30	57.37	D7	77.13	D7	59.67	D7
Puncture	8 hours	30	7.19	A1	9.41	A1	7.61	A1

[a] This route follows part of the Jordan Route. The values listed here as for the longest option including the spurs to the wells after the split, which was estimated using results for the 8-inch Borrow Area Route, since the lengths were similar.

CO_2 = carbon dioxide; m = meter; ppm = parts per million

Table G-10. Estimated Number of People Affected by CO_2 from the Hypothetical Pipeline Releases for Scenario B

Release Type	Exposure Duration	CO_2 Criteria, ppm [Exposure Level]	Number of People Potentially Affected		
			Borrow Area Route	**Jordan Route**	**Eastern Sporn Route**
Rupture	15 minutes	40,000 [PAC-3]	<1	<1	<1
	15 minutes	30,000 [PAC-2]	<1	<1	<1
	15 minutes	5,000 [PAC-0]	<1	<1 to 4	<1 to 5
Puncture	8 hours	40,000 [EPA, 2000]	<1	<1	<1
	8 hours	20,000 [EPA, 2000]	<1	<1	<1
	8 hours	5,000 [TLV]	<1	<1	<1

CO_2 = carbon dioxide; EPA = U.S. Environmental Protection Agency; PAC = Protective Action Criteria; ppm = parts per million; TLV = threshold limit value

Table G-11. Estimated Number of People Affected by Ammonia from the Hypothetical Pipeline Releases for Scenario B

Release Type	Exposure Duration	Ammonia Criteria, ppm [Exposure Level]	Number of People Potentially Affected		
			Borrow Area Route	Jordan Route	Eastern Sporn Route
Rupture	15 minutes	30 [PAC-1]	<1	<1	<1
Puncture	8 hours	30 [AEGL-1]	<1	<1	<1

AEGL = Acute Exposure Guideline Level; PAC = Protective Action Criteria; ppm = parts per million

G.4.1.3 Scenario C Pipeline Routes

Scenario C includes four injection well site locations, which would use a 12-inch pipeline along North Segment A, an 8-inch trunk line to the Western Sporn Tract, a 12-inch trunk line along the rest of the Borrow Area Route, and 8-inch trunk lines for the Jordan Tract and to the Eastern Sporn Tract. The longest route to the Eastern Sporn Tract was Route 2, which used part of the Jordan Tract until splitting off at the start of the Eastern Sporn Corridor.

Table G-12 shows the estimated distances that a given exposure concentration plume could extend out from a hypothetical pipeline release due to a rupture or puncture for the base case with a pressure of 1,500 psi and a temperature of 110°F. The furthest distance along the pipeline route that a CO_2 concentration of 5,000 ppm, which can result in transient, reversible effects could extend from a hypothetical pipeline rupture was estimated to be 0.96 mile for the 12-inch pipeline to the Borrow Area, 1.27 miles for the Jordan Route, 1.0 mile for the Western Sporn Route, and 0.62 mile for the Eastern Sporn Route. The SLAB results for the Western Sporn Route are specific to Scenario C, while the other routes include results developed for Scenario B. Table G-12 shows that for the pipelines to the Western Sporn Tract, CO_2 concentrations of 30,000 ppm averaged over a 15-minute period could extend beyond the permanent pipeline right-of-way of 50 feet. Ammonia concentrations over 30 ppm from a hypothetical rupture along the Western Sporn Route were also predicted to extend beyond 50 feet, but not from a puncture.

The pipeline-walk method and the population density data were used to estimate the estimated numbers of people that could potentially be affected by ruptures or punctures of CO_2 or ammonia along all the route options of Scenario C based on the percent of time that a plume would be transported by the wind in the different directions and speeds. Table G-13 shows the estimated number of people that could be affected by a hypothetical rupture of CO_2 from each of the major pipeline routes for Scenario C. The estimated number of people potentially affected by a release of CO_2 at a concentration over 30,000 ppm, which could potentially cause irreversible adverse effects, were less than 1 for all cases. These estimates are conservative in that the entire distance of a given route was used. The public could be exposed to potential transient, reversible effects of CO_2 concentrations between 5,000 ppm and 30,000 ppm, if a rupture occurred along the Jordan Route or the Eastern and Western Sporn Routes. The estimated number of people affected by a hypothetical release was less than 1 up to a maximum of 3 people for the Western Sporn Route. Table G-14 shows that the estimated numbers of people potentially affected by a release of ammonia are less than 1 for all cases and routes.

Scenario C includes one new route to the Western Sporn Tract. The results for conditions with pressure of 3,000 psi and temperature of 120°F indicated that the distances for the 8-inch pipeline to the Western Sporn Tract were up to 9 percent longer, since the volume is greater, but the duration of the release would be less. The furthest distance that a concentration over 5,000 ppm could occur from a rupture was 1.10 miles, which indicates that if a rupture occurred along this route, offsite receptors could be potentially affected by transient, reversible affects. The estimated number of people that could be affected by a CO_2 concentration of 5,000 ppm was up to 3 people, but all the other cases for CO_2 and ammonia were still less than 1. The estimated number of people that could be affected by higher CO_2 concentrations that could potentially cause adverse effects would be less than 1.

Sensitive receptor locations include schools, hospitals, nursing homes, and child care centers, as discussed in Section 3.12, Noise. A check was made to determine if potential adverse effects could occur to these types of receptors. Based on the estimated distances for the pipeline routes, none of these facilities are likely to be affected by potential ruptures or punctures of the pipelines.

Table G-12. Simulated Plume Transport Distances for the Hypothetical Pipeline Releases for Scenario C

Release Type	Exposure Duration	Criteria (ppm)	Distance (m)	Meteorological Condition[a]	Distance (m)	Meteorological Condition[a]	Distance (m)	Meteorological Condition[a]	Distance (m)	Meteorological Condition[a]
Due to CO_2			**12-Inch Borrow Area Route**		**8-Inch Jordan Route**		**8-Inch Eastern Sporn Route[a]**		**8-Inch Western Sporn Route**	
Rupture	15 minutes	40,000	29.28	D11	116.9	F1	17.41	D11	5.30	D11
	15 minutes	30,000	42.61	D11	175.49	F1	26.14	D11	84.31	F1
	15 minutes	5,000	1,540	F1	2,051	F1	997.29	F1	1,628.15	F1
Puncture	8 hours	40,000	2.50	D11	<5	All	1.55	A1,B3, C5,D10, D11	<4	All
	8 hours	20,000	4.30	D11	8.08	A1	2.37	A1,B3,D 10,D11	4.93	D11
	8 hours	5,000	24.19	F1	59.41	F1	7.27	F1	29.71	D10
Due to Ammonia			**12-Inch Borrow Area Route**		**8-Inch Jordan Route**		**8-Inch Eastern Sporn Route[a]**		**8-Inch Western Sporn Route**	
Rupture	15 minutes	30	57.37	D7	77.13	D7	37.3	A1	59.67	D7
Puncture	8 hours	30	7.19	A1	9.41	A1	5.31	A1	7.61	A1

[a] This route follows part of the Jordan Route. The values listed here as for the longest option including the spurs to the wells after the split, which was estimated using results for the 8-inch Borrow Area Route, since the lengths were similar.

CO_2 = carbon dioxide; m = meter; ppm = parts per million

Table G-13. Estimated Number of People Affected by CO_2 from the Hypothetical Pipeline Releases for Scenario C

Release Type	Exposure Duration	CO_2 Criteria, ppm [Exposure Level]	Number of People Potentially Affected			
			Borrow Area Route	Jordan Route	Eastern Sporn Route	Western Sporn Route
Rupture	15 minutes	40,000 [PAC-3]	<1	<1	<1	<1
	15 minutes	30,000 [PAC-2]	<1	<1	<1	<1
	15 minutes	5,000 [PAC-0]	<1	<1 to 4	<1 to 5	<1 to 3
Puncture	8 hours	40,000 [EPA, 2000]	<1	<1	<1	<1
	8 hours	20,000 [EPA, 2000]	<1	<1	<1	<1
	8 hours	5,000 [TLV]	<1	<1	<1	<1

CO_2 = carbon dioxide; EPA = U.S. Environmental Protection Agency; PAC = Protective Action Criteria; ppm = parts per million; TLV = threshold limit value

Table G-14. Estimated Number of People Affected by Ammonia from the Hypothetical Pipeline Releases for Scenario C

Release Type	Exposure Duration	Ammonia Criteria, ppm [Exposure Level]	Number of People Potentially Affected			
			Borrow Area Route	Jordan Route	Eastern Sporn Route	Western Sporn Route
Rupture	15 minutes	30 [PAC-1]	<1	<1	<1	<1
Puncture	8 hours	30 [AEGL-1]	<1	<1	<1	<1

AEGL = Acute Exposure Guideline Level; PAC = Protective Action Criteria; ppm = parts per million

G.4.2 Potential Effects Related to Releases at the Injection Wells

This section addresses potential health effects of accidental releases from the potential injection wells during operation. Injection of CO_2 for enhanced oil recovery has been practiced for over 30 years, and injection of natural gas for storage has been conducted for the past 100 years (Benson, 2009). Most of the available information on injection well failures comes from the natural gas industry, rather than from CO_2 wells; however, there have been well failures when drilling in natural CO_2 deposits and during CO_2 injection for enhanced oil recovery operations. The estimated frequency of major incidents involving injection wells is 2×10^{-5} per well per year (0.00002 per year), which was the frequency used to evaluate candidate sites for a previous DOE project (DOE, 2007b). This failure rate is based on major incidents in natural gas storage wells estimated from worldwide data from the 1970s and after (IEA, 2006).

Although an injection well failure would be extremely unlikely, DOE used the SLAB model to simulate a release from the surface of the well as a vertical or horizontal jet, assuming gas concentrations similar to those used for the pipeline: (99.5 mol percent of CO_2 and 50 ppm of ammonia). The toxicity analysis used the PAC criteria applicable to the public for an exposure duration of one hour or less (15 minutes for a well failure) and acute worker safety guidelines listed in Table G-1.

Table G-15 shows the furthest distances that CO_2 and ammonia criteria-level plumes would be estimated to migrate after a hypothetical injection well failure and the meteorological stability class used. The depth of the injection wells for these simulations were 7,900 feet for the Rose Run case and 8,400 feet for the Copper Ridge case. Based on the analysis, CO_2 concentrations greater than 5,000 ppm averaged over a 15-minute period (PAC-0 criteria) would occur less than 50 feet from the injection wells. The furthest distance that an ammonia concentration of 30 ppm (PAC-1) criteria would occur due to a release from a well is also less than 50 feet. Thus, at the well sites located on the plant property and at the Borrow Area, the ammonia plume would not extend off the AEP-owned property. At the other sites being considered for injection wells, the estimated number of people affected is less than 1 at the Jordan Tract, Western

Sporn Tract, and Eastern Sporn Tract. In addition, sensitivity analyses were conducted for a hypothetical deep injection well with a depth of 8,900 feet. The furthest distance that a CO_2 concentration of 5,000 ppm averaged over 15 minutes could occur is 54.04 meters, or about 9 percent further than the Copper Ridge base case. Ammonia concentrations of 30 ppm averaged over 15 minutes could occur to a furthest distance of 11.3 meters or about 3 percent further than the base case. The estimated number of people potentially affected at the sites would be similar to the base cases.

Table G-15. Simulated Plume Transport Distances from Injection Well Failure

Compound	Exposure Duration	Criteria (ppm) [Level]	Distance (meters) Rose Run/Copper Ridge	Meteorological Condition[a]
Carbon Dioxide	15 minutes	40,000 [PAC-3]	3.29/3.54	D11
	15 minutes	30,000 [PAC-2]	4.36/4.72	D11
	15 minutes	5,000 [PAC-0]	44.50/49.62	F1
Ammonia	15 minutes	30 [PAC-1]	10.58/10.97	A1

[a] Meteorological Condition for Longest Distance Case; see Table G-4 for description of Pasquill stability classes.
PAC = Protective Action Criteria; ppm = parts per million

The annual frequency of a potential failure in the paired injection wells at a given site would be estimated as 4.04×10^{-5}/year (0.0000404 per year). For Scenario A, two wells would be located at the Plant site and two at the Borrow Area. The annual frequency of a potential failure in any of the four wells would be 8.08×10^{-5}/year (0.0000808 per year). The estimated probability of a potential failure in any one of the four wells over a 20-year operating period would be 1.61×10^{-3} (0.00161) Based on the estimated frequencies of potential well failures, such an occurrence is considered extremely unlikely (1×10^{-4} per year to 1×10^{-6} per year or between 0.0001 per year and 0.00001 per year).

Scenario B would include up to six wells at the Borrow Area, Jordan Tract, and Eastern Sporn Tract, although only four of the wells may be used at one time. For each site with two wells, the annual frequency of a potential failure would be 4.04×10^{-5}/year (0.0000404 per year). At the Eastern Sporn Tract, three potential well sites are being considered, but only two wells are expected to be used. The annual frequency of a potential failure in any of the six wells would be estimated as 1.21×10^{-4} year (0.000121 per year); such a potential failure is considered unlikely. The estimated probability of a potential failure in any one of the six wells over a 20-year operating period would be 2.42×10^{-3} (0.00242).

Scenario C would have up to eight wells at the Borrow Area, Jordan Tract, Western Sporn Tract, and Eastern Sporn Tract, although only four of the wells may be used at one time. The annual frequency of a potential failure in any of the eight wells would be 1.62×10^{-4}/year (0.000162 per year); such a potential failure is considered unlikely. The estimated probability of a potential failure in any one of the eight wells over a 20-year operating period would be 3.23×10^{-3} (0.00323).

G.4.3 Potential Releases from the Geologic Storage Formations or Post-Injection Releases

This section addresses potential releases from the subsurface after injection operations have ceased. DOE analyzed the risks and potential impacts of a release of CO_2 and associated trace gases after their injection into the subsurface injection zone. The geology of the target CO_2 storage formation is described in Section 3.3, Geology. The maximum estimated subsurface plume based on modeling by Battelle (2008a) would be within a 2-mile radius after 20 years of operation for the CO_2 stored in the Rose Run Formation and a 3-mile radius after 20 years of operation for the CO_2 stored in the Copper Ridge Formation.

The evaluation of the potential effects from post-injection releases from the subsurface storage formations was conducted using the following tools:

- An analog database for the FutureGen project (DOE, 2007b) that included results from studies performed at other CO_2 storage locations and from sites with natural CO_2 accumulations and releases was used for characterizing the nature of potential risks associated with surface leakage due to caprock seal failures, faults, and fractures. It was also used to predict CO_2 releases based on similarities with the proposed storage reservoir.
- EPA's SCREEN3 (EPA, 1995) was used to estimate the resulting CO_2 air concentrations if post-injection releases occurred from slow leaks at low flow rates through abandoned wells or seepage through the caprock and overlying formations. The predicted air concentrations were used to estimate the potential for exposure and any resulting impacts on workers, offsite residents, and sensitive receptors.
- The SLAB model was used to estimate the resulting CO_2 air concentrations from deep oil and gas or abandoned wells when the flow rate was high, but the release occurred only for a short duration.

DOE considered potential releases that could cause acute effects (high concentration over a short duration) and chronic effects (low concentration over a longer duration). Three scenarios could potentially cause acute effects: (1) upward leakage through the CO_2 injection wells; (2) upward leakage through a deep oil and gas (or other type) well; and (3) upward leakage through undocumented, abandoned, or poorly constructed deep wells. Six scenarios could potentially cause chronic effects: (1) upward leakage through caprock and seals by gradual failure; (2) release through existing faults due to effects of increased pressure; (3) release through induced faults due to local over-pressure conditions; (4) upward leakage through the CO_2 injection wells; (5) upward leakage through deep oil and gas (or other type) wells; and (6) upward leakage through undocumented, abandoned, or poorly constructed wells.

Table G-16 summarizes the types of potential post-injection releases considered in this analysis. The fluxes (the amounts of CO_2 that would flow through a unit area per unit time) for these releases were estimated based on the characteristics of the Rose Run Sandstone and Copper Ridge Dolomite formation and information on the local geologic setting and nearby wells, compared to the sites included in the database. This approach was used in the EIS for a previous CCS project (DOE 2007b). Not all potential release pathways apply to these sites.

The project considers two formations as the primary, likely target zones for geologic storage, the Rose Run Sandstone and the Copper Ridge Dolomite, as described in Section 3.3, Geology. Additional deeper formations may be considered such as the Maryville Formation, as discussed in Section 3.3. The characteristics that were used to develop the input data for the modeling of potential releases are discussed here. Key properties of the target injection zone include depth, thickness, porosity, permeability, and regional gradient. Both formations contain saline brines.

The Rose Run Sandstone was found at a depth of 7,706 feet and was 116 feet thick in the AEP No. 1 Well located on the Mountaineer Plant property (AEP, 2008). The base of this well as completed was 7,900 feet. This formation is Ordovician age and consists of mostly medium-grained sandstone. Reservoir testing in the AEP No. 1 Well in the Rose Run Formation indicated that the permeability was 7.4 to 9.5 millidarcies (mD), although 20-foot layers are present with permeability up to 70 mD and 8 to 13 porosity (AEP, 2008). Porosity of core samples from the Rose Run in this well ranged from 1.0 to 11.46 percent. The average porosity for the Rose Run sandstone was 8 percent with a peak porosity of 12 percent (Battelle, 2008b). The overlying formation above the Rose Run is the Ordovician age Beekmantown Dolomite, which is 545 feet thick. The Beekmantown Dolomite consists of dense, carbonate layers with a permeability of less than 0.001 mD and a low porosity (less than 1 percent in most areas) (Battelle, 2008b). In addition, there are a series of overlying secondary seals including 800 feet of limestone and 1,300 feet of shale.

Table G-16. Potential Releases from Storage Site Based on Database

Release Scenario	Exposure Duration	Potential Volume	Initial Release to
Upward leakage through the caprock due to catastrophic failure and quick release	Short term	Variable, could be large	Air
Upward leakage through the caprock due to gradual failure and slow release	Long term	Small	Air, Groundwater
Upward leakage through the CO_2 injection wells	Short term and long term	Variable, could be large	Air, Groundwater
Upward leakage through deep oil and gas wells	Short term and long term	Variable, could be large	Air, Groundwater
Upward leakage through undocumented, abandoned, or poorly constructed wells	Short term and long term	Variable, could be large	Air, Groundwater
Release through existing faults due to the effects of increased pressure	Long term	Variable, could be large	Air, Groundwater
Release through induced faults due to the effects of increased pressure	Long term	Variable, could be large	Air, Groundwater
Lateral or vertical leakage into | non-target aquifers	Long term	Variable	Groundwater

CO_2 = carbon dioxide

The Cambrian age Copper Ridge Dolomite has a total thickness of 650 feet, but the most likely injection zone is the permeable Vuggy horizon within the Copper Ridge, which has an average permeability of 50-200 mD and average porosity of 15 to 16 percent (Battelle, 2008b). The primary cap rock for this horizon is a 310-foot thick dolomite with a low permeability (0.001 mD) and porosity (2-5 percent) (Battelle, 2008b).

Factors that affect the potential for post-injection releases from the storage formations include the presence of faults that cut the cap rock, active seismicity, deep wells from past oil and gas operations, and abandoned or poorly constructed wells. As shown in Figure 3.3-3, there are numerous oil and gas wells within 3.5 miles of the injection well sites, although most of the wells are estimated to be less than 5,500 feet deep, as discussed in Section 3.3, Geology. Thus, there would be about 2,200 feet between the wells and the shallowest injection target formation. Because there may be deep wells, potential releases from deep oil and gas and poorly constructed, abandoned deep wells were evaluated. The nearest major fault is the Rome Trough system, which is about 25 miles to the southeast of the Mountaineer Plant. As discussed in Section 3.3, Geology, these are basement faults, which affect Cambrian and Precambrian bedrock at depths of 10,000 feet or more, and do not underlie the potential storage sites. The Crosswell seismic line survey from MW2 to the AEP No. 2 Well conducted in 2003 showed a series of small displacements in the Copper Ridge Formation, which ends at the base of the Rose Run Formation. The general seismic activity of the region is low, as indicated by few recent earthquakes and a zero probability of large earthquakes (magnitude of 5.0) within the next 50 years for a distance of about 30 miles, and a 2 percent probability of peak acceleration greater than 4 to 6 percent of the gravity coefficient (see Section 3.3, Geology, for specific locations of the nearest earthquakes) (USGS, 2010). Because of low seismic activity and the lack of faults displacing the primary cap rock, the Beekmantown Dolomite, potential releases along faults have not been evaluated for these target formations.

DOE used the information summarized above from the Analog database to identify the likelihood of potential releases and estimated flux rates for the releases. The rate of slow leakage through the cap rock and other formations was estimated using data from the Teapot Dome Site for both the Rose Run and Copper Ridge Formations. The seepage rates into shallow formations due to unknown structural or stratigraphic connections were based on data for the sandstone formation at the Weyburn CO_2 Enhanced

Oil Recovery Project for the Rose Run Sandstone; and based on data from the Farnham Dome Site, which had sandstone and dolomite, for the Copper Ridge Dolomite. The SCREEN3 model was used to simulate the resulting ambient air concentrations for CO_2 due to gradual, slow seepage of gases through the caprock and other overlying formations. The slow seepage rates were allowed to continue for an extended period up to 5,000 years as a conservative estimate because the leaks could be hard to detect. Releases of ammonia are unlikely for this release mechanism, because the ammonia gas in the injected fluid would become ammonium ions in the brine or groundwater in the various layers, where it could combine with other ions and form new compounds, e.g., ammonium chloride (ATSDR, 2010). Thus, ammonia would be unlikely to be emitted as a gas from slow seepage through multiple saturated formations.

Potential leakage from the CO_2 injection wells and unknown abandoned or poorly constructed deep wells were also simulated using SCREEN3, since the flux rates were low, and the CO_2 gas would not be supercritical. Potential CO_2 and ammonia releases at a low flux rate through deep wells were analyzed, although the ammonia releases are less likely. Table G-17 shows the subsurface release flux rates and durations pertinent to potential releases from the likely injection zones, the Rose Run and Copper Ridge Formations.

The criteria for ammonia that are pertinent to longer-term exposure durations were listed previously in Table G-2. There are no long-term criteria established for CO_2 since the health effects concern is for acute hazards, not a chronic hazard over a long exposure duration. Thus, the estimated air concentrations were compared to the AEGL-1 criteria of 5,000 ppm. The estimated CO_2 concentrations in ambient air for all the hypothetical well releases were less than 5,000 ppm, thus no effects to the public would be expected from hypothetical well releases.

The estimated ambient air concentrations of ammonia were also less than 30 ppm for all the well releases. The maximum ammonia concentration using the high flux rate from a previous well failure from the Analog database was less than all the criteria, including the chronic minimal risk level (MRL) of 0.1 ppm. The maximum concentration was within a radius of 150 feet from the wells. These simulations overestimate the likely ambient air concentrations from a well release, because the ammonia would dissolve into the brine, rather than remain in a separate gas phase over a period of several years.

For each type of hypothetical well release scenario considered, the frequency of a release was estimated. While there are a large number of plugged, abandoned, and active oil and gas wells within 3.5 miles of the five injection well sites as shown in Figure 3.3-3, most wells are known to be less than 5,000 feet deep (AEP, 2008). The largest number of wells was in the vicinity of the Jordan Tract, and the least number near the Eastern Sporn Tract. The estimated frequency of a release from a hypothetical, deep abandoned well is 1×10^{-3}/well/year (0.001 per well per year), which is considered to be unlikely ($1x10^{-2}$ per year to $1x10^{-4}$ per year or between 0.01 per year and 0.0001 per year)). The probability of a release from one such well over a 20-year period is 2×10^{-2} (0.02).

In addition, there are five deep wells associated with the product validation facillity on the Plant property. Between May 2009 and May 2010, a total of 4,871 tons (4,419 metric tons) of CO_2 was successfully injected into the two formations (Battelle, 2010). There are two injections wells, completed in either the Rose Run or Copper Ridge Formations. Three of these wells are monitoring wells, of which two extend into the Rose Run Formation, and one into the Copper Ridge Formation (Battelle, 2010). These wells were recently installed and permitted under the Underground Injection Control Class V Program; thus there is a lower potential for failure in these wells. Similar deep wells for geologic characterization are planned on the Borrow Area and Jordan Tract to obtain detailed information on the potential injection target formations in those areas. The frequency of potential releases from these newly-constructed wells is estimated to be low, 1×10^{-5} per well per year (0.00001 per year), which is considered extremely unlikely ($1x10^{-4}$ per year to $1x10^{-6}$ per year or between 0.0001 per year and 0.00001 per year). The probability of a potential release from one of these new deep wells over a 20-year period is $1x10^{-3}$ (0.001), which is an order of magnitude less than for the older deep wells.

Table G-17. Potential Subsurface CO_2 Releases and Estimated Flux Rates

Mechanism	Frequency	Frequency Units	Flux Rate, μmol/m²-s	Flux Area	Duration, Years
Leakage via upward migration through caprock due to gradual and slow release	$1x10^{-4}$	1/5,000 year item	0.0048-0.17	RR 12.42 mi²; CR 27.95 mi²	5,000
Leakage via upward migration through caprock due to catastrophic failure and rapid release	$<1x10^{-6}$	1/5,000 year item	NS[a]	RR 12.42 mi²; CR 27.95 mi²	5,000
Leakage through existing faults due to increased pressure (regional overpressure)	$1x10^{-5}$	1/5,000 year item	NS[b]	NA	NA
Leakage through induced faults due to increased pressure (local overpressure)	$1x10^{-5}$	1/5,000 year item	NS[b]	NA	NA
Leakage due to unknown structural or stratigraphic connections	$1x10^{-5}$	1/5,000 year item	RR 0.11-2.6; CR 0.13-0.97	RR 12.42 mi²; CR 27.95 mi²	100
Leakage due to lateral migration from target zone	$1x10^{-6}$	1/5,000 year item	RR 0.11-2.6; CR 0.13-0.97	RR 12.42 mi²; CR 27.95 mi²	100
Leaks from CO_2 injection wells, high rate	$2x10^{-5}$	1/year-well	170	0.0045 m²	0.02 (1 week)
Leaks due to CO_2 injection wells, low rate	$2x10^{-5}$	1/year-well	5	0.0045 m²	5,000
Leaks from deep oil and gas wells, high rate	1x10-3	1/year-well	170	0.03 m²	0.02 (1 week)
Leaks from deep oil and wells, low rate	$1x10^{-3}$	1/year-well	5	0.03 m²	5,000
Leaks from deep abandoned or undocumented wells, high rate	$1x10^{-3}$	1/year-well	170	0.20 m²	0.02 (1 week)
Leaks from deep abandoned or undocumented wells, low rate	$1x10^{-3}$	1/year-well	5	0.20 m²	5,000

Note: 1 μmol/m²-s = 3.84 g/m²-day

[a] NS = not simulated, since release mechanism is considered extremely unlikely (10^{-4} to 10^{-6}).

[b] NS = not simulated, since no faults near estimated plume area.

CO_2 = carbon dioxide; CR = Copper Ridge Formation; g/m²-day = grams per meter squared per day; m² = square meter; mi² = square mile; NA = not applicable; RR = Rose Run Formation; μmol/m²-s = micromoles per meter squared per second

There are two other potential pathways that the CO_2 gas from the subsurface formations could follow, migration into non-target aquifers and migration into overlying coal seams, where methane could be displaced. Migration into the underground sources of drinking water (USDWs) near the potential injection well sites is considered unlikely due to the multiple, thick low permeability layers of shale and dolomite between the deepest USDWs at a depth of about 250 feet below the ground surface and the top of the Rose Run Formation at a depth of 7,706 feet (AEP, 2008). There are no known active subsurface coal mines near the plant, since the closest mine to the plant, Broad Run Mine in West Virginia, is inactive, but there are numerous historical mines in West Virginia and Ohio. The displaced CO_2 from the target formations could hypothetically migrate into the coal seams, found at depths of 1,000 feet or less (see discussion in Section 3.3, Geology), although there are thousands of feet of intervening low permeability formations between the injection formations and potentially mineable coal seams. In addition, CO_2 plumes could enter into old mine shafts or vents from the surface.

G.4.4 Potential Effects Related to Radon Mobilization

Radon is a naturally occurring phenomenon and is detected in indoor environments throughout West Virginia (EPA, 2010c). The average radon levels in Mason County are typically between 2 and 4 pico-Curies per liter (EPA, 2010c.) At present, there is little if any evidence that radon mobilization would occur as a result of geologic CO_2 storage activities. If CO_2 were to leak from a primary storage reservoir and seep into the unsaturated soil zone, naturally occurring radon in soil gas could be swept along with the CO_2, and potentially enter residences through subsurface intrusion. Depending on background radon concentrations, the additional radon might have the potential to increase human health risks through inhalation of the radon and its progeny. However, based on soil gas sampling at the Weyburn CO_2 injection site, there was no evidence of elevated radon due to the CO_2 used for enhanced oil recovery, and therefore, elevated concentrations of radon would not be likely to occur in conjunction with the potential local geologic CO_2 storage (Wilson and Monea, 2004).

G.5 SUPPORTING MATERIAL

G.5.1 Carbon Dioxide Properties

Carbon dioxide is typically transported by pipelines as a supercritical fluid with a density of about 70 to 90 percent of that being liquid water (IPCC, 2005; Annex I). If a leak develops along the pipeline, CO_2 would escape. A portion of the escaping fluid would quickly expand to CO_2 gas; the remainder would form a CO_2 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.

The SLAB model (Version 2) was developed for the DOE 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. Meteorological factors consist of characterizing the wind data into the pertinent Pasquill stability classes (Turner, 1994) and wind speed categories, which includes a calm-wind condition.

Fluid moving at the speed of sound is called choked or critical flow. The speed of sound for a particular gas depends on 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 on 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 was evaluated for choked flow conditions based on equations from (Hanna & Drivas, 1987, page 20), as described in the FutureGen Risk Assessment (DOE, 2007b, Section C.1.4).

The physical and chemical properties used in the SLAB model to simulate choked flow are presented in Section G.5.2. In the pipeline, pressure and temperature would decrease during a release, but for purposes of simulation by SLAB the release mass flow rate for a given case is kept at that of the initial choked flow.

DOE assessed the potential pipeline release risks for the project using the maximum concentration of ammonia and the expected CO_2 concentration shown in Table G-3.

The methods used to estimate the CO_2 phases in the environment after a pipeline release are described in the FutureGen Risk Assessment (DOE, 2007b, Section C.3). The theory of phase behavior indicates that perhaps more than a proportional amount of co-contaminants would be retained with the CO_2 dry ice snow. Co-contaminants are other chemicals such as ammonia that can be present in the captured gas. However, to maintain a conservative approach in the risk assessment, the amount of co-contaminants (e.g., ammonia) that would be initially discharged to the atmosphere following a pipeline release was taken to be proportional to the initial release of CO_2 to the vapor phase. In the 1,500 psi case, 73 percent of the contents of the pipeline section are released directly to the atmosphere as a gas. The remaining 27 percent forms a dry-ice snow which sublimates very slowly. In the 3,000 psi case, 75 percent of the contents of the pipeline section are released directly to the atmosphere as a gas. The remaining 25 percent forms a dry-ice snow, which sublimates very slowly.

G.5.2 Chemical Mass and Release Durations Used in Modeling of Pipeline Releases and Injection Wells during Operation

Input data used in the SLAB model simulations are shown in Tables G-18 through G-20 for potential CO_2 releases from pipeline ruptures, punctures, and injection wells during operation. Not all pipeline route segments were simulated. Tables G-21 through G-23 were developed based on assuming a maximum pipeline concentration of 50 ppm for ammonia. The resultant mass and discharge rates are then obtained by multiplying the corresponding CO_2 values by the constant 0.00005. Hence, the discharge release duration is the same for both gases.

The computed available volumes in each of the potential pipeline routes are presented in Tables G-24 and G-25, so that the potential volumes from a given route could be compared. The mass of CO_2 or ammonia contained in a given pipeline is also a function of the pressure and temperature in the pipe, which also determines the fraction of the gas that would change to a solid phase if a release occurred. The amount released also depends on the release type, as explained in Section G.5.1.

G.5.3 Estimated Release Fluxes from Wells and Hazard Quotients

Potential releases from different types of deep wells from the subsurface formations following injection operations were simulated using the SCREEN3 model. Table G-26 shows the estimated air concentrations with pertinent criteria for CO_2 and ammonia and the computed hazard quotients. A hazard quotient is a risk ratio of the chemical concentration to exposure criteria. If the ratio is greater than 1, there is a potential for non-hazardous effects to human health, as indicated by the level of that criteria. For the simulated well releases, none of the hazard quotient values were greater than 1, indicating there would be no likely effects to human health from such releases at a distance of 150 feet from a hypothetical deep well after operation of the injection wells has ceased.

Table G-18. Choked Flow Conditions for CO_2 Released from a Potential Pipeline Rupture

Pipeline Route	ID and Orifice Area	Length	Pipeline Temp (°C)	Absolute Gauge Pressure (psi)	CO_2 Mass (kg)	$Q_{choked\text{-}CO2}$ (kg/sec)	Release Duration (sec)
Borrow Area Route	11.875 in 0.0714 m^2	2.24 mi	31.1	1,500	198,500	2,063	96.2
					144,900[a]	1,506[a]	
Borrow Area Route	11.875 in 0.0714 m^2	2.24 mi	48.9	3,000	205,800	4,010	51.3
					154,350[b]	3,010[b]	
Borrow Area Route	8.063 in 0.0329 m^2	2.24 mi	31.1	1,500	91,440	95[a]	96.2
					66,750[a]	694[a]	
Borrow Area Route	8.063 in 0.0329 m^2	2.24 mi	48.9	3,000	94,860	1,850	51.3
					71,150[b]	1,390[b]	
Western Sporn Route	8.063 in 0.0329 m^2	5.68 mi	31.1	1,500	231,870	951	244
					169,270[a]	694[a]	
Western Sporn Route	8.063 in 0.0329 m^2	5.68 mi	48.9	3,000	240,540	1,850	130
					180,400[b]	13,902	
Jordan Route 3	11.875 in 0.0714 m^2	9.66 mi	31.1	1,500	856,020	2,063	414
					624,890[a]	1,506[a]	
Jordan Route 3	11.875 in 0.0714 m^2	9.66 mi	48.9	3,000	887,370	4,010	221
					665,530[b]	3,010[b]	
Jordan Route 3	8.063 in 0.0329 m^2	9.66 mi	31.1	1,500	391,120	951	411
					285,520[a]	694[a]	
Jordan Route 3	8.063 in 0.0329 m^2	9.66 mi	48.9	3,000	409,100	1,850	221
					306,830[b]	1,390[b]	
Plant Site	8.063 in 0.0329 m^2	700 ft	31.1	1,500	5,410	951	5.7
					3,950[a]	694[a]	
Plant Site	8.063 in 0.0329 m^2	700 ft	48.9	3,000	5,610	1,850	3.0
					4,210[b]	1,390[b]	

Note: 31.1°C = 88°F; 48.9°C = 120°F

[a] Supercritical density = 771 kg/m^3 at 31.1°C and 1,500 psi. Choked flow $Q_{choked\text{-}CO2}$ is based on CO_2 properties. Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release. Seventy-three percent of the CO_2 is directly released as a vapor; 27 percent forms dry-ice snow which very slowly sublimates.

[b] Supercritical density = 799 kg/m^3 at 48.9°C and 3,000 psi. Choked flow $Q_{choked\text{-}CO2}$ is based on CO_2 properties. Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release. Seventy-five percent of the CO_2 is directly released as a vapor; 25 percent forms dry-ice snow which very slowly sublimates.

°C = degrees Celsius; CO_2 = carbon dioxide; °F = degrees Fahrenheit; ft = feet; ID = inner diameter of pipeline; in = inch; kg = kilogram; m^2 = square meter; mi = mile; psi = pounds per square inch; sec = second

Table G-19. Choked Flow Conditions for CO_2 Released from a Potential Pipeline Puncture (3 feet x 1 foot)

Pipeline Route	ID and Orifice Area	Length	Pipeline Temp (°C)	Absolute Gauge Pressure (psi)	CO_2 Mass (kg)	$Q_{choked\text{-}CO2}$ (kg/sec)	Release Duration (sec)
Borrow Area Route	11.875 in 0.000615 m^2	2.24 mi	31.1	1,500	198,500	55.9	3,550
					144,900[a]	40.8[a]	
Borrow Area Route	11.875 in 0.000615 m^2	2.24 mi	48.9	3,000	205,800	108.6	1,900
					154,350[b]	81.5[b]	
Borrow Area Route	8.063 in 0.000615 m^2	2.24 mi	31.1	1,500	91,440	55.9	1,640
					66,750[a]	40.8[a]	
Borrow Area Route	8.063 in 0.000615 m^2	2.24 mi	48.9	3,000	94,860	108.6	873
					71,150[b]	81.5[b]	
Western Sporn Route	8.063 in 0.000615 m^2	5.68 mi	31.1	1,500	231,870	55.9	4,150
					169,270[a]	40.8[a]	
Western Sporn Route	8.063 in 0.000615 m^2	5.68 mi	48.9	3,000	240,540	108.6	2,215
					180,400[b]	81.5[b]	
Jordan Route 3	11.875 in 0.000615 m^2	9.66 mi	31.1	1,500	169,270[a]	40.8[a]	15,300
					624,890[a]	40.8[a]	
Jordan Route 3	11.875 in 0.000615 m^2	9.66 mi	48.9	3,000	887,370	108.6	8,170
					665,500[b]	81.5[b]	
Jordan Route 3	8.063 in 0.000615 m^2	9.66 mi	31.1	1,500	391,120	55.9	7,000
					285,520[a]	40.8[a]	
Jordan Route 3	8.063 in 0.000615 m^2	9.66 mi	48.9	3,000	409,100	108.6	3,767
					306,830[b]	81.5[b]	
Plant Site	8.063 in 0.000615 m^2	700 ft	31.1	1,500	5,410	55.9	96.8
					3,950[a]	40.8[a]	
Plant Site	8.063 in 0.000615 m^2	700 ft	48.9	3,000	5,610	108.6	51.7
					4,210[b]	81.52	

Note: 31.1°C = 88°F; 48.9°C = 120°F

[a] Supercritical density = 771 kg/m^3 at 31.1°C and 1,500 psi. Choked flow $Q_{choked\text{-}CO2}$ is based on CO_2 properties. Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release. Seventy-three percent of the CO_2 is directly released as a vapor; 27 percent forms dry-ice snow which very slowly sublimates.

[b] Supercritical density = 799 kg/m^3 at 48.9°C and 3,000 psi. Choked flow $Q_{choked\text{-}CO2}$ is based on CO_2 properties. Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release. Seventy-five percent of the CO_2 is directly released as a vapor; 25 percent forms dry-ice snow which very slowly sublimates.

°C = degrees Celsius; CO_2 = carbon dioxide; °F = degrees Fahrenheit; ft = feet; ID = inner diameter of pipeline; in = inch; kg = kilogram; m^2 = square meter; mi = mile; psi = pounds per square inch; sec = second

Table G-20. Choked Flow Conditions for CO_2 Released Vertically from the Rose Run and Copper Ridge Injection Wells Due to a Potential Rupture

Formation	ID and Orifice Area	Depth bgs	Pipeline Temp (°C)	Absolute Gauge Pressure (psi)	CO_2 Mass (kg)	$Q_{choked-CO2}$ (kg/sec)	Release Duration (sec)
Rose Run	2.992 in 0.00454 m^2	7,900 ft	31.1	1,500	8,420	130.9	64.3
					6,150[a]	95.6[a]	
Rose Run	2.992 in 0.00454 m^2	7,900 ft	48.9	3,000	8,725	254.6	34.3
					6,544[b]	190.9[b]	
Copper Ridge	2.992 in 0.00454 m^2	8,400 ft	31.1	1,500	8,960	130.9	68.4
					6,540[a]	95.6[a]	
Copper Ridge	2.992 in 0.00454 m^2	8,400 ft	48.9	3,000	9,277	254.6	36.4
					6,958[b]	190.9[b]	
Deep Well	2.992 in 0.00454 m^2	8,900 ft	31.1	1,500	9,460	130.9	72.2
					6,906[c]	95.6[c]	
Deep Well	2.992 in 0.00454 m^2	8,900 ft	48.9	3,000	9,829	254.6	38.6
					7,372[b]	190.9[b]	

Note: 31.1°C = 88°F; 48.9°C = 120°F

[a] Supercritical density = 771 kg/m^3 at 31.1°C and 1,500 psi. Choked flow $Q_{choked-CO2}$ is based on CO_2 properties. Modeling assumes internal well temperature, pressure, and emission rates remain constant during release. Seventy-three percent of the CO_2 is directly released as a vapor; 27 percent forms dry-ice snow which very slowly sublimates.

[b] Supercritical density = 799 kg/m^3 at 48.9°C and 3,000 psi. Choked flow $Q_{choked-CO2}$ is based on CO_2 properties. Modeling assumes internal well temperature, pressure, and emission rates remain constant during release. Seventy-five percent of the CO_2 is directly released as a vapor; 25 percent forms dry-ice snow which very slowly sublimates.

[c] Supercritical density = 769 kg/m^3 at 31.1°C and 1,500 psi. Choked flow $Q_{choked-CO2}$ is based on CO_2 properties. Modeling assumes internal well temperature, pressure, and emission rates remain constant during release. Seventy-three percent of the CO_2 is directly released as a vapor; 27 percent forms dry-ice snow which very slowly sublimates.

bgs = below ground surface; °C = degrees Celsius; CO_2 = carbon dioxide; °F = degrees Fahrenheit; ft = feet; ID = inner diameter of well; in = inch; kg = kilogram; m^2 = square meter; psi = pounds per square inch; sec = second

Table G-21. Choked Flow Conditions for Ammonia Released from a Potential Pipeline Rupture

Pipeline Route	ID and Orifice Area	Length	Pipeline Temp (°C)	Absolute Gauge Pressure (psi)	Ammonia Mass (kg)	$Q_{choked-NH_3}$ (kg/sec)	Release Duration (sec)
Borrow Area Route	11.875 in 0.0714 m^2	2.24 mi	31.1	1,500	9.94	0.103	96.5
					7.25[a]	0.0753[a]	
Borrow Area Route	11.875 in 0.0714 m^2	2.24 mi	48.9	3,000	10.3	0.201	51.3
					7.73[b]	0.151[b]	
Borrow Area Route	8.063 in 0.0329 m^2	2.24 mi	31.1	1,500	4.57	0.0476	96.2
					3.34[a]	0.0347[a]	
Borrow Area Route	8.063 in 0.0329 m^2	2.24 mi	48.9	3,000	4.74	0.0925	51.3
					3.56[b]	0.0694[b]	
Western Sporn Route	8.063 in 0.0329 m^2	5.68 mi	31.1	1,500	11.6	0.0476	244
					8.47[a]	0.0347[a]	
Western Sporn Route	8.063 in 0.0329 m^2	5.68 mi	48.9	3,000	12.1	0.0925	130
					9.07[b]	0.0694[b]	
Jordan Route 3	11.875 in 0.0714 m^2	9.66 mi	31.1	1,500	42.8	0.103	414
					31.2[a]	0.0753[a]	
Jordan Route 3	11.875 in 0.0714 m^2	9.66 mi	48.9	3,000	44.4	0.201	221
					33.3[b]	0.151[b]	
Jordan Route 3	8.063 in 0.0329 m^2	9.66 mi	31.1	1,500	19.6	0.0475	411
					14.3[a]	0.0347[a]	
Jordan Route 3	8.063 in 0.0329 m^2	9.66 mi	48.9	3,000	20.5	0.0925	221
					15.4[b]	0.0694[b]	
Plant Site	8.063 in 0.0329 m	700 ft	31.1	1,500	0.271	0.0476	5.7
					0.197[a]	0.0347[a]	
Plant Site	8.063 in 0.0329 m	700 ft	48.9	3,000	0.281	0.0925	3.0
					0.211[b]	0.0694[b]	

Note: 31.1°C = 88°F; 48.9°C = 120°F

[a] Supercritical density = 771 kg/m^3 at 31.1°C and 1,500 psi. Choked flow $Q_{choked-NH_3} = 0.00005xQ_{choked-CO_2}$ is based on CO_2 properties. Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release. Seventy-three percent of the CO_2 is directly released as a vapor; 27 percent forms dry-ice snow which very slowly sublimates.

[b] Supercritical density = 799 kg/m^3 at 48.9°C and 3,000 psi. Choked flow $Q_{choked-NH_3} = 0.00005xQ_{choked-CO_2}$ is based on CO_2 properties. Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release. Seventy-five percent of the CO_2 is directly released as a vapor; 25 percent forms dry-ice snow which very slowly sublimates.

°C = degrees Celsius; °F = degrees Fahrenheit; ft = feet; ID = inner diameter of pipeline; in = inch; kg = kilogram; m^2 = square meter; mi = mile; NH_3 = ammonia; psi = pounds per square inch; sec = second

Table G-22. Choked Flow Conditions for Ammonia Released from a Potential Pipeline Puncture (3 feet x 1 foot)

Pipeline Route	ID and Orifice Area	Length	Pipeline Temp (°C)	Absolute Gauge Pressure (psi)	Ammonia Mass (kg)	$Q_{choked\text{-}NH3}$ (kg/sec)	Release Duration (sec)
Borrow Area Route	11.875 in 0.000615 m^2	2.24 mi	31.1	1,500	9.94	0.00280	3,550
					7.25[a]	0.00204[a]	
Borrow Area Route	11.875 in 0.000615 m^2	2.24 mi	48.9	3,000	10.3	0.00543	1,900
					7.73[b]	0.00407[b]	
Borrow Area Route	8.063 in 0.000615 m^2	2.24 mi	31.1	1,500	4.57	0.00280	1,640
					3.34[a]	0.00204[a]	
Borrow Area Route	8.063 in 0.000615 m^2	2.24 mi	48.9	3,000	4.74	0.00543	873
					3.56[b]	0.00407[b]	
Western Sporn Route	8.063 in 0.000615 m^2	5.68 mi	31.1	1,500	11.6	0.00280	4,150
					8.46[a]	0.00204[a]	
Western Sporn Route	8.063 in 0.000615 m^2	5.68 mi	48.9	3,000	12.1	0.00543	2,215
					9.07[b]	0.00407[b]	
Jordan Route 3	11.875 in 0.000615 m^2	9.66 mi	31.1	1,500	42.8	0.00280	15,300
					31.2[a]	0.00204[a]	
Jordan Route 3	11.875 in 0.000615 m^2	9.66 mi	48.9	3,000	44.4	0.00543	8,170
					33.3[b]	0.00407[b]	
Jordan Route 3	8.063 in 0.000615 m^2	9.66 mi	31.1	1,500	19.6	0.00280	7,000
					14.3[a]	0.00204[a]	
Jordan Route 3	8.063 in 0.000615 m^2	9.66 mi	48.9	3,000	21.6	0.00543	3,767
					16.2[b]	0.00407	
Plant Site	8.063 in 0.000615 m^2	700 ft	31.1	1,500	0.271	0.00280	96.8
					0.198[a]	0.00204[a]	
Plant Site	8.063 in 0.000615 m^2	700 ft	48.9	3,000	0.281	0.0054[b]	51.7
					0.211[b]	0.00407[b]	

Note: 31.1°C = 88°F; 48.9°C = 120°F

[a] Supercritical density = 771 kg/m^3 at 31.1°C and 1,500 psi. Choked flow $Q_{choked\text{-}NH3} = 0.00005xQ_{choked\text{-}CO2}$ is based on CO_2 properties. Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release. Seventy-three percent of the CO_2 is directly released as a vapor; 27 percent forms dry-ice snow which very slowly sublimates.

[b] Supercritical density = 799 kg/m^3 at 48.9°C and 3,000 psi. Choked flow $Q_{choked\text{-}NH3} = 0.00005xQ_{choked\text{-}CO2}$ is based on CO_2 properties. Modeling assumes internal pipeline temperature, pressure, and emission rates remain constant during release. Seventy-five percent of the CO_2 is directly released as a vapor; 25 percent forms dry-ice snow which very slowly sublimates.

°C = degrees Celsius; °F = degrees Fahrenheit; ft = feet; ID = inner diameter of pipeline; in = inch; kg = kilogram; m^2 = square meter; mi = mile; NH_3 = ammonia; psi = pounds per square inch; sec = second

Table G-23. Choked Flow Conditions for Ammonia Released Vertically from the Rose Run and Copper Ridge Injection Wells Due to a Potential Rupture

Formation	ID and Orifice Area	Depth bgs	Pipeline Temp (°C)	Absolute Gauge Pressure (psi)	Ammonia Mass (kg)	$Q_{choked\text{-}NH3}$ (kg/sec)	Release Duration (sec)
Rose Run	2.992 in 0.00454 m^2	7,900 ft	31.1	1,500	0.421	0.00654	64.3
					0.307[a]	0.00478[a]	
Rose Run	2.992 in 0.00454 m^2	7,900 ft	48.9	3,000	0.436	0.0127	34.3
					0.327[b]	0.00955[b]	
Copper Ridge	2.992 in 0.00454 m^2	8,400 ft	31.1	1,500	0.448	0.00655	68.4
					0.327[a]	0.00478[a]	
Copper Ridge	2.992 in 0.00454 m^2	8,400 ft	48.9	3,000	0.464	0.0127	36.4
					0.348[b]	0.00955[b]	
Deep Well	2.992 in 0.00454 m^2	8,900 ft	31.1	1,500	0.473	0.00655	72.2
					0.345[c]	0.00477[c]	
Deep Well	2.992 in 0.00454 m^2	8,900 ft	48.9	3,000	0.491	0.0127	38.6
					0.369[b]	0.00955[b]	

Note: 31.1°C = 88°F; 48.9°C = 120°F

[a] Supercritical density = 771 kg/m^3 at 31.1°C and 1,500 psi. Choked flow $Q_{choked\text{-}NH3} = 0.00005xQ_{choked\text{-}CO2}$ is based on CO_2 properties. Modeling assumes internal well temperature, pressure, and emission rates remain constant during release. Seventy-three percent of the CO_2 is directly released as a vapor; 27 percent forms dry-ice snow which very slowly sublimates.

[b] Supercritical density = 799 kg/m^3 at 48.9°C and 3,000 psi. Choked flow $Q_{choked\text{-}NH3} = 0.00005xQ_{choked\text{-}CO2}$ is based on CO_2 properties. Modeling assumes internal well temperature, pressure, and emission rates remain constant during release. Seventy-five percent of the CO_2 is directly released as a vapor; 25 percent forms dry-ice snow which very slowly sublimates.

[c] Supercritical density = 769 kg/m^3 at 31.1°C and 1,500 psi. Choked flow $Q_{choked\text{-}CO2}$ is based on CO_2 properties. Modeling assumes internal well temperature, pressure, and emission rates remain constant during release. Seventy-three percent of the CO_2 is directly released as a vapor; 27 percent forms dry-ice snow which very slowly sublimates.

bgs = below ground surface; °C = degrees Celsius; °F = degrees Fahrenheit; ft = feet; ID = inner diameter of well; in = inch; kg = kilogram; m^2 = square meter; mi = mile; NH_3 = ammonia; psi = pounds per square inch; sec = second

Table G-24. Volume of Storage in Pipelines with Inside Diameter of 11.875 Inches for Route Options

Pipeline Route	Pipe Type	Total Pipe Volume (m^3)
Mountaineer Plant Route	Trunk[a]	15.24
Western Sporn Route	Trunk	652.56
Borrow Area Route	Trunk	257.16
	Spur to BA-1	2.54
Jordan Route 1	Trunk	963.61
	Spur to JT-1	27.9
Jordan Route 2	Trunk	1,060.13
	Spur to JT-1	27.9
Jordan Route 3	Trunk	1,110.00
	Spur to JT-1	27.9
Jordan Route 4	Trunk	1,109.20
	Spur to JT-1	27.9
Eastern Sporn Route 1	Trunk	573.39
	BR Spur to ES-1	5.0
	BR Spur to ES-2	15.9
	BR Spur to ES-3	24.9
Eastern Sporn Route 2	Trunk	943.59
	ES Spur to ES-1	27.6
	ES Spur to ES-2	24.9
	ES Spur to ES-3	7.95
Eastern Sporn Route 3	Trunk	586.60
	BR Spur to ES-1	5.0
	BR Spur to ES-2	15.9
	BR Spur to ES-3	24.9
Eastern Sporn Route 4	Trunk	768.96
	ESC Spur to ES-1	27.6
	ESC Spur to ES-2	24.9
	ESC Spur to ES-3	7.95

[a] Trunk lines are shown here with an inside diameter of 11.875 inches, although large sized pipe would be used to carry 100 percent of the flow and thus may not be used for all routes. Spur lines to the potential injection wells are shown with an inside diameter of 8.063 inches.

BR = Blessing Road; ES = Eastern Sporn; ESC = Eastern Sporn Corridor; m^3 = cubic meter

Table G-25. Volume of Storage in Pipelines with Inside Diameter of 8.063 Inches for Route Options

Pipeline Route	Pipe Type	Total Pipe Volume (m^3)
Mountaineer Plant Route	Trunk[a]	7.03
Western Sporn Route	Trunk	300.85
Borrow Area Route	Trunk	118.55
	Spur to BA-1	2.54
Jordan Route 1	Trunk	444.24
	Spur to JT-1	27.9
Jordan Route 2	Trunk	488.74
	Spur to JT-1	27.9
Jordan Route 3	Trunk	511.73
	Spur to JT-1	27.9
Jordan Route 4	Trunk	511.36
	Spur to JT-1	27.9
Eastern Sporn Route 1	Trunk	264.34
	BR Spur to ES-1	5.0
	BR Spur to ES-2	15.9
	BR Spur to ES-3	24.9
Eastern Sporn Route 2	Trunk	435.01
	ES Spur to ES-1	27.6
	ES Spur to ES-2	24.9
	ES Spur to ES-3	7.95
Eastern Sporn Route 3	Trunk	270.43
	BR Spur to ES-1	5.0
	BR Spur to ES-2	15.9
	BR Spur to ES-3	24.9
Eastern Sporn Route 4	Trunk	354.50
	ESC Spur to ES-1	27.6
	ESC Spur to ES-2	24.9
	ESC Spur to ES-3	7.95

[a] Trunk lines are shown here with an inside diameter of 8.063 inches and spurs with an inside diameter of 8.063 inches.

BR = Blessing Road; ES = Eastern Sporn; ESC = Eastern Sporn Corridor; m^3 = cubic meter

Table G-26. Estimated Air Concentrations and Hazard Quotients for CO_2 and Ammonia from Wells

Release Scenario for Wells	Chemical	Level (ppmv)	Criteria Type[b]	Exposure Concentration at 150 Feet (ppmv)	Hazard Quotient
Upward leakage through CO_2 injection wells[a]: high rate (days)	CO_2	5,000	PAC-0	0.0033	6.6E-07
	NH_3	30	PAC-1	4.29E-06	1.43E-07
		1.7	Acute MRL	4.29E-06	2.5E-06
Upward leakage through CO_2 injection wells[a]: low rate (years)	CO_2	5,000	PAC-0	9.8E-05	1.96E-08
	NH_3	30	PAC-1	1.26E-07	4.2E-09
		1.7	Acute MRL	1.26E-07	7.41E-08
		0.14	RfC	1.26E-07	9.0E-07
		0.1	Chronic MRL	1.26E-07	1.26E-6
Upward leakage through deep oil and gas wells: high rate (days)	CO_2	5,000	PAC-0	0.0085	1.7E-06
	NH_3	30	PAC-1	2.0E-05	3.7E-07
		1.7	Acute MRL	2.0E-05	6.5E-06
Upward leakage through deep oil and gas wells: low rate (years)	CO_2	5,000	PAC-0	0.00025	5.0E-08
	NH_3	30	PAC-1	3.23E-07	1.1E-08
		1.7	Acute MRL	3.23E-07	1.9E-07
		0.14	RfC	3.23E-07	2.31E-6
		0.1	Chronic MRL	3.23E-07	3.2E-06
Upward leakage through deep abandoned wells: high rate (days)	CO_2	5,000	PAC-0	0.053	1.1E-05
	NH_3	30	PAC-1	6.86E-05	2.3E-06
		1.7	Acute MRL	6.86E-05	4.0E-05
Upward leakage through deep abandoned wells: low rate (years)	CO_2	5,000	PAC-0	0.00156	3.1E-07
	NH_3	30	PAC-1	2.02E-06	6.7E-08
		1.7	Acute MRL	2.02E-06	1.1E-6
		0.14	RfC	2.02E-06	1.4E-05
		0.1	Chronic MRL	2.02E-06	2.0E-5

[a] Leakage for injection wells computed using the innermost casing outside of the injection tubing, which has 5-feet diameter.

[b] Explanation of criteria provided in Tables G-1 and G-2 of Appendix Potential Impact from CO_2 Releases.

CO_2 = carbon dioxide; MRL = minimal risk level; NH_3 = ammonia; PAC = Protective Action Criteria; ppmv = parts per million by volume; RfC = reference concentration

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