IEc

Valuation of Potential Risks Arising from a Model, Commercial-Scale CCS Project Site

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CCS Valuation Project Sponsor Group

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ABSTRACT

A diverse group of organizations from industry, government, and the environmental community jointly sponsored Industrial Economics (IEc), an expert in environmental economics and natural resource damage assessment, to develop and test a model approach for valuing the economic damages arising from a well-sited and well-managed CCS project. These damages included environmental and human health impacts arising from a range of potential events such as pipeline ruptures and subsurface leakage. They do not address potential impacts from facility construction or routine operation, nor do they address potential impacts to workers, business interruption, facility repair or similar 'private' costs internal to the operator. The model was successfully developed and applied to a 'realistic' project based on the publicly available risk assessment for a site from the FutureGen 1.0 site selection process. The project was planned to inject 50 million metric tons of CO_2 over 50 years and to have a 50 year post-injection period (for a 100-year analysis period).

This site-specific application of the model showed that the 'most likely' (50^{th} percentile) estimated damages arising from CO_2[1] totaled approximately $7.3 million and 'upper end' (95^{th} percentile) estimated damages totaled approximately $16.9 million.[2] On a per metric ton basis, these results translate into 'most likely' (50^{th} percentile) estimated damages of $0.15 per metric ton and 'upper end' (95^{th} percentile) estimated damages of $0.34 per metric ton. When combined, the estimated damages for CO_2 and H_2S were roughly 10-15% higher.

It is important to note that the range of damage estimates is highly sensitive to site-specific data. The sponsor group concludes that the tools exist to estimate prospective financial damages. Further, the sponsor group has developed insight into the magnitude and timing of dollar amounts that are likely to be at risk and the conditions under which they may be at risk at a well-selected and well-managed CCS project. This analytic approach is based on generally accepted practices within the financial and insurance industries, and can be applied, with adjustment for location, to CCS projects around the world.

[1] Note: The process used at the Jewett, TX site resulted in an emission stream with CO_2 and trace amounts of H_2S. The model addresses both constituents and results are included in the report.

[2] All dollars are $2010.

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FORWARD

The 2005 IPCC Special Report on Carbon Dioxide Capture and Storage (CCS) found that:

> "Observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years. For well-selected, designed and managed geological storage sites, the vast majority of the CO_2 will gradually be immobilized by various trapping mechanisms and, in that case, could be retained for up to millions of years. Because of these mechanisms, storage could become more secure over longer timeframes."[3]

Yet, concern over the 'liability' arising from carbon capture and storage (CCS) projects often is cited as an important barrier to implementation. At the heart of this concern is uncertainty about the magnitude of potential economic damages from a well-sited and well-managed CCS project. To begin to answer this question, a diverse group of organizations jointly sponsored Industrial Economics Incorporated (IEc), an expert in environmental economics and natural resource damage assessment, to develop and test a model approach for valuing the human health and ecological damages arising from CCS at such a site.[4]

The sponsor group comprised representatives from industry, government, and the environmental community, including: Wade, LLC, CO_2 Capture Project, Chevron, Duke Energy, Environmental Defense Fund, Global CCS Institute, Government of Alberta, ICO2N, Industrial Economics, Incorporated, Natural Resources Defense Council, Southern Company, State of Wyoming, and World Resources Institute. Although individual sponsors may have differing views on CCS, they share a common interest in understanding how potential damages from a CCS project can be valued, and the likely magnitude of prospective economic damages at a well-selected and well-managed site.

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[3] IPCC, Special Report on Carbon Dioxide Capture and Storage, Summary for Policy Makers, 2005 - Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos and Leo Meyer (Eds.), Cambridge University Press, U.K., page 14.

[4] The damages contemplated by this analysis do not address potential impacts from facility construction or routine operation, nor do they address potential impacts to workers, business interruption, facility repair or similar 'private' costs internal to the operator.

The project had two objectives:

- Develop a computational model of the interaction between risks, CO_2 releases and damage values to derive overall damages estimates associated with CCS using generally accepted tools from the damage assessment field. The approach relies on site specific conditions and information.
- Apply this model to a 'realistic' project. The project sponsors selected the FutureGen 1.0 project proposed in Jewett, TX as a suitable 'realistic' project for purposes of analysis. Because the emissions at this site include a combined CO_2 and H_2S stream, and the FutureGen risk assessment considered impacts from both constituents, the model was constructed to include both.

This report meets the above objectives by identifying the dollar amounts that need to be managed, the set of circumstances under which these amounts will present, and the time frame over which these dollars will be needed. It presents a model that is based on standard practices within the financial and insurance industries, and can be applied, with adjustment for location, to CCS projects around the world.

Using a publicly available risk assessment for a finalist FutureGen site as a 'realistic' base case, the magnitude of likely economic damages over a 100-year assessment period is estimated to be $0.17 per metric ton, or less than 1% of total estimated project costs.[5] From a damages perspective, the FutureGen site is 'well-sited' in a highly rural area, with limited potential to affect sensitive resources.

This report documents IEc's analysis and provides detailed information on the findings.

ANALYTIC METHOD

Using a model developed by IEc, this study calculates damages by combining the information from the environmental impact studies for the Jewett site and other risk assessments to estimate probabilities and magnitudes of harm to people and the environment at the site. The model incorporates the potential magnitude of CO_2 and H_2S releases resulting from modeled release events at the capture plant, pipeline and storage site; release event probabilities; estimated human health and ecological effects resulting from release events; and, estimated costs arising from compensation for, or remediation of, these effects. Damage estimates associated with individual events are derived by drawing on valuation methods from legal systems for accident compensation, natural resource damage assessments and cost-benefit studies. By combining risks, event outcomes and damage assessment, IEc populated the cost curves used in the model. The study applies Monte Carlo modeling, a well-accepted probabilistic method, to estimate probability distributions for important input variables and damages.

[5] For estimates of CCS project costs, see: Gresham *et al*. (2010), McCoy and Rubin (2009), Rubin *et al*. (2007), MIT Future of Coal (2007), ETIP-Harvard (2009), Simbeck, D. MIT (2009), McCoy and Rubin (2007).

To demonstrate application of the modeling approach to a real-world, a ‘realistic’ case study was developed, with parameters for risk and likely volumes of release based on the publicly available information contained in environmental impact studies and risk assessments developed as part of the FutureGen 1.0 project. Relying on this material, IEc assessed release events at the capture plant site, the pipeline, and the storage site (i.e., the subsurface). In the few instances where quantitative data needed for the analysis were not available from the FutureGen risk assessment and/or other relevant data sources, the sponsor group developed a set of assumptions for use in testing the model based on experience or background literature. The period of analysis was 100 years, reflecting 50 years of injection operations and 50 years post-injection monitoring.

SITE SPECIFIC ESTIMATED DAMAGES

Overall, estimated total damages for CO_2 alone are approximately \$7.3 million (50th percentile) and \$16.9 million (95th percentile). These estimates include all credible potential adverse events (as determined in FutureGen risk assessment analyses) over the 100-year analysis period, and are expressed in 2010\$. These estimates translate to approximately \$0.15 (50th percentile) and \$0.34 (95th percentile) per metric ton of CO_2 sequestered (50 million metric tons of CO_2 are expected to be sequestered at the Jewett, TX site).

Estimated total damages for CO_2 and H_2S are approximately \$8.5 million (50th percentile) and \$18.6 million (95th percentile). These estimates include all credible potential adverse events (as determined in FutureGen risk assessment analyses) over the 100-year analysis period, and are expressed in 2010\$. These estimates translate to approximately \$0.17 (50th percentile) and \$0.37 (95th percentile) per metric ton of CO_2 sequestered (50 million metric tons of CO_2 are expected to be sequestered at the Jewett, TX site). Several types of potential damages contribute to this total, including the cost of actions to: 1) stop subsurface releases to groundwater and address groundwater contamination; 2) pay for emissions offsets to address CO_2 leakage; 3) compensate for human health damages; and 4) address habitat/other damages.

KEY SITE SPECIFIC DRIVERS AND UNCERTAINTIES

If there were no H_2S in the sequestration stream, total estimated damages would be approximately 10-15% lower. CO_2 is the dominant stream at the Jewett site. However, the planned process would result in the presence of trace amounts of H_2S (0.01%) in the captured stream. This trace amount of H_2S is the primary driver of estimated human health effects in the study and would not be present in some projects that used a different capture process. Further, although H_2S is the primary driver of human health risks in this analysis, the extremely rural location for plant, pipeline and sequestration operations severely limits potential human health damages, minimizing the added impact of H_2S.

Potential releases at oil & gas/other wells in the sequestration site area are responsible for over 95% of estimated total damages. At the Jewett, TX site there are believed to be numerous deep oil & gas wells and potentially other older abandoned wells.

FutureGen analyses assign total (or aggregate) release probabilities from any one of those wells that are multiple orders of magnitude higher than any other type of release event at the plant or sequestration site, contributing substantially to the prominence of this potential damages category. A site with this characteristic could potentially mitigate the effect by selecting a location with fewer existing wells, or undertake measures to prevent the frequency or size of releases.

Potential damages associated with other release events are negligible. Estimated damages for the following incidents are negligible for both 50th and 95th percentile cases, reflecting their extremely low event probabilities and/or site characteristics that limit potential impacts if an event occurs: other aboveground wellhead events, plant site events, and pipeline events including ruptures and punctures.

CONCLUSION

The sponsor group includes representatives from industry, government, and the environmental community. Although individual sponsors may have differing views on CCS, they share a common interest in understanding how potential damages from a CCS project can be valued, and the likely magnitude of prospective economic damages at a well-selected and well-managed site.

This report answers those questions by identifying the dollar amounts that need to be managed, the set of circumstances under which these amounts will present, and the time frame over which these dollars will be needed at a specific CCS project. It presents an approach that is based on standard practices within the financial and damage assessment industries, and can be applied, with adjustment for location, to CCS projects around the world.

Using a publicly available risk assessment for a finalist FutureGen site as a 'realistic' base case, which has certain site-specific characteristics including both relative isolation from human populations and limited groundwater use, the magnitude of likely economic damages over a 100-year assessment period is estimated to be in the range of $0.15 - $0.34 per metric ton over the 100-year period, i.e., less than 1% of total estimated project costs.

EXECUTIVE SUMMARY

The public debate as it relates to Carbon Capture and Storage (hereinafter, CCS) has been clouded by subjective perceptions of what is at risk, and whether the consequences of such risks are material from a financial perspective. In our view, analytic evaluation of the range of potential impacts and calculation of the financial consequences arising from CCS can illuminate the risks requiring mitigation, the dollar amounts that need to be managed, the set of circumstances under which amounts will present, and the time frame over which these dollars will be needed.

Although the probability of a release at a well-sited, well-operated CCS project may be small, prudent risk management requires estimates of the dollars necessary to remediate or compensate for harm, should a release occur. Damages are a function of location, plant design, fuel source, and technology, and therefore must be estimated on a site-specific basis. With the availability of site-specific data, the analytic tools exist to estimate dollar values of potential damages at individual CCS sites.

The objective of this study is to derive damages estimates for a CCS project, with a clear understanding of the statistical range of outcomes. Specifically, study objectives include:

- Construct a computational spreadsheet model to derive damages estimates for a CCS project. This model integrates analytic tools that are generally accepted in the damage assessment field to assess the array of potential impacts associated with a CCS project. The model outputs are designed to provide a clear understanding of the statistical range of outcomes. Notably, because harms are uncertain, the study focuses on 'most likely' damages (50^{th} percentile) and 'upper end' damages (95^{th} percentile).
- As a proof of concept, apply this model to a 'realistic' project. After reviewing potential options, the three finalist sites for the FutureGen 1.0 project were determined to be suitable 'realistic' projects for purposes of analysis. This study focuses on deriving damages estimates for the Jewett, TX site.

The remainder of this document summarizes preliminary results derived from the spreadsheet model, including an overview of the analytic approach and the underpinning assumptions.

1.0 ANALYTIC METHOD

To achieve analytic rigor and to appropriately characterize the array of uncertainties underpinning the calculations, this study calculates damages using a set of linked mathematical equations through a 'spreadsheet model.' The model incorporates the potential magnitude of CO_2 and H_2S releases resulting from modeled events, event probabilities, estimated human health and ecological effects resulting from releases, and estimated costs arising from compensation for, or remediation of, these effects.

The model has the ability to factor in data, event probabilities, and effect values from multiple sources, which lends itself to broader application as additional, site-specific data become available. This analysis relies on publicly available information contained in environmental impact studies and risk assessments developed as part of DOE's FutureGen project. It monetizes harm to people and the environment using valuation methods from legal systems for accident compensation, natural resource damage assessments and cost-benefit studies. The study applies Monte Carlo modeling, i.e., a well-accepted probabilistic method, to characterize the array of uncertainties underpinning the calculations. Specifically, the study estimates probability distributions for important input variables, and uses Monte Carlo analysis to derive resulting probability distributions for damages. These probability distributions illustrate the statistical range of possible damage amounts for different components of damages.

Key study parameters are summarized below:

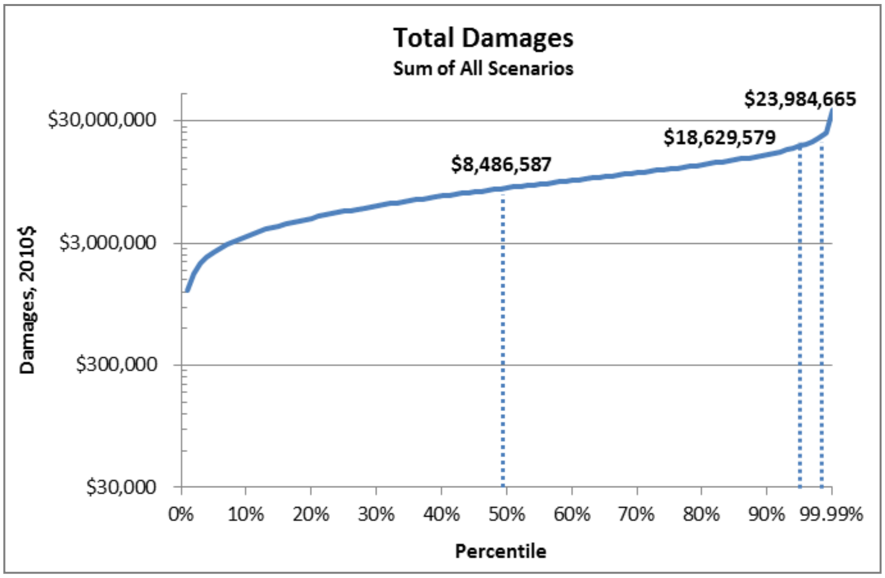
- Candidate Site. Jewett, Texas DOE FutureGen site.
- Plant Site Events. Events singular to CCS (i.e., 'above and beyond' or incremental to what might be experienced by a similar plant without CCS capability).
- Pipeline Events. Two pipeline release scenarios: (1) a 'hole-puncture'; and (2) a complete severing of the pipeline.
- Sequestration Site Events. Variety of release mechanisms and pathways modeled in FutureGen analyses (e.g., aboveground injection equipment failure, injection well releases and other well releases).
- Chemical Constituents. CO_2 and H_2S.
- Period of Analysis. 100 years (50 years of injection operations, and 50 years post-injection, i.e., after cessation of injection operations).
- Groundwater and Surface Water Modeling. Groundwater damages estimates reflect bounding calculations incorporating readily available, site-specific information; surface water addressed qualitatively because of the limited surface water resources present in the vicinity of the Jewett, TX site.
- Atmospheric Release. Damages assume the required purchase of carbon offsets to address accidental release of CO_2 to the atmosphere, at prices ($ per tonne CO_2) identified in the analysis.

2.0 OVERVIEW OF PRELIMINARY FINDINGS FOR JEWETT, TX SITE

2.1 CALCULATED DAMAGES

Figure 1 summarizes damages estimates for all contaminants (i.e., CO_2 and H_2S) across all modeled accident events for the Jewett, TX site. Estimated damages are calculated over a 100-year time horizon, including the 50-year operational period and the 50 years following the cessation of injection operations. Results are presented in 2010$.

Fig. 1



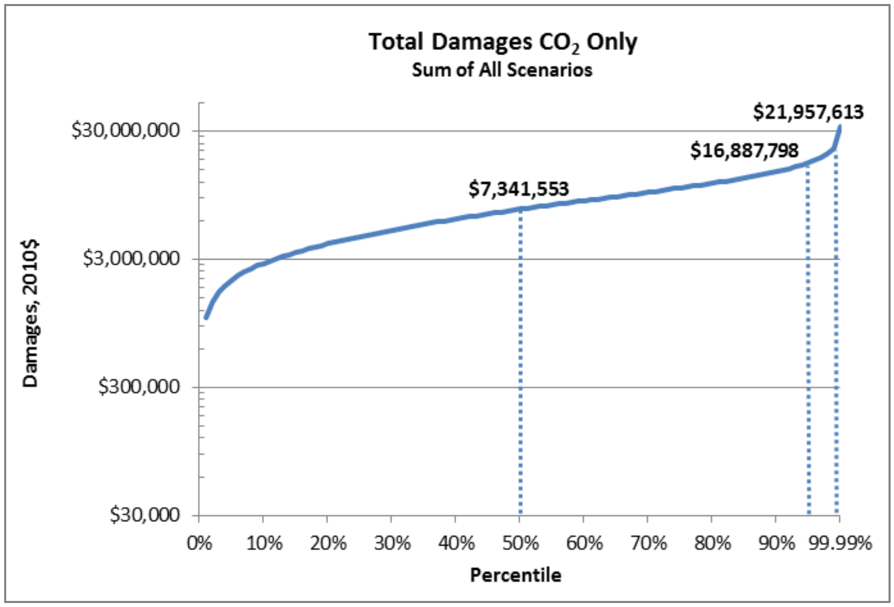
As shown, 'most likely' (50th percentile) estimated damages total approximately $8.5 million. This means that there is a 50% chance that damages would be either higher or lower than the 50th percentile figure. 'Upper end' (95th, 99th percentiles) total approximately $18.6 million and $24.0 million, respectively. This means that there is a 95% or 99% chance of damages being equal to or lower than the stated damages figure, and only a five or one percent chance that damages would exceed the stated damages figure. The curve in Figure 1 illustrates the range of estimated damages associated with cumulative probabilities of occurrence generated from 100,000 trials.

On a per ton basis, assuming 50MMt stored CO_2, these results translate into 'most likely' (50th percentile) estimated damages of $0.17 per ton, with a 50% chance that damages would be either higher or lower than this estimate. 'Upper end' (95th, 99th percentiles) are approximately $0.37 per ton and $0.48 per ton, respectively. This means that there is a 99% chance of damages over the 100-year analysis period would be less than or equal to $0.50 per ton, and only a one percent chance that damages would exceed this estimate.

It is important to note that the above absolute and per ton damages estimates are predicated on data available for the Jewett, TX FutureGen site, which by all accounts was designed to be a well-sited, well-operated – 'platinum-plated'– site. The range of damages estimates is highly sensitive to site-specific data. Therefore, relaxed siting and operating decisions will have a material impact on the estimate of 'most likely' and 'upper end' damages. In later sections, we model alternative scenarios to better assess the impacts of various uncertainty parameters on the damages estimates resulting from this study.

Figure 2 presents estimates of the portion of total damages assigned to CO_2 only at the Jewett, TX site; results are presented in 2010$. We present this information to help stakeholders better understand the potential damages associated with a 'pure' CO_2 sequestration stream.

Fig. 2



As shown, 'most likely' (50th percentile) estimated damages total approximately $7.3 million for CO_2. This means that there is a 50% chance that damages would be either higher or lower than the 50th percentile figures. 'Upper end' (95th, 99th percentiles) total approximately $16.9 million and $22.0 million, respectively, for CO_2. This means that there is a 95% or 99% chance that damages over the 100-year analysis period would be less than or equal to the stated damages figures, and only a five or one percent chance, respectively, that damages would exceed the stated damages figures. Similar to Figure 1, the curves in Figure 2 illustrate the range of estimated damages associated with cumulative probabilities of occurrence generated from 100,000 trials.

2.2 KEY DRIVERS

Composition and Toxicity of CCS Stream

The CCS stream includes CO_2, with varying levels of H_2S, CH_4, CO, SOx, NOx, Hg and Cyanide. The purity of the injected stream will dictate the severity of damages arising from harms following an accident event. The basis of this study's analyses is the FutureGen risk assessment. Specifically, this study focuses on the Jewett, TX site, which assumes that captured gas will be 95% CO_2 and 0.01% H_2S. [1]

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[1] U.S. Department of Energy (DOE). Final Risk Assessment Report for the FutureGen Project Environmental Impact Statement; Contract No. DE-AT26-06NT42921. 22 December 2006; Revision 1 April 2007; Revision 2 October 2007, pg. 4-3.

Impacts arising from CO_2 and H_2S are quantitatively estimated in the FutureGen risk assessments, and this study relies on these impacts assessments in deriving damages estimates.[2]

Although CO_2 is the dominant constituent in captured gas, CO_2 is not a potent toxicant relative to the other constituents present in the CCS stream. Simply stated, relatively high concentrations of CO_2 are necessary to cause adverse impacts to human health. For example, as shown in Table 1, the CO_2 health effects thresholds in the FutureGen risk assessment range from 10,000 ppmv (part per million by volume) (adverse effects, chronic) to 70,000 ppmv (life-threatening effects, chronic). In contrast, relative to CO_2 concentrations, H_2S can cause harm to human health at much lower concentrations. As shown in Table 1, the H_2S human health effects thresholds range from 0.0014 ppmv (adverse effects, chronic) to 50 ppmv (life-threatening effects, 15 minute exposure).

For the above reasons, H_2S is the primary driver of estimated human health-related damages. All else equal, the smaller the amount of H_2S in the constituent stream, the lower the likely estimated human health damages arising from CCS at the Jewett, TX site.

Table 1. Summary of H_2S and CO_2 Human Health Effects Thresholds for the Jewett, TX site

	15 Minute Exposure		8 Hour Exposure		Chronic Exposure	
Effect	CO_2	H_2S	CO_2	H_2S	CO_2	H_2S
Adverse	30,000	0.51	20,000	0.33	10,000	0.0014
Irreversible	30,000	27	20,000	17	50,000	0.0014
Life-threatening	40,000	50	40,000	31	70,000	0.0014
Source: FutureGen Risk Assessment (pp. 6-6 and 6-7 and Table 3-7)						

However, damages associated with potential groundwater and the potential need to purchase offsets for greenhouse gas releases are of concern when considering CO_2. Notwithstanding the fact that H_2S releases can result in impacts to groundwater, CO_2 is much more likely to be the driver of potential groundwater damages at the Jewett site, due to: 1) the much greater volume of CO_2 present in the sequestration stream (CO_2 and H_2S comprise 95% and 0.01% of the sequestration stream, respectively); and 2) the more severe types of impacts that can result from the presence of CO_2 in groundwater (e.g., lower pH, mobilization of metals, and increased total dissolved solids/hardness) relative to H_2S (e.g., potential odor, tarnishing/staining issues).

[2] Other constituents expected to be present in the captured gas in trace amounts include CH4, CO, SOx, NOx, mercury and cyanide (see FutureGen Final Risk Assessment Report, pg. 3-1). FutureGen documents do not develop quantitative risk assessment information for these constituents.

With respect to atmospheric leakage, H_2S is not a greenhouse gas, limiting the potential need to purchase greenhouse gas offsets to CO_2.

Event Probabilities

All else equal, the lower the probability (or likelihood) of an event occurring, the lower the damages that are likely to result. In a study of this nature, 'event probabilities' are a key driver in calculating the range of damages likely to arise from an event. Table 2 offers estimates of the annual likelihood of various events used in this study.

Table 2. Event Probabilities by Release Scenario for Jewett, TX Site

Release Scenario	Release Likelihood (annual)
Plant Events	
Failure of CO_2 Separation Equipment	5.5-in-100,000 (0.0055%)
Pipeline Events	
Pipeline Rupture	1-in-200 (0.5%)
Pipeline Puncture	1-in-100 (1.0%)
Sequestration Site Events	
Wellhead Equipment Rupture	6-in-100,000 (0.006%)
CO_2 Injection Well Leak	3-in-100,000 (0.003%)
Other Well Leak	7-in-100 (7.0%)
Rapid Leakage through Caprock	2-in-10 billion (0.00000002%)
Slow Leakage through Caprock	4-in-100,000 (0.004)%
Release through Existing, Induced Faults	2-in-100 million (0.000002%)
Source: FutureGen Risk Assessment Table 6-11, except for plant events, which are based on data and communications provided by industry and trade associations.	

The FutureGen risk assessment analyses for the Jewett, TX site provide pipeline and sequestration site event probabilities. Specifically, for event probabilities related to pipeline events, FutureGen relies on CO_2 pipeline data available through the Office of Pipeline Safety. Sequestration event probabilities are based on FutureGen analysis of site-specific data and data from analogous natural and industrial CO_2 storage sites. This study relies on those estimated event probabilities. Estimates of event probabilities arising at the CCS plant site, itself, are not addressed in FutureGen and instead are based on information from relevant technical literature.

As shown in Table 2, the most frequent adverse event is expected to be a leak through a deep oil & gas, or undocumented, well with an estimated annual chance of occurrence of 7-in-100 (7%). Although the annual probability of a leak for one such well is estimated to be between 1-in-1,000 (0.1%) and 1-in-1,000,000 (0.0001%), the FutureGen analyses suggest that there may be as many as 70 such wells at the Jewett site that are located above the sequestered CO_2 plumes (see FutureGen Risk Assessment, Table 6-11). For these reasons, this study conservatively uses the upper end of the range of the probabilities of occurrence for these types of risks, or 7-in-100 (7%).

Pipeline rupture and puncture events are expected to be the next most probable events (i.e., a 1-in-200 (0.5%) and 1-in-100 (1.0%) annual chance of occurrence, respectively). These rates are based on Office of Pipeline Safety data from 1994-2006, which underpinned the FutureGen risk assessment. The FutureGen risk assessment identifies 31 CO_2 pipeline accidents during this time period. This study relies on these data to derive accident rates per mile of pipeline. These rates then were applied to the pipeline lengths of the Jewett, TX site, i.e., 59 miles. To corroborate the data underpinning the FutureGen risk assessment, this study also integrates Office of Pipeline Safety data from 2002-2009 for CO_2, natural gas transmission, and hazardous liquid pipelines found comparable accident frequencies.

Plant site events directly associated with CCS activities are expected to have a 5.5-in-100,000 annual frequency of occurrence, conservatively reflecting the highest failure rate identified by the UK Health and Safety Executive.[3]

Valuation of Human Health Effects

This study considers human health effects potentially caused by CO_2 and H_2S, arising from accident events at a CCS project in Jewett, TX.

The objective of this analysis is to forecast the amount of money damages that a Texas jury would award members of the public (e.g., nearby residents) harmed by a release arising from CCS at the Jewett operation. Possible harms include death, severe or permanent effects, and minor or temporary effects.

Based on Texas laws, which are similar to laws in many other U.S. states, health effect values per case include:

(1) **Medical Costs**, which include the past and future medical expenses incurred due to the injury or death;

(2) **Productivity Losses**, which include both past and future losses. Further, diminished earning capacity reflects the value of lost fringe benefits plus the value of lost household services less earnings and services the victim would have consumed but for his/her injury or death. and

(3) **Non-Economic Losses**, which include compensation for physical pain and impairment, mental anguish, disfigurement, loss of consortium, loss of advice and counsel, and similar losses.

Figures 3, 4 and 5, summarize the distribution of values for fatalities, hospital cases (associated with severe effects, categorized as ‘irreversible’ in FutureGen), and non-hospital cases (associated with temporary effects, categorized as ‘reversible’ in FutureGen) used in this study.[4] These distributions reflect judgments based on the

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[3] See Appendix A.

[4] Figures 3, 4 and 5 were developed from IEc analysis of several data sources. See Chapter 2 for a detailed discussion of their derivation.

results of literature searches to locate studies and databases describing jury awards in personal injury and wrongful death cases, medical expenses associated with hospital stays, and estimates of lost productivity values.

Fig. 3

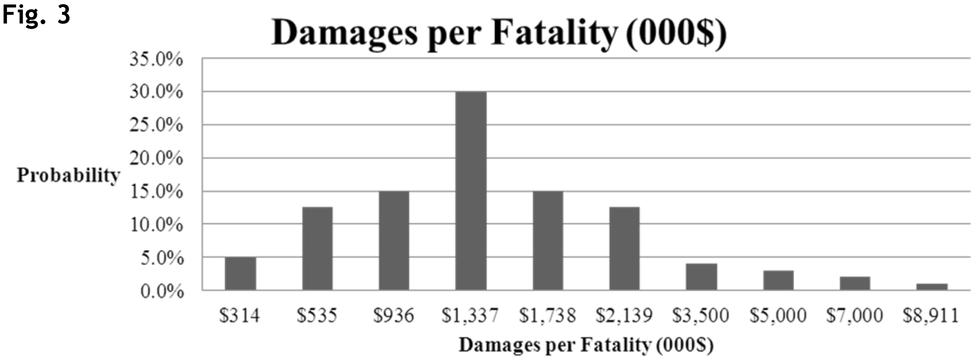


Fig.4

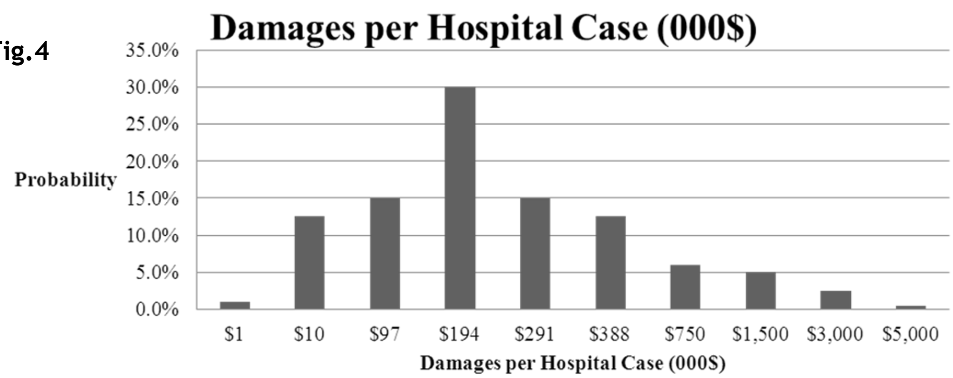
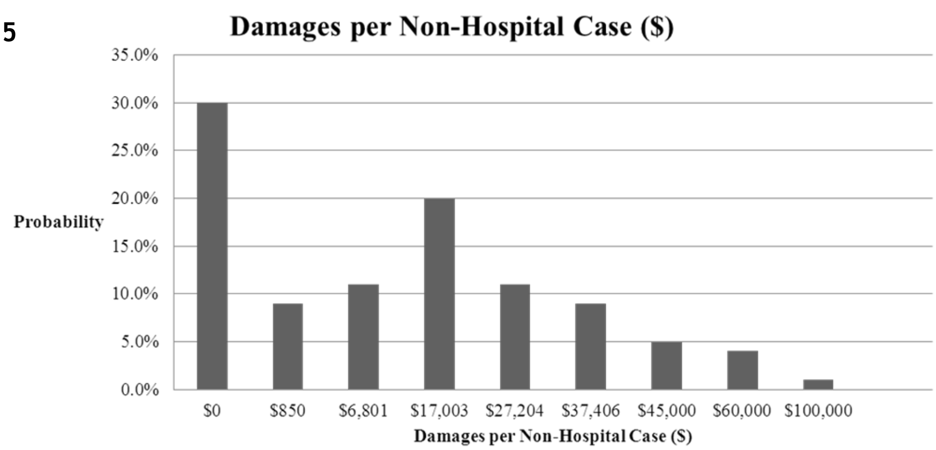


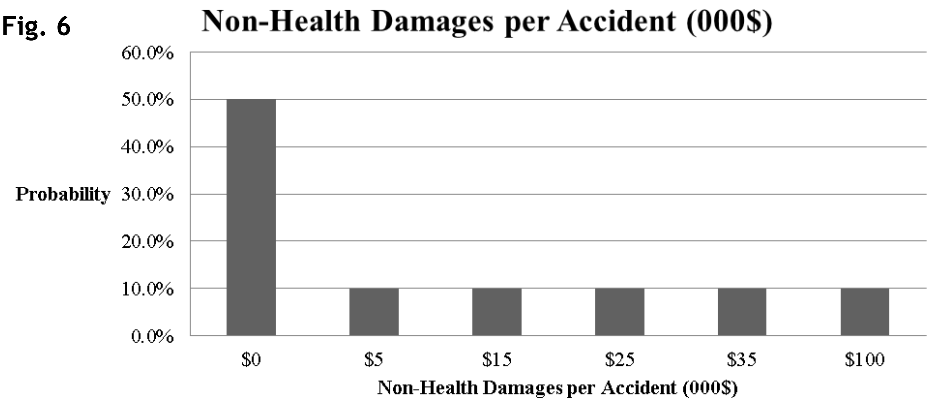
Fig.5



Valuation of Environmental/Other Effects

This study also considers environmental effects potentially caused by CO_2 and H_2S. Figure 6, on the following page, summarizes the distribution of environmental/other damages. These distributions reflect data from myriad sources, including Office of Pipeline Safety CO_2 pipeline accident data from 2002-2009, a publicly available pipeline damages estimation model based on 1,582 hazardous liquid pipeline accidents from 2002-2005, and professional judgment based on communications with industry and trade associations. The damages estimates summarized in Figure 6 serve as a proxy for environmental/other damages caused by plant, pipeline and sequestration site accidents. The exception is groundwater damages, which is addressed separately in this study.

Fig. 6



Plant, Pipeline and Sequestration Characteristics of the Jewett, TX Operation

The Jewett, TX operation is located in a highly rural setting with a low population density, which limits the magnitude of potential damages shown in Figures 1 and 2. Notably, as shown in Figures 7, 8 and 9, imagery of the area surrounding the proposed plant, pipeline and sequestration location indicates relatively few residences, contributing to limited human health exposure.

As shaded in purple in Figure 7, the plant site is approximately 400 acres in size. The plant footprint is expected to be only 75 acres, allowing for several hundred feet of open space buffer around the plant itself. There are no residences within 0.3 mile (0.5 kilometer) of the proposed plant site, and population densities beyond that radius are very low. One small church, with limited use, is located approximately 0.3 mile (0.5 kilometer) north of the northern corner of the proposed power plant site.

If accident events were to occur, the rural nature of the plant, pipeline and sequestration locations limit the potential for damages. Notwithstanding the rural nature of the site today, the study does not introduce projections for changing demographics at the plant, pipeline or sequestration locations. As part of subsequent scenario analyses, and upon consideration by the sponsor group, the study variables could be adjusted to reflect possible future changes in population growth, as well as changes in land use.

Figure 8 illustrates the location of CO_2 pipeline that connects the proposed plant to the sequestration area. The pipeline is expected to be approximately 59 miles long, with an inner diameter of 19 inches. The pipeline would be buried 3 feet beneath the earth’s surface. Substantial portions of the pipeline are expected to use existing natural gas transmission rights of way.

Fig. 7

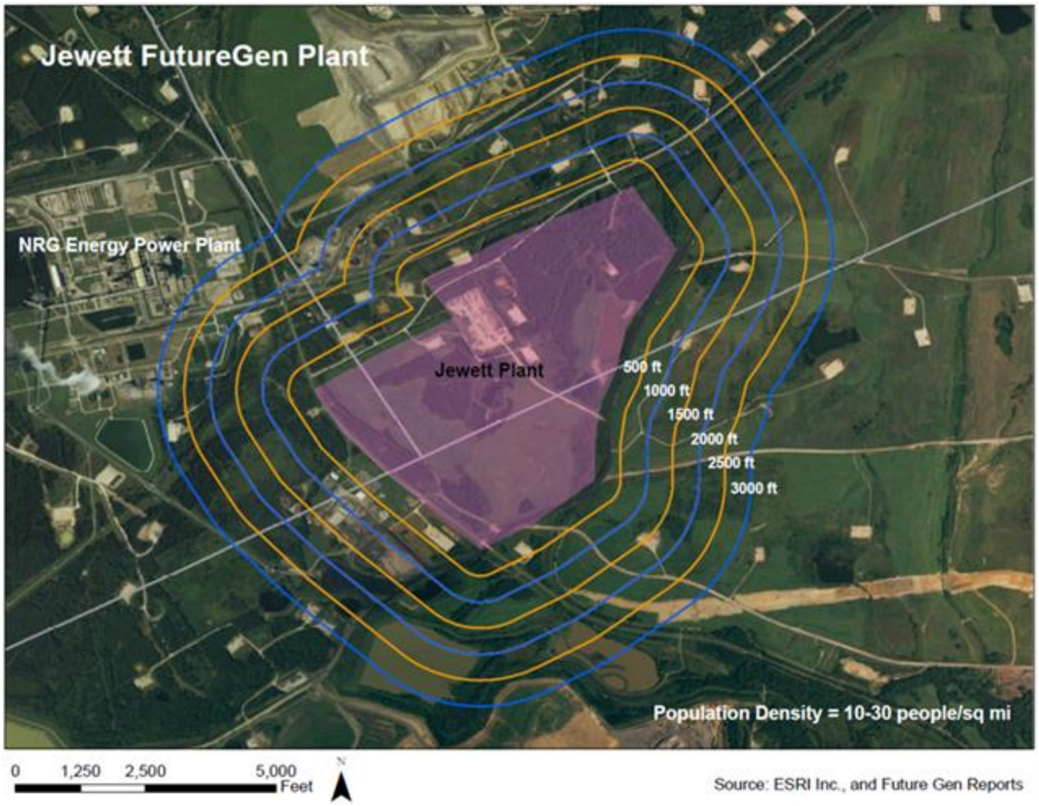
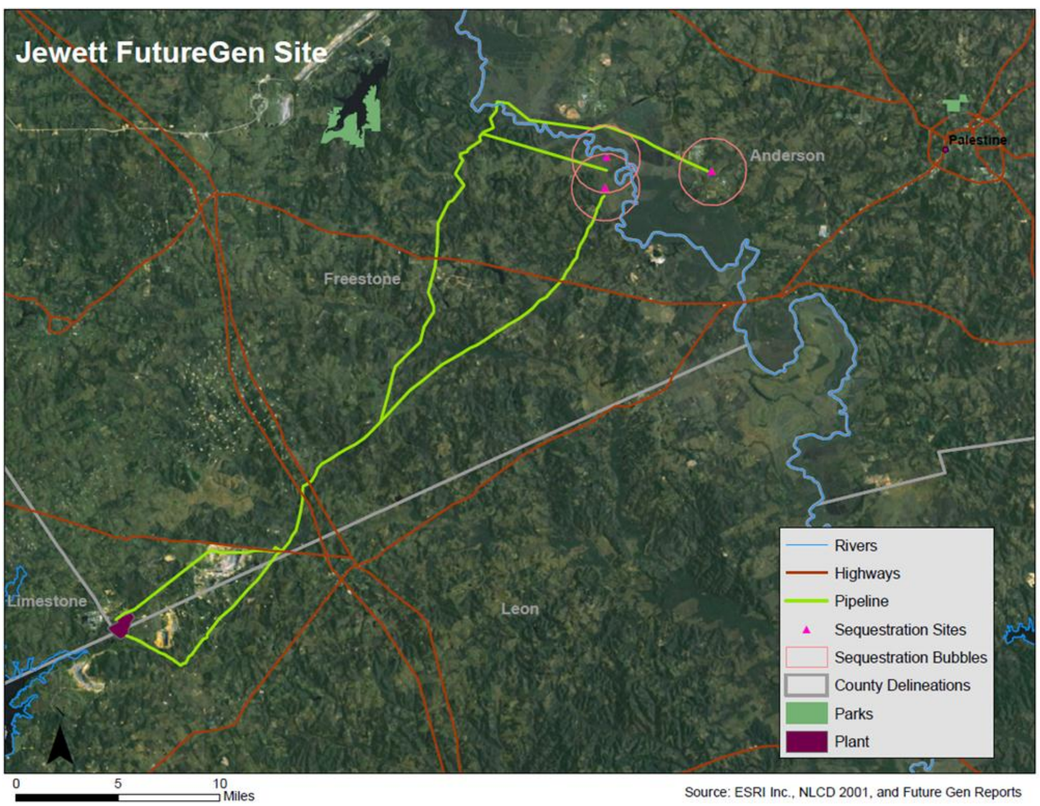


Fig. 8



Presently, there is very little development near the pipeline. Table 3 summarizes the frequency of land cover types within 100 meters of the pipeline. Approximately 30% of the area (acreage) nearest the pipeline is pasture, 20% is forest, and 16% is shrub habitat. Developed areas only account for approximately 8%. Further, there do not appear to be any significant parks, campgrounds or other recreational/cultural areas close to the pipeline. The Trinity River is the only water body of note that crosses the pipeline.

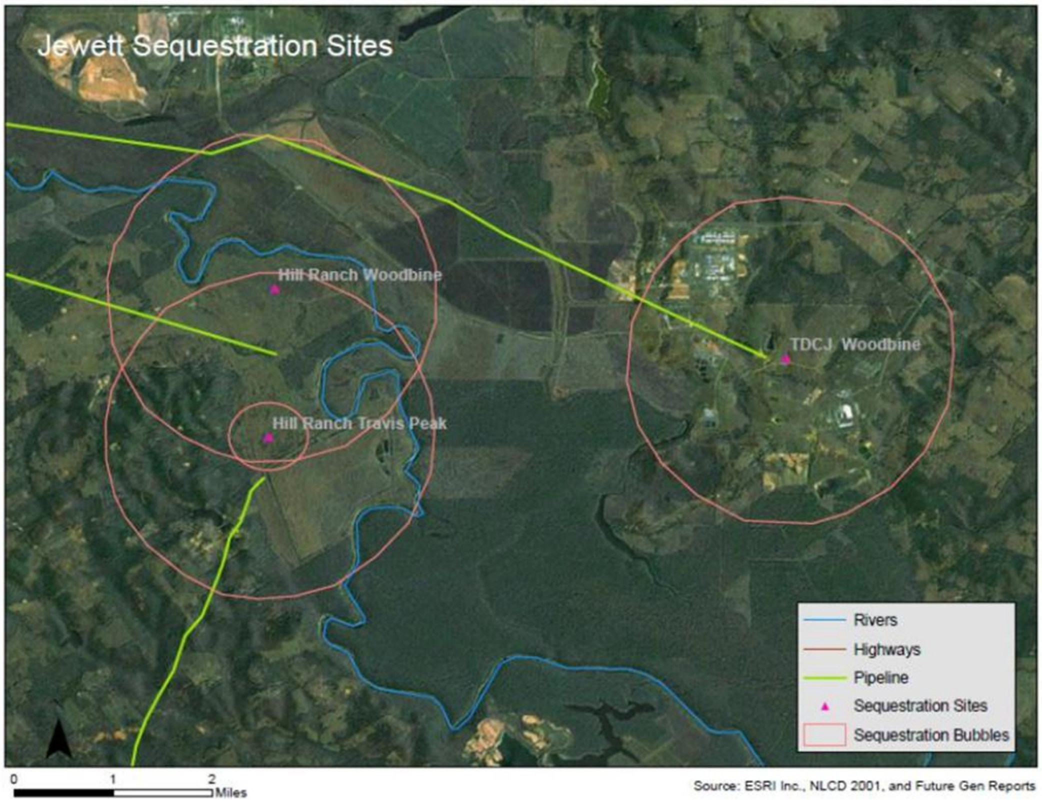
Table 3. Land Cover Types within 100 meters of the Pipeline

LAND COVER TYPE	AREA (ACRES)	%
Water	46	0.8
Developed	437	8.0
Barren	372	6.8
Forest	1,078	19.8
Shrub	888	16.3
Grassland	371	6.8
Pasture	1,634	29.9
Wetland	630	11.5

Figure 9 illustrates the sequestration site, itself, which is located in a rural area about 33 miles northeast of the Jewett, TX plant site. Two of the proposed CCS injection well sites are located about 16 miles east of the Town of Fairfield in Freestone County, about 60 miles east of Waco. The third proposed CCS injection well site would be located about 5 miles east on Texas Department of Criminal Justice (TDCJ) property in Anderson County, which is about 16 miles west of the City of Palestine.

Presently, the proposed sequestration site is forest and grassland, with limited use for ranching purposes. There are few residences. The exceptions are TDCJ facilities located directly over the proposed CCS plume. According to the FutureGen risk assessments, injection would occur on a private ranch (i.e., Hill Ranch) and on adjoining state property managed by the TDCJ. Further, FutureGen documentation indicates that a 50-year lease was proffered for the sequestration site with 100 percent surface access and a waiver of mineral and water rights for at least three injection sites, totaling approximately 1,550 acres in two locations (FG Alliance, 2006c).

Fig. 9



GroundWater Damages

Potential groundwater damages reflect several factors, including but not necessarily limited to: ownership of water rights; the likelihood of events that can lead to groundwater contamination; the constituents in the sequestration stream; the potential spatial extent, severity and duration of groundwater contamination events; the type and amount of groundwater use in the area; appropriate remediation and restoration costs; and the presence of alternate sources of potable water. The FutureGen analyses conclude that there is a low potential for damages to groundwater at the Jewett, TX sequestration site. As a result, they do not attempt to quantify the potential severity or magnitude of impacts that would arise in the unlikely event of a release into groundwater.

This study includes a series of bounding calculations designed to broadly assess potential groundwater damages arising from CCS at the Jewett, TX site. If the CCS plume were to migrate beyond the containment zone of the sequestration site, at least four types of potential adverse impacts to groundwater resources could occur:

1) **Diminished pH (acidity) of the potable portion of the aquifer to a level that renders the water unusable for drinking or for other normal beneficial uses.** The degree to which the pH could be lowered depends on the relative amount of carbonate mineral material in the aquifer matrix. If greater than approximately 1% by weight of carbonate mineral material is present, associated buffering capacity would prevent appreciable pH change. If virtually no carbonate materials were present, pH might be lowered to about 3.5 near the area of the infusion of the CO_2. Publicly available groundwater sampling data from the area suggest a high likelihood that carbonate minerals in the

matrix exceed 1%. To confirm this finding, physical sampling of the aquifer matrix and associated laboratory buffering capacity experiments are needed. With data confirming the amount of carbonate minerals present, more extensive geochemical modeling equilibrium calculations are possible.

2) **Increased concentrations of H_2S to a level that presents risk to human health or the environment, or results in other non-health-related adverse impacts.** When inhaled, H_2S in gaseous form is highly toxic, but H_2S is much less of a concern in groundwater. Presently, H_2S has no regulatory maximum contaminant level (MCL), and is not considered a risk to human health or the environment at water solubility levels. Nonetheless, H_2S can still have an adverse impact on water use. Specifically, if it is present above 1 ppm (part per million), H_2S can cause undesirable odor problems and corrosion or tarnishing of metals and staining. In the event of a release, bounding calculations used in this study indicate that maximum H_2S concentrations in groundwater are unlikely to exceed about 5 ppm. At a level of 5 ppm, there is no threat to human health or the environment, but as noted above, this level could result in odor or staining/tarnishing issues. An inexpensive point-of-use treatment to reduce the H_2S would correct these impacts.

3) **Altered chemistry of existing water sources sufficient to cause the release of naturally-occurring toxic metals in the groundwater and the mineral matrix of the aquifer.** Publicly available data indicate that aquifer water in the proximity of the Jewett, TX sequestration site contains detectable concentrations of trace metals, such as arsenic, beryllium, cadmium, lead and manganese. The vast majority of these concentrations are below regulatory MCLs. Greater amounts of these metals could be dissolved from the aquifer minerals into the water, if the pH were lowered sufficiently to cause the dissolution. This, however, would happen only if the relative abundance of carbonate minerals in the aquifer matrix were below approximately 1% of the total aquifer mineral composition. As noted above, this does not appear to be the case, but aquifer matrix sampling and associated laboratory buffering capacity are needed to confirm this assumption.

4) **Increased total dissolved solids and/or hardness in the water to a level that exceeds secondary drinking water standards, or otherwise decreases the normal usefulness and value of the water.** In concept, dissolution of CO_2 into the aquifer water could raise the total amount of dissolved solids and/or hardness to a level that renders the water unusable or undesirable for certain purposes. Bounding calculations used in this study indicate that the maximum concentration of dissolved solids under the assumed scenario are likely to be in the range of the solubility limit of calcium bicarbonate, which is about 166 grams per liter (166,000 ppm). Even though this scenario does not necessarily present a health threat, it does render the water undrinkable and unusable for most common applications. However, should this accident event arise, the impact is likely to be limited to a very localized zone in the vicinity of the conveyance pathway of the leaking CO_2. These types of impacts could be

mitigated by point-of-use treatment (water softening ion exchange), water blending, or alternate water supplies.

At the Jewett, TX site, groundwater damages within the 100-year period evaluated by this analysis are most likely (by far) to arise from leaks in deep oil & gas/other pre-existing wells in the sequestration area. As indicated in Table 2 (see page ES-6), the annual likelihood of a release from these types of wells at the Jewett, TX sequestration location is estimated to be 7%, i.e., three orders of magnitude greater than releases from wellhead equipment or injection wells. In addition, the 'central' location of injection wells within the sequestration site make it likely that injection well-related groundwater impacts (if any) are likely to be well within areas for which the project sponsor has obtained water rights, limiting the potential for damages. In contrast, deep oil & gas/other wells can be located throughout the sequestration area, potentially closer to areas for which water rights have not been secured by the project sponsor.

Therefore, this study analyzes potential groundwater damages as part of the 'other well' release scenario at the sequestration site. If an 'other well' release event occurs as part of the Monte Carlo trials in this study, damages are assumed to include the costs necessary to stop the release, and costs necessary to address the impacts of the release to groundwater and groundwater services.

With respect to the costs to stop a release, the Monte Carlo model assigns a 90% likelihood that the cost will be between \$50,000 and \$300,000 (randomly choosing a cost within that range for each event).[5] Occasionally, old oil & gas or other wells will require more complicated, expensive actions to address a release. The model in this study assigns a 10% likelihood that the cost to repair/address the well leak will be between \$2,000,000 and \$3,650,000 (randomly choosing a cost within that range for each event).[6]

A more detailed assessment of additional potential site-specific monetary damages arising from impacts to groundwater require data that are not readily available for the Jewett, TX site, and so is beyond the scope of this analysis. However, the Monte Carlo calculations use bounding estimates, reflecting information that is publically available as well as expert professional judgment based experience with groundwater damages cases. If an 'other well' release event occurs in a Monte Carlo trial, damages are assigned in the following manner: \$50,000 (75% probability), \$500,000 (20% probability) or \$5,000,000 (5% probability).

A variety of factors influence these damages estimates. Specifically, the 'low' estimate (\$50,000) applies to all of the following scenarios:

- A release occurs, but the release volume into groundwater prior to detection/corrective action is too low to cause adverse impacts;
- A release occurs in subsurface areas that do not contain useable groundwater resources; or

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[5] See Appendix A.

[6] See Appendix A.

- A release occurs in subsurface areas that contain useable groundwater resources, but the CCS project proponent owns the water rights for the affected area

The costs associated with these scenarios reflect relatively modest expenses to investigate the release and confirm the lack of potential impact to groundwater resources.

The 'moderate' and 'high' damages estimate ($500,000 and $5,000,000, respectively) reflect circumstances where potential or actual impacts to groundwater resources not under the control of the project proponent require actions to address the impact (e.g., point-of-use treatment, plume containment, groundwater mixing, pump and treat, provide alternate water, etc.) and/or otherwise compensate groundwater rights owners for any reductions in groundwater quality and/or availability. Although groundwater contamination cases in other parts of the country have resulted in damages substantially exceeding the amounts used in this analysis, in our view, several site-specific factors act to limit the potential magnitude of damages at the Jewett, TX sequestration location, including but not limited to:

- Prior to the sequestration project moving forward, project sponsors likely would exercise their existing options to purchase groundwater rights in the sequestration area;
- Groundwater surrounding the Jewett, TX sequestration site currently is not used for commercial, industrial, or other purposes;
- The sequestration site and surrounding area has very few residences;
- Publicly available groundwater sampling data from the area suggest a high likelihood that carbonate minerals in the matrix exceed 1%, providing a natural buffering capacity that substantially limits the potential for pH-related impacts; and
- Inexpensive point-of-use treatment technologies are readily available for the types of impacts that might occur.

CO_2 Leakage

The FutureGen Risk Assessment provides estimates of potential leakage rates for a variety of release mechanisms. However, the FutureGen reports do not quantify the potential volume of CO_2 that could be released to the atmosphere in the event of such a release. Further, the magnitude of potential future damages due to CO_2 leakage will depend on the design and implementation of a GHG regime. The timing and specific design of any such program in the U.S. is uncertain.

Despite these uncertainties, there are sources of information that can bound potential damages estimates. For example, the U.S. Government Interagency Working Group on Social Cost of Carbon recently (February 2010) developed estimates of the 'social cost of carbon.' These estimates include changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. Estimates included in this report range from $4.7 per metric ton of CO_2 to $136.2 per metric ton of CO_2 (2007$). While these estimates provide a useful benchmark, their relationship to actual damages that entities may be required to pay for future accidental releases of CO_2 to the atmosphere remains uncertain.

Attachment 1 summarizes predictions of CO_2 allowance prices in future decades, based on regulatory scenarios contemplated in the U.S. In general, these estimates fall within the range identified in Social Cost of Carbon analysis, and provide additional context for potential offset costs.

This valuation study uses the schedule of offset prices identified in Table 4, based on information in Nordhaus (2010). A range of prices based on the schedule in Table 4, is assigned to every year in the 100-year period analyzed in this study, assuming 'straight-line' price changes in the years between those identified in the table. If a CO_2 leakage event occurs as part of a Monte Carlo trial in this study, an offset price is chosen randomly from within the specified range for the year associated with the release.

Table 4. Range of CO_2 Offset Prices used in Monte Carlo Analysis

	Low	**High**
Year	\$/tonne CO_2	\$/tonne CO_2
2015	10.28	21.49
2025	17.46	38.58
2035	24.12	61.45
2045	32.21	95.50
2055	41.85	144.45
2065	53.15	201.31
2075	66.30	273.04
2085	81.40	321.71
2095	98.49	253.46
2105	117.43	197.30
2115	137.95	193.21

Source: Nordhaus 2010, 'Economic aspects of global warming in a post-Copenhagen environment', Proceedings of the National Academy of Sciences, 107(26): 11721-11726.

The 'low' and 'high' estimates reflect the 'optimal 600 ppm' and 'limit to 2 degrees' scenarios identified in Nordhaus, 2010. The optimal path in Nordhaus, 2010 peaks at just under 600 CO_2 ppm in around 2080, before stabilizing at around 500ppm in 2200.

In addition to a unit price for carbon offsets, the Monte Carlo analysis in this study requires estimates of leakage volumes to the atmosphere if a release occurs. As shown in Table 5, CO_2 leakage rates are estimable from information provided in the FutureGen analyses. However, the FutureGen analyses do not attempt to estimate: (1) the proportion of leaks expected to be observed and stopped; (2) the release duration; or (3) the fraction of leaked volumes that ultimately reach the atmosphere. Further, potential damages arising from CO_2 leakage at the sequestration site are likely to be substantially dependent on the type, density and duration of attendant monitoring efforts at the site.

Table 5. FutureGen Risk Assessment Table 5-8, pp. 5-41 to 5-46 with Study Analysis

Site	Mechanism	Annual Flux if Event Occurs	
		Minimum (MT/yr)	Maximum (MT/yr)
Jewett	Leakage via Upward Migration through Caprock due to Gradual and slow release	0	4,918
	Leakage via Upward Migration through Caprock due to catastrophic failure and quick release	NA	NA
	Leakage through existing faults due to increased pressure (regional overpressure)	118	3,526
	Release through induced faults due to increased pressure (local overpressure)	24	705
	Leakage into non-target aquifers due to unknown structural or stratigraphic connections	2,350	79,910
	Leakage into non-target aquifers due to lateral migration from the target zone	28,928	867,845
	Leaks due to deep CO_2 wells, high rate	11,000	11,000
	Leaks due to deep CO_2 wells, low rate	200	200
	Leaks due to deep O&G wells, high rate	11,000	11,000
	Leaks due to deep O&G wells, low rate	200	200
	Leaks due to undocumented deep wells, high rate	11,000	11,000
	Leaks due to undocumented deep wells, low rate	200	200

Researchers have attempted to estimate bounds for potential CO_2 leakage volumes. For example, Dooley and Wise (pg. 3) state:

> In one of the most comprehensive studies to date looking at CO_2 sequestration in relationship to enhanced oil recovery, Stevens et. al. [10] "conservatively estimate that 10% of net CO_2 purchased is emitted" during the lifetime of EOR operations in a field. It is critical to note that in the context of the Stevens' study which was principally focused on the economics of using CO_2 for hydrocarbon recovery, the 10% figure should be interpreted as the authors' estimate of an upper bound for leakage from this class of reservoirs and indeed Stevens and his coauthors note that "the actual percentage may be lower."[7]

The IPCC Special Report on CCS (2005) estimates that appropriately selected and managed geologic reservoirs are very likely to exceed 99% over 100 years (pg. 14). Overall, site-specific data and information from the general technical literature are insufficient to assign precise probabilities to potential leakage volumes. Nonetheless,

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[7] Dooley JJ and MA Wise, 2003. Retention of CO_2 in Geologic Sequestration Formations: Desirable Levels, Economic Considerations, and the Implications for Sequestration R&D. Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies. J Gale and Y Kaya (eds). Elsevier Science, Amsterdam pp. 273-278.

this study applies an array of leakage volume estimates in order to bound resulting damages estimates. In the absence of site-specific data, the bounding estimates identified below are used in the Monte Carlo analysis underpinning this study:[8]

- If an injection well release occurs during the operational period (2011 – 2060), the Monte Carlo analysis randomly assigns a release volume to the atmosphere between 0.1 and 16.5 tonnes of CO_2;
- If an injection well release occurs between 2061 and 2110, the Monte Carlo analysis randomly assigns a release volume to the atmosphere between 0.6 and 99 tonnes of CO_2; and
- If an 'other well' release occurs at any time in the analysis period (2011 – 2110), the Monte Carlo analysis randomly assigns a release volume to the atmosphere between 99 and 5,400 tonnes of CO_2.

3.0 CONCLUSIONS AND UNCERTAINTIES

The Monte Carlo approach used in this study provides an analytically rigorous foundation for understanding and managing prospective risks that could arise from CCS projects. The application of this model to a 'realistic' site-specific project, e.g., Jewett, TX FutureGen site, provides successful proof of concept that estimates of monetized damages with associated probabilities can be developed on a site-specific basis for CCS projects.

A key consideration that is reaffirmed by the results from this study is the importance of site location. Specifically, estimated damages are driven by the composition of the CCS plume, the operating structure of the plant, the integrity of the pipeline and site-specific geology. Notably, changes in these risk categories can vary damages estimates by orders of magnitude. Accordingly, results from this study suggest that well-sited, well-operated CCS projects have a relatively small potential for damages, but sound site selection and site-specific monitoring are essential.

Deriving estimates of prospective damages for the Jewett, TX CCS project necessitates that this study impute a variety of assumptions, each of which is associated with varying degrees of uncertainty. Specifically, the damages estimates discussed herein rely in substantial part on the FutureGen Risk Assessment and EIS analyses, both of which were subject to significant public review and comment. In general, the FutureGen analyses apply conservative assumptions, which are more likely to overstate the potential for damages when applied without modification in this study.

As described throughout this document, FutureGen analyses do not provide all of the inputs needed to estimate potential financial consequences if one or more releases occur at the plant, pipeline and/or sequestration portions of the project. We relied on publicly available information to address these additional data needs wherever possible, supplemented by expert professional judgment, as well as communications with industry and trade association experts.

[8] See Appendix A.

With respect to the key conclusions and drivers of this analysis and associated results, we make the following observations, specific to the Jewett, TX site evaluated as proof of concept:

- **Overall, estimated total damages are approximately $8.5 million (50th percentile) and $18.6 million (95th percentile)** – These estimates include all potential adverse events over the 100-year analysis period, and are expressed in 2010$. These estimates translate to approximately $0.17 (50th percentile) and $0.37 (95th percentile) per tonne of CO_2 sequestered (50 million tonnes of CO_2 are expected to be sequestered at the Jewett, TX site);

- **Potential releases at oil & gas/other wells in the sequestration site area are responsible for over 95% of estimated total damages** – At the Jewett, TX site there are believed to be dozens of deep oil & gas wells and potentially other old wells. FutureGen analyses assign release probabilities to those wells (i.e., 7-in-100 annual chance of a release incident) that are multiple orders of magnitude higher than any other type of release event at the plant or sequestration site, contributing substantially to the prominence of this potential damages category.[9] Several types of potential damages contribute substantially to this total, including the cost of actions to: 1) stop the release; 2) address groundwater contamination; 3) pay for offsets to address CO_2 leakage; 4) compensate for human health damages; and 5) (much less significantly) address habitat/other damages.

- **Potential damages associated with other types of sequestration site events are negligible** – Estimated damages for aboveground wellhead incidents and injection well incidents are $0 for both 50th and 95th percentile cases, reflecting their extremely low event probabilities, i.e., 3-in-100,000 annual probability for injection well releases and 6-in-100,000 annual probability for aboveground wellhead releases;

- **Potential damages associated with plant site events are negligible** – Estimated damages for plant site releases are $0 for both 50th and 95th percentile cases, reflecting their extremely low event probabilities, i.e., 5.5-in-100,000 annual probability;

- **Potential damages associated with pipeline events are low** – Estimated damages for pipeline rupture events are $0 for 50th percentile and approximately $0.3 million for 95th percentile cases. Estimated damages for pipeline puncture events are $0 for 50th percentile and approximately $0.2 million for 95th percentile cases. Although the likelihood of pipeline rupture and puncture events are reasonably likely to occur during the 50-year operational

[9] Pipeline punctures or ruptures are the next most common type of release (annual probabilities of 1-in-100 and 1-in-200, respectively), but for reasons described elsewhere are associated with much smaller potential monetary damages.

period (i.e., annual probabilities of 1-in-200 and 1-in-100, respectively), the extremely rural setting would severely limit potential human health damages. In addition, if an event occurs, the relatively low amount of CO_2 (1,290 tonnes) in the affected 5 mile section of pipeline between the safety shutoff valves and the limited potential for ecological/other damages also contributes to the low estimate of calculated damages.

- **If there were no H_2S in the sequestration stream, total estimated damages would be approximately 10% - 15% lower -** Although H_2S is the primary driver of human health risks in this analysis, the extremely rural location for plant, pipeline and sequestration operations severely limits potential human health damages, minimizing the added impact of H_2S.

With respect to key uncertainties, we make the following observations specific to the Jewett, TX site evaluated:

- **Estimated damages associated with CO_2 leakage are highly uncertain** – The potential volume of CO_2 released to the atmosphere if an adverse event occurs, and the potential cost ($ per tonne) associated with such releases, are both highly uncertain. For purposes of uncertainty analysis, the study's 'base case' Monte Carlo model estimates CO_2 leakage damages at the sequestration site of approximately $2.0 million (50th percentile) and $4.0 million (95th percentile).

  To address CO_2 offset pricing uncertainty, the Monte Carlo model includes a relatively broad range of unit costs for CO_2 leakage; that is, between approximately $10 and $320 per tonne depending on the year. Based on currently available information and forecasts, it is difficult to envision offset prices exceeding this range. However, it is possible that CO_2 emissions remain unregulated in the future, resulting in no cost to project proponents for CO_2 releases to the atmosphere. In such a scenario, there would be no CO_2 leakage damages.

  With respect to volume uncertainty, in the 'base case' Monte Carlo model, potential leakage volumes at the sequestration site range between 99 tonnes and 5,400 tonnes. For sensitivity analysis purposes, if the model were changed to assume that each sequestration site leakage event released 50,000 metric tonnes to the atmosphere (instead of a randomly selected volume between 100 and 5,400 tonnes) 50^{th} and 95^{th} percentile damages estimates for CO_2 leakage would increase to approximately $36.6 million and $67.7 million, respectively using 'base case' Monte Carlo CO_2 offset pricing assumptions.

- **Potential groundwater damages are uncertain, but likely constrained by site-specific factors** – This study includes a series of bounding calculations designed to broadly assess potential groundwater damages arising from CCS at the Jewett, TX site. A more detailed assessment of site-specific damages arising from potential impacts to groundwater would require data that are not readily available for the Jewett, TX site, and a commitment of resources beyond the scope of this analysis.

Nevertheless, readily available information indicates that there are several site-specific factors that act to limit the potential magnitude of damages at the Jewett, TX sequestration location, including but not limited to:

- Prior to the sequestration project moving forward, project sponsors likely would exercise their existing options to purchase groundwater rights in the sequestration area;
- Groundwater surrounding the Jewett, TX sequestration site currently is not used for commercial, industrial, or other purposes;
- The sequestration site and surrounding area has very few residences;
- Publicly available groundwater sampling data from the area suggest a high likelihood that carbonate minerals in the matrix exceed 1%, providing a natural buffering capacity that substantially limits the potential for pH-related impacts; and
- Inexpensive point-of-use treatment technologies are readily available for the types of impacts that might occur.

Factoring for the above considerations, as well as for readily available site information and expert professional judgment, the Monte Carlo analysis assigns damages to ‘other well’ release events in the following manner: $50,000 (75% probability); $500,000 (20% probability); or $5,000,000 (5% probability). Given the considerations noted above, it is difficult to envision ‘per-event’ damages exceeding this range. However, the percentages assigned to each portion of the assigned damages range also are uncertain. For sensitivity analysis purposes, changing the damages distribution percentages to 50% (damages of $50,000), 30% (damages of $500,000) and 20% (damages of $5,000,000) increases sequestration site groundwater damages from $1.3 million to $6.7 million (50th percentile) and from $7.9 million to $20.2 million (95th percentile).

- **FutureGen use of averaged atmospheric conditions could understate potential ‘upper end’ estimates of human health effects** – The Monte Carlo analysis uses FutureGen estimates of human health impacts ‘as is’, and as previously noted those estimates reflect averaged atmospheric conditions. While averaged conditions likely provide a reasonable estimate of ‘most likely’ impacts, that approach can lead to understatement of ‘upper end’ effects if a subset of atmospheric conditions could lead to higher plume concentrations, longer plume durations and/or plumes directed towards areas with higher populations densities. Publicly available information from FutureGen analyses is not sufficient to plausibly quantify the potential significance of this factor, although the highly rural setting for the Jewett, TX plant, pipeline and sequestration site likely limits the potential magnitude of understatement.

- **FutureGen estimates of sequestration site event probabilities are used 'as is' in the Monte Carlo model, and FutureGen does not quantify the potential magnitude of underlying uncertainties** – FutureGen estimates of sequestration site event probabilities are based on evaluation of site-specific data, industrial and natural analogs and expert judgment. While the underlying uncertainty in these estimates is not quantified, in some cases FutureGen identifies ranges for event probabilities (e.g., other well releases). In such cases, the Monte Carlo model conservatively uses the highest event frequency within the range (rather than the midpoint or low end) and therefore may be more likely to overstate than understate potential damages.

- **FutureGen estimates of pipeline event probabilities are used 'as is' in the Monte Carlo model, and likely have a relatively low level of uncertainty** – FutureGen estimates of pipeline failure frequencies are based on a substantial database of pipeline failure incidents maintained by the Office of Pipeline Safety. The existence and direct relevance of this event frequency data suggests a relatively low level of uncertainty for pipeline event probabilities.

- **FutureGen does not estimate plant event probabilities, estimates used in the Monte Carlo model are based on information in published technical literature and expert judgment** – While there is uncertainty associated with this parameter, failure of plant equipment like that used for CO_2 removal purposes is rare. Given the low population density around the Jewett, TX plant, the event failure frequency used in the Monte Carlo model (5.5-in-100,000 annual chance) would have to understate event frequency by at least a factor of 5 before potential plant site event damages would become something other than a negligible contributor to 'most likely' and 'upper end' damages for the Jewett, TX plant.

Attachment 1. Summary of CO_2 Allowance Price Forecasts

CITATION	ABSTRACT	FORECAST CARBON PRICE(S) (2009 DOLLARS)				
		SCENARIO NAME	2010	2015	2030	2050
U.S. EPA. 2009. Analysis of the American Clean Energy and Security Act of 2009 H.R. 2454 in the 111th Congress. Office of Atmospheric Programs. June 23. Available online at: http://www.epa.gov/climatechange/economics/pdfs/HR2454_Analysis.pdf	The American Clean Energy and Security Act of 2009 (H.R. 2454) proposes the establishment of an economy wide cap-and-trade program with the goal of reducing covered greenhouse gas emissions to 17 percent below 2005 levels by 2020 and 83 percent below 2005 levels by 2050. EPA undertook an analysis of H.R. 2454 at the request of the House Energy and Commerce Committee. Specifically, EPA analyzed seven different scenarios; for each scenario, EPA forecasted the price of carbon from 2015 to 2050. For more details on each scenario, please see U.S. EPA 2009.	Core Scenario (ADAGE)		\$13.88	\$29.13	\$77.27
		Core Scenario (IDEM)		\$13.72	\$28.53	\$75.69
		Without Energy Efficiency Programs		\$14.17	\$29.73	\$78.85
		Without Output-Based Rebates		\$13.93	\$29.24	\$77.58
		With Reference Nuclear		\$15.94	\$33.43	\$88.65
		Without Energy Efficiency, Output-Based Rebates, or LDC Allocations		\$13.91	\$29.24	\$77.55
		Without International Offsets		\$25.92	\$53.89	\$143.00
Montgomery, D., et al., 2009. Impact on the Economy of the American Clean Energy and Security Act of 2009 (H.R. 2454). Prepared for the National Black Chamber of Commerce. Washington, D.C., pp. 24-31.	Based on its proprietary, state-of-the-art MRN-NEEM and MS-MRT modeling systems, this study analyzes the potential economic impacts of the H.R. 2454. This report is intended to help decision makers and the public understand some of the impacts the legislation could have on the U.S. economy and energy markets. As part of this analysis, the authors developed a range of assumptions about specific future economic and technology factors that will influence the level of carbon emissions and associated costs. For more information on the underlying assumptions, see Montgomery et al. 2009.	Low Cost Scenario		\$20.24	\$40.47	\$111.30
		Reference Case		\$22.26	\$45.53	\$123.45
		High Cost Scenario		\$42.50	\$86.01	\$228.68
U.S. Congressional Budget Office (CBO). 2009. Cost Estimate - H.R. 2454 American Clean Energy and Security Act of 2009. As ordered reported by the House Committee on Energy and Commerce. Washington, D.C. June 5. 41 pp.	As requested by the House Committee on Energy and Commerce, CBO developed a cost estimate over the period beginning 2010 through 2019 for the implementation of H.R. 2454. Specifically, H.R. 2454 proposes to establish a cap-and-trade program designed to reduce emissions associated with eight (8) greenhouse gases. According to CBO's estimates, the program would cover about 72 percent (or 7,400 facilities) of U.S. emissions in 2010.	H.R. 2454		\$19.00		
CBO. 2009. Cost Estimate - S. 1733 Clean Energy Jobs and American Power Act. As ordered reported by the Senate Committee on Environment and Public Works. Washington, D.C. December 16. 31 pp.	As requested by the Senate Committee on Environment and Public Works, CBO developed a cost estimate over the period beginning 2010 through 2019 for the implementation of S. 1733. Specifically, S. 1733 proposes to establish a cap-and-trade programs designed to reduce emissions associated with seven (7) greenhouse gases. According to CBO's estimates, the program would cover about 72 percent (or 7,400 facilities) of U.S. emissions in 2010. For most years, S. 1733 and H.R. 2454 follow identical emissions caps, with the exception of year 2014 and between 2017 and 2019, when S. 1733 follows a more stringent cap - about 1 percent to 4 percent lower than the cap under H.R. 2454 in the same years.	S. 1733		\$23.00		
CBO. 2008. Cost Estimate - S. 2191 America's Climate Security Act of 2007. As ordered reported by the Senate Committee on Environment and Public Works. Washington, D.C. April 10. 24 pp.	As requested by the Senate Committee on Environment and Public Works, CBO developed a cost estimate over the period beginning 2009 through 2018 for the implementation of S. 2191. Specifically, S. 2191 proposes to establish a cap-and-trade program to limit or cap the volume of certain greenhouse gases emitted from electricity-generating facilities and from other activities involving industrial production and transportation. (approximately 2,000 to 3,000 facilities).	S. 2191	\$24.00	\$35.00		
Enkvist, P., T. Nauclér, and J. Rosander. 2007. A cost curve for greenhouse gas reduction. The McKinsey Quarterly. Number 1. 2007. p. 38.	This article aims to provide policymakers and other stakeholders an understanding of the significance and cost of the range of the technologies available to reduce emissions and the relative importance of different regions (including North America, Europe, and China) and sectors (including power generation, manufacturing industry, transportation, residential and commercial buildings, forestry, agriculture and waste disposal). The analysis spans three emission targets - 550, 450 or 400 parts per million.	550 ppm			\$18.24	
		450 ppm			\$29.18	
		400 ppm			\$36.47	
MIT. 2007. The Future of Coal: Options for a Carbon-Constrained World. Cambridge, MA. 175 pp.	This study examines the role of coal in a world where significant constraints are placed on emissions of CO2 and other greenhouse gases. In particular, the study focuses on the performance and cost of different coal combustion technologies when combined with an integrated system for CO2 capture and sequestration.	Low price trajectory	\$7.00	\$8.93	\$18.57	\$49.28
	In characterizing the CO2 emission price, this study uses two price trajectories: (1) a low trajectory starting at a price of \$7 per ton CO2 in 2010 and increasing at a rate of five percent thereafter; and (2) a "high" price trajectory that starts at \$25 per ton CO2 in 2015 and increases thereafter at a real rate of 4% per year.	High price trajectory		\$25.00	\$45.02	\$98.65

CHAPTER 1 | STUDY FRAMEWORK AND ANALYTIC METHOD

Chapter 1 introduces the study framework and orients the reader to the intricacies of the analytic method used to arrive at observations of calculated damages for the Jewett, TX FutureGen site. Specifically, the damages calculations underpinning the findings of this study rely on three key variables:

- **Valuation of Effects,** or the potential value of damages awarded per effect. This valuation may be based on medical costs, productivity losses, environmental damages, etc. Chapters 2 and 3 of this report discuss these elements in more detail, with particular focus on developing a range of possible damages per effect.
- **Number of Potential Effects**, or the degree of harm arising from a CO_2 leak. Chapters 4 through 6 discuss the potential plumes that may result from pipeline, plant, or sequestration events, and the associated number of resulting effects from exposure to this plume.
- **Event Probabilities**, or the likelihood that a specific release event or accident occurs in a given year. All else equal, the lower the probability (or likelihood) of an event occurring, the lower the damages that are likely to result. Chapters 4 through 6 of this report also focus on the probability of an event occurring at either the pipeline, plant, or sequestration site.

Chapters 3 and 4 provide additional detail on potential damages associated with groundwater and CO_2 leakage, given the greater levels of uncertainty in each of the above variables for those impact categories.

The remainder of this chapter focuses on the study's analytic method, with particular attention paid to the design and application of the Monte Carlo model, a well-accepted, probabilistic method used to quantitatively incorporate the effects of input parameter uncertainties into damages calculations. For a full technical description of the model, see Appendix B.

1.1 ANALYTIC METHOD

The damages calculations performed in this study use a set of linked mathematical equations through a 'spreadsheet model.' The model incorporates the potential magnitude of CO_2 and H_2S releases resulting from modeled events, event probabilities, estimated human health and ecological effects resulting from releases, and estimated costs arising from compensation for, or remediation of, these effects.

The analysis underpinning this study relies on publicly available information contained in environmental impact studies and risk assessments developed as part of DOE's FutureGen project. The FutureGen study uses a deterministic modeling approach (see Figure 1-1) to monetize harm to people and the environment using valuation methods from legal systems for accident compensation, natural resource damage assessments and cost-benefit studies. Key study parameters are summarized below:

- **Candidate Site.** Jewett, Texas DOE FutureGen site.
- **Plant Site Events.** Events singular to CCS (i.e., 'above and beyond' or incremental to what might be experienced by a similar plant without CCS capability).
- **Pipeline Events.** Two pipeline release scenarios: (1) a 'hole-puncture'; and (2) a complete severing of the pipeline.
- **Sequestration Site Events.** Variety of release mechanisms and pathways modeled in FutureGen analyses (e.g., aboveground injection equipment failure, injection well releases and other well releases).
- **Chemical Constituents.** CO_2 and H_2S.
- **Period of Analysis.** 100 years (50 years of injection operations, and 50 years post-injection, i.e., after cessation of injection operations).
- **Groundwater and Surface Water Modeling.** Bounding calculations to better understand the potential for groundwater damages; surface water addressed qualitatively because of the limited surface water resources present in the vicinity of the Jewett, TX site.

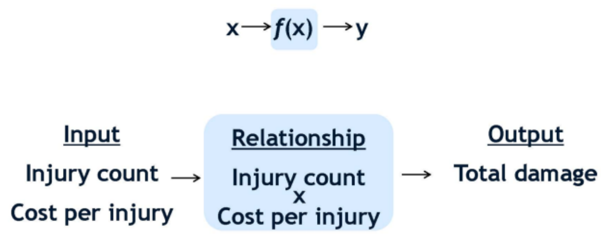
MONTE CARLO MODEL

This study generates monetized estimates of potential damages through use of Monte Carlo analysis, a well-accepted analytic method that introduces variation and uncertainty into the input parameters in order to improve upon the point estimates produced from a simple deterministic model. That is, improving upon the simple point estimates that describe a single, stable damage estimate from an array of input point estimates, this study estimates not merely a single, 'most likely', 'worst case', or 'best case' damage value but rather a continuous estimate of the varying probability associated with continuous points along the range of possible damage values.

In essence, a Monte Carlo model begins with a simple mathematical model that specifies calculations between an array of input variables in order to arrive at an output. In this study, example inputs are adverse plant events per year, cases of adverse health effects, or health costs per adverse effect. Examples of outputs include total groundwater damages, total health damages, or estimates of carbon offset values. While a simple deterministic model may use a single point estimate input such as an average health cost to create a single output estimate, a Monte Carlo uses ranges and probability distributions of inputs to estimate a detailed output value distribution. The detail afforded by the output distributions resulting from a Monte Carlo analysis may better serve project management by providing a more complete description of possible project outcomes in addition to estimated probabilities associated with each.

The detailed damage probability distribution is obtained from equally detailed input value distributions. Whereas a deterministic model relies on single, stable inputs in order to calculate a single, stable output value as illustrated in Figure 1-1, a stochastic or probabilistic analysis such as a Monte Carlo model allows for multiple inputs to calculate multiple outputs.

Figure 1-1. Example of a Deterministic Model



A deterministic model must use a measure of central tendency (such as a mean, median, or mode), an extreme value such as a maximum or minimum, or another method to choose a single value for each input variable. With only a single value for each input, the output similarly has only one value. Depending on the structure of the model used in the analysis, the properties of the resulting output value can be vague or unknown. For example, for some models, the output value resulting from the maximum of each input may not necessarily be the maximum possible output value. Similarly, the mean values of all input values may not necessarily produce the mean output value. Further, the use of averages may result in unrealistic input values such as fractions of human health effects, essentially assuming that a fraction of a person experiences an effect (see Figure 1-2).

Figure 1-2. Example of a Deterministic Model Using Average Inputs

	A	B	C	D	E	F
1	PIPELINE PUNCTURE DAMAGES CALCULATIONS		Scenario name:	Puncture		
2		Data Point	Source	Year 1	Year 2	Year 3
3		Pipeline Puncture Probability				
4	[B]	1.0%		0.01	0.01	0.01
5	HYDROGEN SULFIDE (H2S) EVENT CALCULATIONS					
6	H2S	H2S Damages - Fatal Effects				
7	[C]	# of Fatal Effects Per Event (xxx ppmv)		0.23	0.23	0.23
8	[D]	Total Number of H2S Fatal Effects	= [B] * [C]	0.0023	0.0023	0.0023
9	[E]	Damages Per Fatal Effect		$1,670,881	$1,670,881	$1,670,881
10	[F]	Total Damages from H2S Fatal Effects	= [D] * [E]	$3,895	$3,895	$3,895
11		H2S Damages - Irreversible Effects				
12	[G]	# of Irreversible Effects Per Event (xxx ppmv)		0.23	0.23	0.23
13	[H]	Total Number of H2S Irreversible Effects	= [B] * [G]	0.0023	0.0023	0.0023
14	[I]	Damages Per Irreversible Effect		$385,927	$385,927	$385,927
15	[J]	Total Damages from H2S Irreversible Effects	= [H] * [I]	$900	$900	$900
16		H2S Damages - Temporary Effects				
17	[K]	# of Temporary Effects Per Event (xxx ppmv)		14.34	14.34	14.34
18	[L]	Total Number of H2S Temporary Effects	= [B] * [K]	0.1434	0.1434	0.1434
19	[M]	Damages Per Temporary Effect		$16,234	$16,234	$16,234
20	[N]	Total Damages from H2S Temporary Effects	= [L] * [M]	$2,328	$2,328	$2,328
21		**Total H2S Damages per year**	= [F]+[J]+[N]	**$7,122**	**$7,122**	**$7,122**

In order to construct a more detailed estimate of the output value, a stochastic model repeats a deterministic model's calculation through multiple iterations. Each iteration varies input values by selecting at random many different input variables. Input values can be limited to the domain of each input; for example, limiting health effects to non-negative integers disallows fractions of human beings to be analyzed. Because many different values will be analyzed, the population mean can be approximated even while maintaining input selections only from the defined domain. That is, a scenario with a mean of 2.5 health effects can be analyzed with a set of integer inputs whose mean approximates the non-integer population mean.

Additionally, estimates of input value characteristics include probability distributions constructed from historical analysis or other research. Because each iteration chooses a value for each input variable according to the defined probability distribution, each iteration is equally likely. Thus, the resulting output values can be analyzed as a frequency distribution that approximates the true probability distribution of the outcome as specified by the model's structure and input values.

Figure 1-3. Example of Monte Carlo Inputs

A	B	C	D	E	F	G
PIPELINE PUNCTURE DAMAGES CALCULATIONS		**Scenario name:**	Puncture			
	Data Point	**Source**	**Year 1**	**Year 2**	**Year 3**	**Year 4**
	Pipeline Puncture Probability					
[B]	1.0%		1	0	0	0
HYDROGEN SULFIDE (H2S) EVENT CALCULATIONS						
H2S	H2S Damages - Fatal Effects					
[C]	# of Fatal Effects Per Event (xxx ppmv)		1.00	0.00	1.00	1.00
[D]	Total Number of H2S Fatal Effects	= [B] * [C]	1.0000	0.0000	0.0000	0.0000
[E]	Damages Per Fatal Effect		$534,630	$1,336,575	$935,603	$313,750
[F]	Total Damages from H2S Fatal Effects	= [D] * [E]	$534,630	$0	$0	$0
	H2S Damages - Irreversible Effects					
[G]	# of Irreversible Effects Per Event (xxx ppmv)		0.00	0.00	0.00	0.00
[H]	Total Number of H2S Irreversible Effects	= [B] * [G]	0.0000	0.0000	0.0000	0.0000
[I]	Damages Per Irreversible Effect		$387,544	$290,658	$9,689	$290,658
[J]	Total Damages from H2S Irreversible Effects	= [H] * [I]	$0	$0	$0	$0
	H2S Damages - Temporary Effects					
[K]	# of Temporary Effects Per Event (xxx ppmv)		45.00	50.00	2.00	1.00
[L]	Total Number of H2S Temporary Effects	= [B] * [K]	45.0000	0.0000	0.0000	0.0000
[M]	Damages Per Temporary Effect		$0	$17,003	$0	$0
[N]	Total Damages from H2S Temporary Effects	= [L] * [M]	$0	$0	$0	$0
	Total H2S Damages per year	= [F]+[J]+[N]	**$534,630**	**$0**	**$0**	**$0**

The use of Monte Carlo analysis provides a broad array of probability-based information that can inform evaluations and decision-making. For example, analysts are often interested in (and Monte Carlo results provide) reliable estimates of the 'mid-range' (50^{th} percentile) damages. The mid-range, 50^{th} percentile damage value lies in the distribution such that half of all calculated damage values are below and half are above the mid-range damage total. As opposed to a deterministic model's mid-range estimate, the Monte Carlo model identifies the damage value that appears in the middle of the full range of damage outputs, not merely the damage value calculated by holding input values at their respective means.

This summary report also provides Monte Carlo results for estimates of 'upper end' damages at the 95^{th} and 99^{th} percentiles. These points in the damage outcome distribution signify that 95% and 99% of damages calculated from the model are equal to or lower than the stated damages amount. Conversely, these statistics can be depicted as limiting values by virtue of the fact that, according to the model, there is only a five or one percent chance, respectively, that actual damages will be above these calculated damage values.

CHAPTER 2 | HUMAN HEALTH EFFECTS

This study considers effects to both human health and the environment. This Chapter focuses on the valuation of human health effects potentially caused by CO_2 and H_2S, arising from accident events at a CCS project in Jewett, TX. The objective of this analysis is to forecast the amount of money damages that a Texas jury would award members of the public (e.g., nearby residents) harmed by a release from the Jewett operation. This Chapter begins by providing an overview of the effects of CO_2 and H_2S and a discussion of applicable effects thresholds. It then discusses the sources relied upon to develop estimates of health effect values, including (1) medical costs; (2) productivity losses; and (3) non-economic losses. These health effect values underpin the calculations of damages per event in Chapters 4 through 6.

2.1 EFFECTS OF CO_2 AND H_2S EXPOSURE

The analysis considers two main chemical constituents, CO_2 and H_2S. IEc focused on these two constituents because the FutureGen risk assessment assumes that captured gas will be 95% CO_2 and 0.01% H_2S.[10]

Both CO_2 and H_2S can cause death, as well as other effects. Specifically:

- CO_2 can cause severe or permanent ('irreversible') effects such as convulsions and coma. CO_2 can cause minor or temporary ('adverse') effects such as headache, difficulty breathing and shortness of breath, increased blood pressure, tremors, and sweating.
- H_2S can cause severe or permanent ('irreversible') effects such as eye damage, pulmonary edema, poor memory, olfactory paralysis and tremors. H_2S can cause minor or temporary ('adverse') effects such as irritation of the eyes, mucous membranes and upper respiratory system; headaches and migraines; dizziness; sore throat; cough; fatigue; and nausea.

2.2 HEALTH EFFECT THRESHOLDS

Health effects *may* occur when people are exposed to concentrations that exceed inhalation thresholds, expressed in units of parts per million by volume, or ppmv. In evaluating health effects, FutureGen considers three severity levels:

- 'Adverse' effects are minor and temporary,

[10] FutureGen Final Risk Assessment Report, pg. 4-3.

- 'Irreversible' effects are severe and permanent, and
- 'Life-threatening' effects can result in death.

These levels generally are consistent with 'Protective Action Criteria' (PACs) set up by the U.S. Department of Energy (EPA), as well as with U.S. Environmental Protection Agency criteria. Exposure concentration by the three severity levels are summarized in Table 2-1.

As shown in Table 2-1, although CO_2 is the dominant constituent in captured gas, CO_2 is not a potent toxicant relative to the other constituents present in the CCS stream. Simply stated, relatively high concentrations of CO_2 are necessary to cause adverse impacts to human health. For example, as shown in Table 2-1, the CO_2 health effects thresholds in the FutureGen risk assessment range from 10,000 ppmv (adverse effects, chronic) to 70,000 ppmv (life-threatening effects, chronic). Normal atmospheric concentrations of CO_2 range from 300 to 400 ppmv.

In contrast, relative to CO_2 concentrations, H_2S is the more potent toxicant and likely would dominate most human health effects caused by a release from Jewett. For example, as shown in Table 2-1, the H_2S human health effects thresholds range from 0.0014 ppmv (adverse effects, chronic) to 50 ppmv (life-threatening effects, 15 minute exposure). For the above reasons, H_2S is the primary driver of estimated damages estimated in Chapters 4 through 6 for the Jewett, TX site.

Table 2-1. Summary of Threshold Effects by Constituent for Jewett, TX site

	15 Minute Exposure		8 Hour Exposure		Chronic Exposure	
Effect	CO_2	H_2S	CO_2	H_2S	CO_2	H_2S
Adverse	30,000	0.51	20,000	0.33	10,000	0.0014
Irreversible	30,000	27	20,000	17	50,000	0.0014
Life-threatening	40,000	50	40,000	31	70,000	0.0014

These thresholds were drawn from a variety of sources, including:

- Fifteen minute exposure thresholds are drawn from Temporary Emergency Exposure Limits (TEELs) developed by the U.S. DOE.
- Eight hour exposure thresholds for H_2S are drawn from Acute Exposure Guideline Levels (AEGLs) developed by U.S. EPA and reviewed by the National Academy of Science.
- Chronic exposure thresholds for H_2S are drawn from U.S. EPA Reference Concentrations (RfCs).
- The CO_2 eight hour and chronic thresholds are drawn from EPA research on fire suppression systems, and other scientific literature.

All thresholds aim to protect the general population, *including susceptible individuals*.

In general, thresholds are based on the relationship between the dose received and the individual's response. Ideally, in determining appropriate effect thresholds, IEc would quantify the relationship between the dose of CO_2 and H_2S received, and the incidence of health effects. However, there are many difficulties with quantifying this relationship, including:

i. What health effects are most important?

ii. What exactly is 'dose' and 'response?'

iii. Individuals vary greatly; how to estimate population dose-response?

iv. What human and animal data are available, and how to judge data quality?

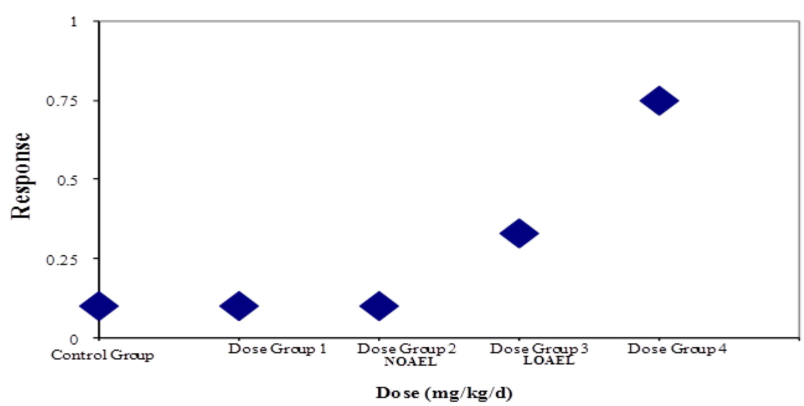
v. How to extrapolate to different doses and across species?

vi. Are there synergistic or antagonistic effects between the toxicants?

vii. What is the shape of the dose-response function (e.g., linear or logarithmic curve)?

In developing these curves, the objective is to determine the 'safe' level of exposure. One (or more) 'best' dose-response data sets are selected, and a 'point of departure' (POD) is identified. The no observed effect level (NOAEL) or lowest observed effect level (LOAEL) often is used as the POD (see Figure 2-1).

Figure 2-1. Example Dose Response Curve



Thresholds are computed by applying a series of adjustments called 'uncertainty factors,' denoted as UF, to the POD (see Figure 2-2 for an example). These adjustments account for the need to scale from animals to humans, account for human heterogeneity, and deal with inadequacies in the available data. Uncertainty factors often equal 10, resulting in order of magnitude adjustments.

Figure 2-2. Example Threshold Calculation

$$Threshold = \frac{POD}{UF_A * UF_H * UF_D}$$

CAVEATS AND AREAS OF UNCERTAINTY

Thresholds are designed to be 'protective.' Therefore, conservative assumptions are adopted repeatedly during their derivation. For example, thresholds do not reflect variations in human susceptibility. Instead, thresholds are set to protect the most susceptible individuals. In addition, differences in severity of health effects are difficult to reflect in thresholds. Generally thresholds are based on the first adverse effect caused by increasing dose. As a result, thresholds will *overestimate* the number and severity of health effects that would occur if the general population is exposed to CO_2 or H_2S.

Due to many theory and data limitations, thresholds are highly uncertain, with professional judgment playing a key role in threshold calculations. This uncertainty is not reflected in the single number thresholds used in the FutureGen report.

The results presented in the rest of this report are based on the FutureGen thresholds, and thus *overestimate* health effects to an unknown degree. To refine these estimates, it would be possible, for well-studied chemicals (such as H_2S), to develop dose-response distributions that better reflect both variability and uncertainty. Developing a dose-response distribution would be a major undertaking, and may not be possible for CO_2.

That said, the use of FutureGen thresholds may be appropriate from a legal perspective. Legally, damages may be awarded based on exceeding thresholds rather than 'proven' health effect incidence. That is, to be awarded damages, a claimant may not need to prove he/she experienced an actual health effect as long as a particular health threshold was exceeded.

2.3 VALUATION OF HEALTH DAMAGES

This section discusses the potential range of health damages that may be awarded in the event of a release event. It begins by discussing the types of awards allowed under Texas law. It then summarizes the data sources used to develop health effect values. It concludes by developing a range of potential health effect values that underpin the damages calculations in the rest of this report.

HEALTH DAMAGES ALLOWED UNDER TEXAS LAW

In determining the appropriate amount of damages per health effect, IEc researched the amount of money damages a Texas jury would potentially award nearby residents harmed by a release from Jewett. IEc found that Texas guidelines for money damages in personal injury and wrongful death cases generally are consistent with other states.

In *personal injury cases* Texas plaintiffs are entitled to:

- Loss of past and future earning *capacity*,
- Past and future medical expenses;
- Compensation for past and future physical pain and mental anguish, disfigurement, and physical impairment.
- Plaintiff's spouse is entitled to loss of past and future household services, and past and future loss of consortium.

In *wrongful death* cases, Texas plaintiffs are entitled to loss of past and future pecuniary support and loss of inheritance.

- **Pecuniary support** includes care, maintenance, support, services, advice, counsel, and pecuniary contributions that would have been received from the Deceased had he or she lived.
- **Loss of inheritance** includes the present value of assets that would have been added to the estate of the Deceased and left to the plaintiff.

In our view, allowed damages for personal injury and wrongful death in Texas are functionally equivalent.

Notably, Texas requires future losses to be converted to a present value, but past losses are not adjusted for time value. Texas does not provide guidance on the appropriate discount rate to use in these present value calculations. Therefore, per case (or effect), this analysis assumes that health damages may include: (1) medical costs, (2) productivity losses, and (3) non-economic losses.

- **Medical costs** include the past and future medical expenses incurred due to the injury or death.
- **Productivity losses** include past and future diminished earning capacity, including the value of lost fringe benefits; plus value of lost household services; less earnings and services the victim would have consumed but for his/her injury or death.
- **Non-economic losses** include compensation for physical pain and impairment, mental anguish, disfigurement, loss of consortium, loss of advice and counsel, and similar losses.

DATA SOURCES

IEc conducted a computerized literature search to locate studies and databases describing jury awards in personal injury and wrongful death cases, both for the U.S. overall and for Texas. IEc could not locate valuation data for the specific health effects and jurisdiction of interest (i.e., Jewett area). Useful data are available from other jurisdictions, although each data set has limitations and no single data source is sufficient to meet our valuation needs.

In lieu of jury awards, we rely on three key data sources to develop our estimates of potential damages. We draw our estimates of medical expenses and lost productivity from The Incidence and Economic Burden of Injuries in the United States by Eric A. Finkelstein, Phaedra S. Corso, Ted R. Miller, and Associates, Oxford University Press, 2006 ('Finkelstein *et al.*'). We draw our estimates of non-economic damages from 'The Consumer Product Safety Commission's Revised Injury Cost Model' by Ted R. Miller *et al.*, a report submitted to the Consumer Product Safety Commission in December 2000 ('Miller *et al.*'). Finally, we compare our estimates with awards made by the 9/11 Commission found in 'Final Report of the Special Master for the September 11th Victim Compensation Fund of 2001, Volume I' by Kenneth R. Feinberg, Esq. *et al.*, undated ('9/11 Fund'). These data sources are discussed in greater detail below.

Finkelstein et al

Finkelstein *et al*. consider a broad range of injuries such as fractures, dislocations, internal injuries, open wounds, burns, traumatic complications, poisonings, and toxic effects of nonmedicinal substances; but do not include chronic diseases such as cancer, heart disease or diabetes. The study considers three severities:

- Injuries resulting in death, within or outside a health care setting,
- Injuries resulting in hospitalization, with survival to discharge, and
- Injuries receiving medical attention in an emergency department visit, a hospital outpatient visit or a visit to a doctor's office.

IEc equates these three severities to the adverse, irreversible and life-threatening severities used in FutureGen.

Notably, the Finkelstein *et al*. data that underlie our values do not include:

- Injuries for which no medical treatment was given,
- Mental health or psychological treatment costs, and
- Expenses and productivity losses for caregivers (other than medical professionals).

In addition, productivity losses are based on actual wages rather than earnings potential, resulting in possible understatement for women and retirees.

The Finkelstein *et al*. data are based on multiple, disparate data sets as well as many professional judgments by Finkelstein and his collaborators. While best efforts were used, resulting biases and errors are unknown. As a result, formal treatment of uncertainty using the Finkelstein *et al*. data is not possible. Instead, we rely on a general characterization of the 'spread' in the data as well as our professional judgment.

Medical Expenses and Lost Productivity Estimates

Finkelstein *et al*. estimate *medical expenses* (2000$) using data from a multitude of sources. Thus, no standard errors can be generated for the expense estimates. Finkelstein *et al*. estimates of lifetime *lost productivity* (2000$) include lost wages (including future growth due to productivity increases), the lost value of fringe benefits, and the value of lost household work. The values are summarized in Table 2-2. Again a multitude of data sources are used and no standard errors are generated for the lost productivity estimates.

Table 2-2. Finkelstein et al Estimates of Medical Expenses and Lost Productivity

Injury Severity	Medical Expenses	Lost Productivity	Total
Fatal	$7,463	$952,820	**$960,283**
Hospitalized	$18,042	$31,402	**$49,444**
Non-Hospitalized	$944	$2,604	**$3,548**

IEc compared the estimates derived from Finkelstein *et al*. with awards made by the 9/11 Fund. The 9/11 Fund made 2,880 death awards and 2,680 injury awards. These awards included medical expenses, lost earnings, and non-economic compensation based on $250,000 per victim plus $100,000 for each dependent of the victim, including the spouse. (All figures are 2000$.) While the Finkelstein *et al*. figures do not include non-economic damages, the 9/11 Fund awards appear to be relatively in line with the Finkelstein *et al*. estimates (see Table 2-3)

Table 2-3. Comparison of 9/11 Awards and Finkelstein et al Estimates

	9/11 Fund Minimum	9/11 Fund Maximum	9/11 Fund Mean	9/11 Fund Median	Finkelstein et al
Death	$250,000	$7,100,000	$2,082,035	$1,677,633	$960,283
Injury	$500	$8,597,732	$392,968	$108,747	$49,444

Miller et al

We draw our estimates of non-economic damages from 'The Consumer Product Safety Commission's Revised Injury Cost Model' by Ted R. Miller *et al*., a report submitted to the Consumer Product Safety Commission in December 2000 ('Miller *et al*.'). Miller *et al*. estimate *non-economic costs* using data from jury awards for 'pain and suffering' in 655 cases adjudicated between 1988 and 1995 in the U.S. All cases involved consumer products. Miller *et al*. use these data to estimate a log-linear regression model to predict pain and suffering awards as a function of demographic, product-specific and injury-specific variables. The final regression includes 34 variables and accounts for 56% of the variation in pain and suffering awards.

Stated in 2000$, pain and suffering awards ranged from $243 to $43,731,422, with a mean value of $679,248 and a median value of $105,083. We then use these values to develop a range of non-economic damages.

2.4 PRELIMINARY DAMAGE ESTIMATES

Figure 2-3 below illustrates our estimated range of damages per fatality, and the estimated probability of these damages being awarded. To develop this range, minimum and maximum values are set at the 9/11 Fund minimum and maximum awards, inflated to 2010$. The most likely estimate (MLE) is set at Finkelstein *et al*. average cost, plus $105,000 in non-economic damages, inflated to 2010$.

The distribution of damages assumes a standard deviation equal to 0.3 of the most likely estimate. The curve is set to achieve a 60% probability of values within one standard deviation, and an 85% probability of values within two standard deviations. Finally, IEc fit the curve to the minimum and maximum values derived from the 9/11 awards.

Figure 2-3. Range of Damages per Fatality

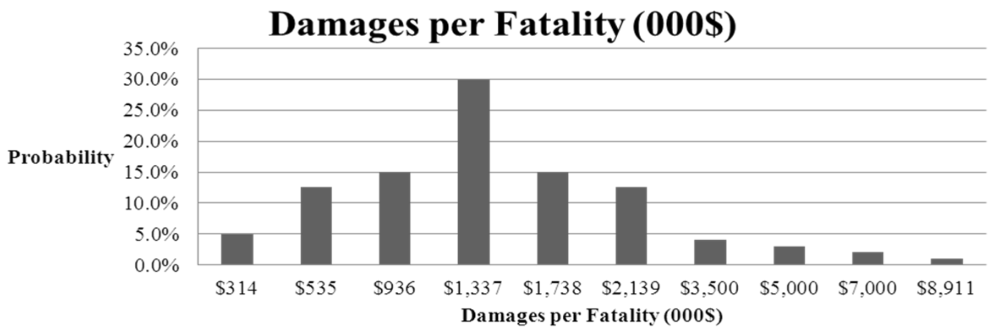
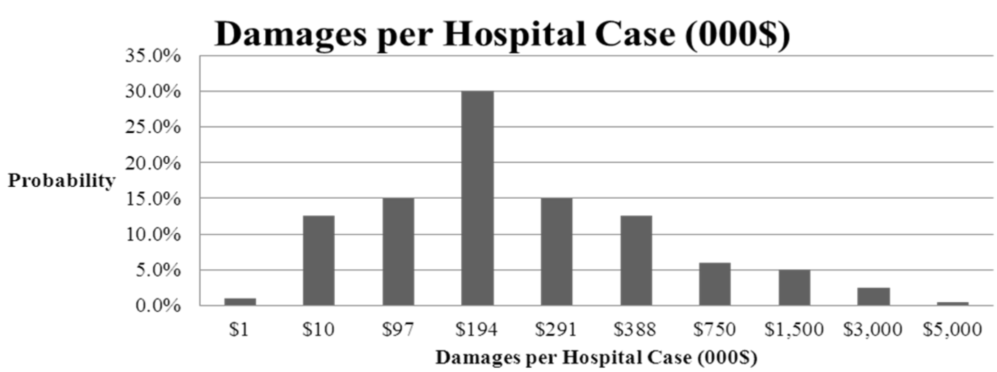


Figure 2-4 below illustrates our estimated range of damages per hospitalized health effect, and the estimated probability of these damages being awarded. To develop this range, we applied a similar methodology as for fatalities. The minimum value was set to $1,000, and the maximum award to $5 million.[11] The most likely estimate (MLE) is set at Finkelstein *et al*. average cost, plus $105,000 in non-economic damages, inflated to 2010$.

The distribution of damages assumes a standard deviation equal to 0.5 of the most likely estimate. The curve is set to achieve a 60% probability of values within one standard deviation, and an 85% probability of values within two standard deviations. Finally, IEc fit the curve to the minimum and maximum values.

Figure 2-4. Range of Damages per Hospital Case

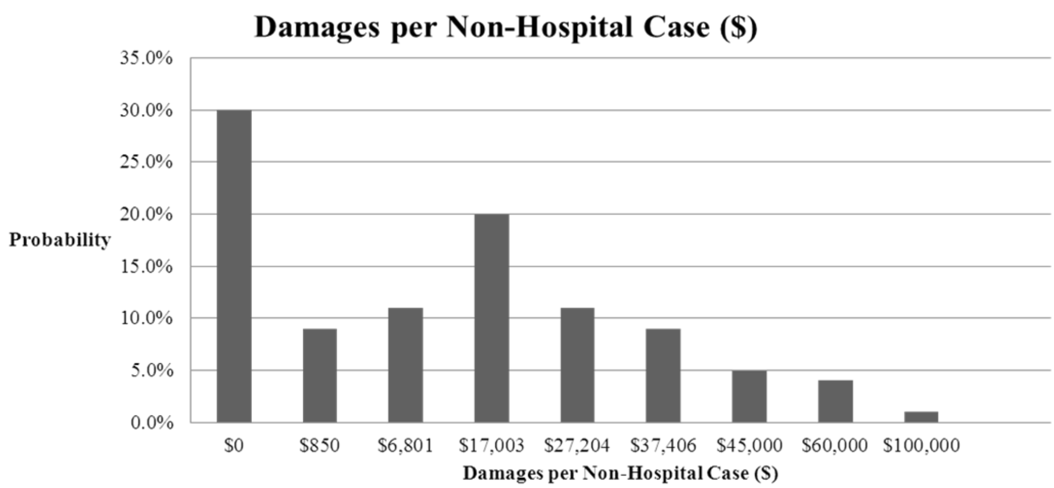


[11] 9/11 Fund minimum award was $628 in 2010$, while the 9/11 Fund maximum award was $11 million in 2010$.

Figure 2-5 below illustrates our estimated range of damages per non-hospitalized health effect, and the estimated probability of these damages being awarded. To develop this range, we applied a similar methodology as for fatalities and hospitalized health effects. First, we assume that 30% of victims do not claim any compensation. For victims that do seek compensation, the minimum value was set to $850, and the maximum award to $100,000, based on professional judgment. The most likely estimate (MLE) is set at Finkelstein *et al*. average cost, plus $10,000 in non-economic damages, inflated to 2010$.

The distribution of damages assumes a standard deviation equal to 0.6 of the most likely estimate. The curve is set to achieve a 60% probability of values within one standard deviation, and an 85% probability of values within two standard deviations. Finally, IEc fit the curve to the minimum and maximum values.

Figure 2-5. Range of Damages per Non-Hospital Case



CHAPTER 3 | GROUNDWATER

FutureGen analyses conclude that there is a low potential for damages to groundwater at the Jewett, TX sequestration site. As a result, they do not attempt to quantify the potential severity or magnitude of impacts that would arise in the unlikely event of a release into groundwater. In recognition of the potential for some level of groundwater impacts, the Monte Carlo analysis incorporate bounding calculations designed to broadly assess potential groundwater damages arising from CCS at the Jewett, TX site.

3.1 OVERVIEW OF ESTIMATION METHODOLOGY

The bounding calculations in the Monte Carlo model:

- Assume groundwater exposure to sequestered constituents; and
- Rely on publicly available information about aquifer characteristics at the sequestration site.

The analysis also considers additional factors that affect groundwater valuation, in light of methods commonly applied in litigation. Figure 3-1 illustrates the typical approach used when valuing groundwater damages, while Table 3-1 summarizes the different methods available to estimate damages to groundwater. Definitions of terms used in Figure 3-1 include:

- **Extractive Use Value.** Value derived from direct human use of groundwater resources.
- **Existence Value and Bequest Value.** Value public holds for groundwater independent of own use (i.e., even if no plan to use the water).
- **Option Value.** Value primarily derived from the public willingness to pay to reduce future risks of adverse outcome. Function of both use and non-use values.

3.2 DATA SOURCES

There are some publicly available data on the location of groundwater receptors surrounding the Jewett site. In particular, the Texas Water Development Board provide information on the location of groundwater wells, as well as information about the chemical characteristics of these wells, including measures of the wells' pH, hardness, etc. A summary of these data is provided in Figure 3-2 (see page 3-3).

Figure 3-1. Groundwater Valuation Approach

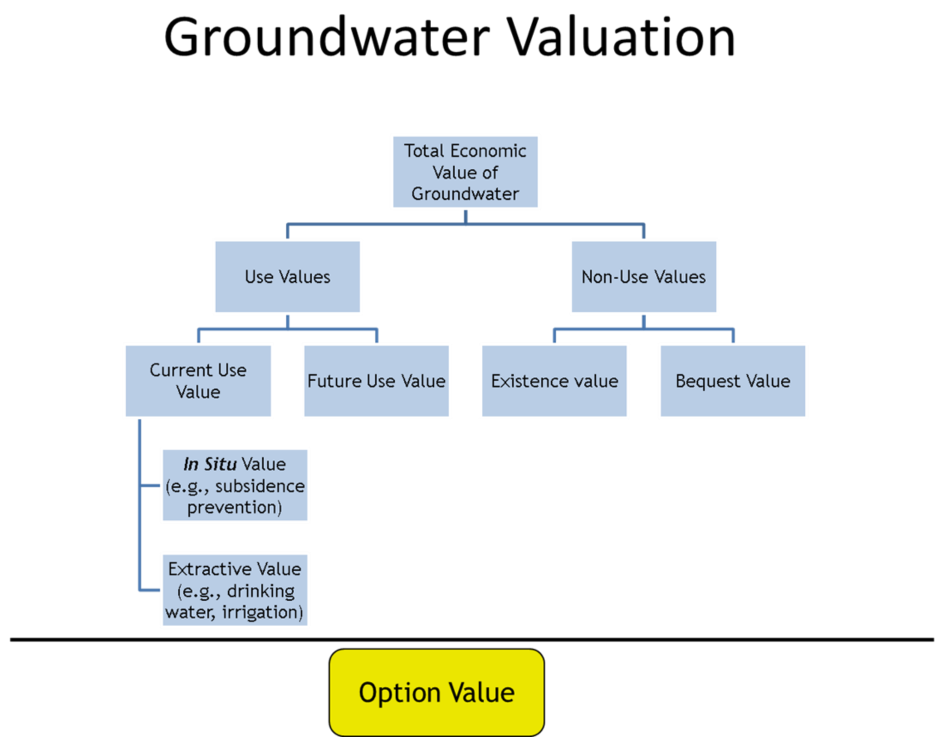
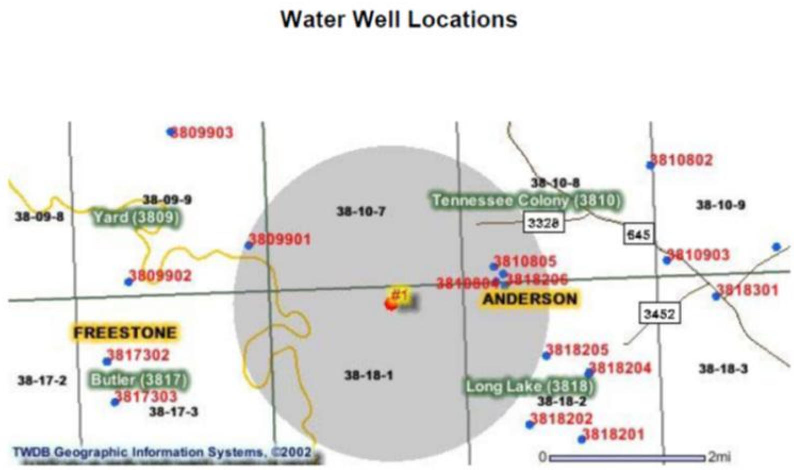


Table 3-1. Methods for Groundwater Valuation

Approach	Application
Treatment Cost	The cost of treatment either *in situ* or at wellhead/point of use.
Added cost	Contamination can impose added costs on current and future water users (e.g., cost of treatment or access to a substitute source of water).
Market Price	The application of observed prices in competitive markets. Limited to locations with active water markets.
Stated preference	Values derived through surveys of the public.
Hedonic property analysis	Econometric analysis of patterns in residential property prices to reveal environmental amenity/disamenity.
Benefits transfer	Application of existing valuation literature in a new setting. Values based on the methods listed above.
Replacement cost	Damages based on cost to restore, replace or acquire the equivalent of the injured resource, such as cost to protect an aquifer of equivalent yield and quality.

Figure 3-2. Publicly Available Data on Well Location



No.	STATE WELL NUMBER	YEAR	SAMPLE NUMBER	SILICA MG/L	CALCIUM MG/L	MAGNESIUM MG/L	SODIUM MG/L	CARBONATE MG/L	BICARBONATE MG/L	SULFATE MG/L	CHLORIDE MG/L	FLUORIDE MG/L	NITRATE MG/L	PH	TDS MG/L	PHENOLPHTHALEIN ALKALINITY	TOTAL ALKALINITY	TOTAL HARDNESS	PERECNT SODIUM	SAR	RSC	SPECIFIC CONDUCTANCE
Wells Inside the 2 mile buffer																						
1	3810805	1994	1	13	1.7	0.4	240	13	456	0	75	0.5	0	8.5	567	10.83	395.32	5	98	43.03	7.79	1100
2	3810805	1994	1		27	< 1	278	16.8	580.88	12	77	0.6	0.04	8.6	698	14	504	71	89	14.3	8.65	1251
1	3810803	1982	1		2.4	0.5	258	19.2	523.53	13	67	0.6	0.5	8.6	618	16	461	8	98	39.57	9.06	1000
1	3810804	1981	1		1.6	1	253	24	507.66	6	68	0.5	0	8.7	603	20	456	8	98	38.65	8.96	861
1	3818206	1978	1	14	2	0	253	0	543.05	1	76	0.5	< 0.1	8.1	613	0	445	5	99	49.27	8.8	1030
Wells Near the 2 mile buffer																						
1	3818203	1983	1		2.4	1	290	12	497.9	28	130	0.3	0	8.3	708	10	428	10	98	39.69	8.36	1200
1	3818202	1970	1	13	35	8	19	0	124.48	43	16	< 0.1	< 0.4	7.3	197	0	102	120	25	0.75	0	346

3.3 POTENTIAL IMPACTS TO GROUNDWATER

This analysis considers four potential impacts to groundwater: (1) diminished pH, (2) increased levels of H_2S, (3) dissolved metals, and (4) increased total amount of dissolved solids and/or hardness. These potential impacts are discussed in greater detail in the following sections.

POTENTIAL IMPACT – DIMINISHED PH

The secondary drinking water standard (MCL) for pH is between 6.5 and 8.5. Released CO_2 potentially could reduce pH below the lower regulatory threshold. The amount of pH reduction will depend directly on the amount of carbonate mineral material in the aquifer matrix.

- If above 1% by weight, pH is unlikely to change.
- If virtually no carbonate materials were present, pH might be lowered to about 3.5 near the area of the infusion with CO_2.

Readily available information suggests the matrix for the Jewett site exceeds 1% carbonate minerals. To confirm this finding, physical sampling of the aquifer matrix would be required, along with laboratory buffering capacity experiments.

POTENTIAL IMPACT – INCREASED H_2S

Currently there is no secondary drinking water standard for H_2S, and H_2S is not considered a risk to human health or the environment at water solubility levels. If present above 1 ppm, H_2S can cause undesirable odor problems and corrosion or tarnishing of metals and staining.

Bounding calculations indicate that maximum H_2S concentrations resulting from a release could exceed the odor/staining threshold. However, H_2S concentrations are unlikely to exceed five ppm. Notably, inexpensive point-of-use treatments are available to reduce H_2S. That said, there appears to be little residential use of groundwater at the sequestration site, which would also reduce potential impacts associated with increased H_2S levels.

POTENTIAL IMPACT – DISSOLVED METALS

Sequestration site groundwater contains detectable concentrations of trace metals, such as arsenic, beryllium, cadmium, lead and manganese. More than 90% of measured concentrations of these trace metals are below the applicable MCLs. Greater amounts of these metals could be dissolved from the aquifer minerals into the water if the pH were lowered sufficiently to cause dissolution.

That said, these types of impacts would only occur if aquifer matrix carbonate mineral content were less than 1%, which does not appear to be the case for the Jewett site. As noted previously, aquifer matrix sampling and associated laboratory buffering capacity would be needed to confirm this finding.

POTENTIAL IMPACT – INCREASED TDS AND/OR HARDNESS

In concept, dissolution of CO_2 into the aquifer water could raise the total amount of dissolved solids and/or hardness to a level that renders the water unusable or undesirable. Bounding calculations indicate that the maximum concentration of dissolved solids would be in the range of the solubility limit of calcium bicarbonate, which is about 166 grams per liter (166,000 ppm). This scenario clearly renders the water undrinkable and unusable for most common applications.

However, this potential impact would be limited to a very localized zone in the vicinity of the conveyance pathway of the released CO_2. Such impacts could be mitigated by point-of-use treatment (water softening ion exchange), water blending, or alternate water supplies.

3.4 POTENTIAL GROUNDWATER DAMAGES

If a release to groundwater occurs as part of the Monte Carlo trials in this study, damages are assumed to include the costs necessary to stop the release, and costs necessary to address the impacts of the release to groundwater and groundwater services.

With respect to the costs to stop a release, the Monte Carlo model assigns a 90% likelihood that the cost will be between $50,000 and $300,000 by randomly choosing a cost within that range for each event.[12] Occasionally, abandoned oil & gas or other

[12] See Appendix A.

wells will require more complicated, expensive actions to address a release. The model in this study assigns a 10% likelihood that the cost to repair/address a leak from such wells will be between $2,000,000 and $3,650,000 by randomly choosing a cost within that range for each event.[13]

A more detailed assessment of additional site-specific monetary damages arising from impacts to groundwater require data that are not readily available for the Jewett, TX site. Notwithstanding the inability to gather such site-specific data, the Monte Carlo calculations use bounding estimates to arrive at reasonable proxies for potential groundwater damages at the Jewett,TX site. These bounding estimates reflect information that is publically available, as well as expert professional judgment based on IEc's extensive experience with groundwater damages cases.

If a release potentially impacting groundwater resources occurs in a Monte Carlo trial, damages are assigned in the following manner: $50,000 (75% probability), $500,000 (20% probability) or $5,000,000 (5% probability).

A variety of factors influence these damages estimates. Specifically, the 'low' estimate ($50,000) applies to all of the following scenarios:

- A release occurs, but the release volume into groundwater prior to detection/corrective action is too low to cause adverse impacts; or
- A release occurs in subsurface areas that do not contain useable groundwater resources; or
- A release occurs in subsurface areas that contain useable groundwater resources, but the CCS project proponent owns the water rights for the affected area.

The costs associated with these scenarios reflect relatively modest costs to investigate the release and confirm the lack of potential impact to groundwater resources.

The 'moderate' and 'high' damages estimates ($500,000 and $5,000,000, respectively) reflect circumstances where adverse potential or actual impacts to groundwater resources, not under the control of the project proponent, require actions to address the impact. Such actions may include point-of-use treatment, plume containment, groundwater mixing, pump and treat, or providing alternate water, etc. In addition, groundwater rights owners may need to be otherwise compensated for any reductions in groundwater quality and/or availability. Although groundwater contamination cases in other parts of the country have resulted in damages substantially exceeding the amounts used in this analysis, in our view, several site-specific factors act to limit the potential magnitude of damages at the Jewett, TX sequestration location, including but not limited to:

- Prior to the sequestration project moving forward, project sponsors likely would exercise their existing options to purchase groundwater rights in the sequestration area;

[13] See Appendix A.

- Groundwater surrounding the Jewett, TX sequestration site currently is not used for commercial, industrial, or other purposes;
- The sequestration site and surrounding area has very few residences;
- Publicly available groundwater sampling data from the area suggest a high likelihood that carbonate minerals in the matrix exceed 1%, providing a natural buffering capacity that substantially limits the potential for pH-related impacts; and
- Inexpensive point-of-use treatment technologies are readily available for the types of impacts that might occur.

CHAPTER 4 | CO_2 LEAKAGE

This chapter addresses calculated damages arising from CO_2 leakage. The FutureGen Risk Assessment provides estimates of potential leakage rates for a variety of release mechanisms. However, the FutureGen reports do not quantify the potential volume of CO_2 that could be released to the atmosphere in the event of such a release. Further, the magnitude of potential future damages due to CO_2 leakage will depend on the design and implementation of a greenhouse gas (GHG) regime. The timing and specific design of any such program in the U.S. is uncertain. Nevertheless, in recognition of the potential for damages arising from CO_2 leakage within the 100 year timeframe of this analysis, the Monte Carlo analysis includes a series of bounding calculations designed to broadly assess potential CO_2 leakage damages arising from CCS at the Jewett, TX site

4.1 COST OF CARBON

Two sources of information can help bound potential unit values ($/ton) for leaked CO_2 in the U.S.:

- U.S. Government Interagency Working Group on Social Cost of Carbon report (February 2010); and
- Predictions of CO_2 allowance prices in future decades, based on regulatory scenarios contemplated in the U.S.

Estimates of the social cost of carbon from the U.S. Government Interagency Working Group on Social Cost of Carbon report are presented in Table 4-1. This report, developed by a wide range of governmental agencies, including CEA, CEQ, DOA, DOC, DOE, DOT, EPA, NEC, OECC, OMB, OSTP, Treasury, is intended to allow agencies to incorporate the social benefits of reducing carbon dioxide (CO_2) emissions into cost-benefit analyses of regulatory actions that have small, or 'marginal,' impacts on cumulative global emissions. At a minimum, these estimates attempt to include changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change.

In recent years, numerous entities have developed predictions of CO_2 allowance prices. Several entities (e.g., CBO, EPA, individual researchers) made allowance price forecasts based on requirements in legislative proposals, including H.R. 2454, S. 1733, S.2191. Others such as McKinsey at MIT, developed estimates without regard to specific legislative proposals. A table summarizing these estimates is provided in the Executive Summary (see Executive Summary Attachment 1). Generally, these values fall within the (broad) range identified in the Social Cost of Carbon report, although some present 'upper end' estimates that, for some years, exceed the highest values presented in Table 4-1.

Table 4-1. Social Cost of Carbon Per U.S. Govern Interagency Working Group

Social Cost of CO_2, 2010 – 2050 (in 2007 dollars)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

The Monte Carlo analysis used in this analysis relies on the schedule of offset prices identified in Table 4-2, based on information in Nordhaus (2010). A range of prices based on the schedule in Table 4-2 is assigned to every year in the 100-year period analyzed in this study, assuming 'straight-line' price changes in the years between those identified in the table. If a CO_2 leakage event occurs as part of a Monte Carlo trial in this study, an offset price is chosen randomly from within the specified range for the year associated with the release.

4.2 CO_2 LEAKAGE QUANTITIES

The magnitude of potential future damages due to CO_2 leakage also will depend on the amount of CO_2 released into the atmosphere. The FutureGen Risk Assessment provides estimates of potential leakage rates for a variety of release mechanisms. These estimates are based on site-specific analysis and review of natural and industrial CO_2 storage analogs (see Table 4-3). For well events, they reflect flux rates to surface. For other events, they reflect flux rates to subsurface receptors.

However, the FutureGen analyses do not attempt to estimate: (1) the proportion of leaks expected to be observed and stopped; (2) the release duration; or (3) the fraction of leaked volumes that ultimately reach the atmosphere. Further, potential damages arising from CO_2 leakage at the sequestration site are likely to be substantially dependent on the type, density and duration of attendant monitoring efforts at the site.

Table 4-2. Range of CO_2 Offset Prices used in Monte Carlo Analysis

	Low	High
Year	\$/tonne CO_2	\$/tonne CO_2
2015	10.28	21.49
2025	17.46	38.58
2035	24.12	61.45
2045	32.21	95.50
2055	41.85	144.45
2065	53.15	201.31
2075	66.30	273.04
2085	81.40	321.71
2095	98.49	253.46
2105	117.43	197.30
2115	137.95	193.21

Source: Nordhaus 2010, 'Economic aspects of global warming in a post-Copenhagen environment', Proceedings of the National Academy of Sciences, 107(26): 11721-11726.

The 'low' and 'high' estimates reflect the 'optimal 600 ppm' and 'limit to 2 degrees' scenarios identified in Nordhaus, 2010. The optimal path in Nordhaus, 2010 peaks at just under 600 CO_2 ppm in around 2080, before stabilizing at around 500 ppm in 2200.

Researchers have attempted to estimate bounds for potential CO_2 leakage volumes. For example, Dooley and Wise (pg. 3) state:

> In one of the most comprehensive studies to date looking at CO_2 sequestration in relationship to enhanced oil recovery, Stevens et. al. [10] "conservatively estimate that 10% of net CO_2 purchased is emitted" during the lifetime of EOR operations in a field. It is critical to note that in the context of the Stevens' study which was principally focused on the economics of using CO_2 for hydrocarbon recovery, the 10% figure should be interpreted as the authors' estimate of an upper bound for leakage from this class of reservoirs and indeed Stevens and his coauthors note that "the actual percentage may be lower."

Table 4-3. Flux Rates by Event Type

Site	Mechanism	Annual Flux if Event Occurs Minimum (MT/yr)	Annual Flux if Event Occurs Maximum (MT/yr)
Jewett	Leakage via Upward Migration through Caprock due to Gradual and slow release	0	4,918
	Leakage via Upward Migration through Caprock due to catastrophic failure and quick release	NA	NA
	Leakage through existing faults due to increased pressure (regional overpressure)	118	3,526
	Release through induced faults due to increased pressure (local overpressure)	24	705
	Leakage into non-target aquifers due to unknown structural or stratigraphic connections	2,350	79,910
	Leakage into non-target aquifers due to lateral migration from the target zone	28,928	867,845
	Leaks due to deep CO_2 wells, high rate	11,000	11,000
	Leaks due to deep CO_2 wells, low rate	200	200
	Leaks due to deep O&G wells, high rate	11,000	11,000
	Leaks due to deep O&G wells, low rate	200	200
	Leaks due to undocumented deep wells, high rate	11,000	11,000
	Leaks due to undocumented deep wells, low rate	200	200

The IPCC Special Report on CCS (2005) estimates that appropriately selected and managed geologic reservoirs are very likely to exceed 99% over 100 years (pg. 14). Overall, site-specific data and information from the general technical literature are insufficient to assign precise probabilities to potential leakage volumes. Nonetheless, this study applies an array of leakage volume estimates in order to bound resulting damages estimates. In the absence of site-specific data, the bounding estimates identified below are used in the Monte Carlo analysis underpinning this study:[14]

- If a pipeline rupture or puncture occurs, all of the CO_2 in the affected 5 mile section of pipeline (1,290 tonnes) is assumed to be released to the atmosphere;[15]
- If an injection well release occurs during the operational period (2011 – 2060), the Monte Carlo analysis randomly assigns a release volume to the atmosphere between 0.1 and 16.5 tonnes of CO_2;
- If an injection well release occurs between 2061 and 2110, the Monte Carlo analysis randomly assigns a release volume to the atmosphere between 0.6 and 99 tonnes of CO_2;
- If an 'other well' release occurs at any time in the analysis period (2011 – 2110), the Monte Carlo analysis randomly assigns a release volume to the atmosphere between 99 and 5,400 tonnes of CO_2.

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[14] See Appendix A.

[15] The FutureGen Risk Assessment indicates that the volume of CO_2 released during a pipeline incident (1,290 tonnes) reflects the volume present in between safety shutoff valves placed every 5 miles along the pipeline. Although some of the CO_2 released would be in solid phase, the Monte Carlo analysis conservatively assumes that all CO_2 would eventually vaporize.

Other release events within the 100 year period of analysis have low probabilities and/or atmospheric release volumes, resulting in a negligible contribution to potential CO_2 leakage damages.

CHAPTER 5 | OTHER POTENTIAL DAMAGES

This Chapter addresses the derivation of other potential damages, including potential environmental response and remediation costs, damage to public/private property, and other damages categories unrelated to human health, groundwater or CO_2 leakage. Notably, pipeline accidents are the key data source underlying the damages distribution derived for these types of impacts, and the best proxy for similar types of impacts that could result from plant site accidents and surficial releases at the sequestration site.

5.1 OFFICE OF PIPELINE SAFETY DATA

As noted above, pipeline accidents are the key data source underpinning the damage distribution for non-human health damages. Data on pipeline accidents is available through the Office of Pipeline Safety. Since 2002, pipeline operators have been required to report pipeline accidents if they result in any of the following consequences:

- explosion or fire not intentionally set by the operator;
- release of 5 gallons or more of hazardous liquid or carbon dioxide;
- death of any person;
- personal injury necessitating hospitalization; or
- estimated property damage, including cost of clean-up and recovery, value of lost product, and damage to the property of the operator or others, or both, exceeding $50,000.

FutureGen reviewed accident data from 1994 through 2006 to estimate pipeline accident probabilities. These accident data identified 31 CO_2 pipeline accidents during this time period (see Figure 5-1 for a map of CO_2 pipelines in the United States). The U.S. DOE categorized the two accidents with the largest carbon dioxide releases (4,000 barrels and 7,408 barrels) as rupture type releases, and the next four highest releases (772 barrels to 3,600 barrels) as puncture type releases. FutureGen modeled the volume of a pipeline release at Jewett, and estimated such a release would be about 12,700 barrels (31.5 gallons/barrel).

Figure 5-1. Existing CO_2 Pipelines in the United States

To evaluate accident probabilities and damages, IEc updated FutureGen's accident data by reviewing data from 2002 through 2009. This time frame was considered more appropriate because it represented:

- The most recent data available
- Consistent reporting requirements across the time period.

This review identified 37 CO_2 pipeline accidents in total (see Table 5-1 for a summary of identified accidents). Key information derived from this review included:

- The largest release was 24,659 barrels. In contrast, 19 of the events involved a release of less than five barrels.
- None of the events resulted in a fatality. Only one injury resulted from the 37 events.

Table 5-1. CO_2 Pipeline Accidents from 2002 through 2009

DATE	LOCATION	AMOUNT LOST
3/7/2002	Yukon, OK	24 gallons
8/26/2002	Chaves, NM	312 barrels
11/7/2002	Denver City, TX	4 barrels
11/8/2002	McCarney, TX	5 gallons
1/30/2003	Denver City, TC	5 gallons
1/22/2003	Penwell, TX	5 gallons
1/10/2003	Borger, TX	3 barrels

DATE	LOCATION	AMOUNT LOST
2/25/2003	Borger, TX	5 barrels
8/7/2003	Snyder, TX	5 gallons
8/6/2003	Brandon, MC	Not applicable
6/28/2004	Levelland, TX	3,608 barrels
7/5/2004	Yoakum County, TC	100 gallons
9/30/2004	Placitas, NM	772 barrels
10/13/2004	Garden City, TX	7,408 barrels
1/10/2005	Eddy County, NM	2,394 barrels
7/13/2005	Edgewood, NM	7 barrels
1/16/2006	Perryton, TX	1 barrel
5/10/2006	Snyder, TX	20 gallons
8/1/2006	Snyder, TX	307 barrels
9/21/2006	McGregor, ND	100 barrels
10/10/2006	Upton County, TX	19 barrels
1/21/2007	Cortez, CO	98 barrels
1/9/2007	Sharon, MS	24,319 barrels
12/28/2006	Raleigh, MS	24,659 barrels
4/26/2007	Iraan, TX	73 barrels
6/18/2007	Madison, MS	50 barrels
5/5/2008	Tatum, NM	5 barrels
5/14/2008	Tatum, NM	12 gallons
5/30/2008	Cortez, CO	49 barrels
6/24/2008	Snyder, TX	46 barrels
8/3/2008	Placitas, NM	5 gallons
8/13/2008	Tatum, NM	2 barrels
10/19/2008	Bloomfield, NM	1 barrel
7/2/2009	Beaver County, OK	850 barrels
7/30/2009	Idkiff, TX	224 barrels
8/2/2009	Placitas, NM	4 gallons
9/8/2009	McCarney, TX	3 barrels
Total	**37 Reported Incidents**	**2,743,583 gallons**

5.2 PIPELINE DAMAGES (NON-HUMAN HEALTH)

Based on the 2002 through 2009 CO_2 pipeline data from the Office of Pipeline Safety, damages for all 37 accident events totaled $1.05 million, including:

- $749,454 in ‘other operator costs’ (repair costs);
- $166,602 in lost product costs;

- $126,530 in 'other public costs' (repair costs);
- $2,500 in public/private property damage;
- $700 in emergency response costs; and
- $0 in environmental remediation costs.

To supplement the data from the Office of Pipeline Safety, IEc also considered Restreppo *et al.*, (2009) 'Causes, Cost Consequences, and Risk Implications of Accidents in U.S. Hazardous Liquid Pipeline Infrastructure'. Notably, the Restreppo *et al*. study focuses on hazardous liquid pipelines, rather than only CO_2 pipelines. A summary of hazardous liquid accidents is provided in Table 5-2.

Table 5-2. Hazardous Liquid Pipeline Incidents

Table 1 – Commodities spilled in hazardous liquid accidents (10 or more accidents).

Commodity	Frequency	Percent
Crude oil	552	34.9
Gasoline	167	10.6
Propane	55	3.5
Diesel fuel	53	3.4
Unleaded gasoline	46	3.0
Crude	39	2.5
Petroleum crude oil	37	2.3
Diesel	34	2.1
Fuel oil	33	2.1
Anhydrous ammonia	27	1.7
Jet fuel	25	1.6
Transmix	18	1.1
Normal butane	16	1.0
Carbon dioxide	12	0.8
Propylene	12	0.8
Kerosene	11	0.7
Natural gasoline	10	0.6

Percentages do not add to 100% since commodities with fewer than 10 accidents do not appear in the table.

Restreppo *et al.*, (2009) developed a damages estimation model based on 1,582 hazardous liquid pipeline accidents from 2002 through 2005 as reported in the Office of Pipeline Safety data (see Figure 5-2 for example results from the Restreppo model). These estimated damages include: value of product lost; public, private and operator property damage; emergency response costs; environmental remediation costs; and other operator and public costs (typically repair). Human health effects are not considered. The factors that most affect the modeled damages estimates for an event include: spill volume; system part involved in the accident; location characteristics; and whether there was liquid ignition, and explosion or a liquid spill. IEc replicated Restreppo regression model to help inform damages estimation (see Figure 5-3).

Figure 5-2. Example Results of Application of Restreppo Regression Model

Table 10 – Scenarios for hazardous liquid pipeline accidents.

Cause	High consequence area?	System part involved	Onshore/offshore	Did liquid ignite?	Was there an explosion?	Amount spilled (gallons)	Value of product lost (US$ '000) with probability of nonzero value	Property damage (US$ '000) with probability of nonzero value	Cleanup and recovery (US$ '000) with probability of nonzero value	Total cost estimates assuming all costs occur (US$ '000)
Internal corrosion	No	Onshore pipeline	Onshore	No	No	420,000	$58 ($16, $205) 0.936	$9 ($2, $36) 0.499	$90 ($28, $282) 0.952	$157($46, $523)
Third party excavation	Yes	Onshore pipeline	Onshore	Yes	Yes	420,000	$264 ($107, $645) 0.936	$186 ($47, $733) 0.767	$63 ($22, $174) 0.916	$513 ($176, $1552)
Control equipment malfunction	Yes	Storage tank	Onshore	Yes	Yes	1,260,000	$383 ($141, $1037) 0.909	$210 ($53, $825) 0.463	$8 ($2, $44) 0.904	$601 ($196, $1906)
High winds	Yes	Offshore pipeline	Offshore	No	No	840,000	$396 ($252, $624) 0.900	$292,796 ($74333, $1153323) 0.200	$46,174 ($11632, $183285) 0.884	$339366 ($86217, $1337232)
Incorrect operation	Yes	Onshore pipeline	Onshore	Yes	Yes	840,000	$309 ($113, $845) 0.944	$111 ($28, $436) 0.767	$30 ($11, $82) 0.916	$450 ($152, $1363)

Restreppo et al., (2009)

Figure 5-3. IEc Results from Restreppo Regression Model

Inputs							Outputs			
							Probability of Non-Zero Cost		Predicted Cost	
Cause (select one)	High consequence area? (1 = Yes, 0 = No)	System part involved (select one)	Offshore? (1 = Yes, 0 = No)	Did liquid ignite? (1 = Yes, 0 = No)	Was there an explosion? (1 = Yes, 0 = No)	Amount spilled (gallons)	Property damage	Cleanup and recovery	Property damage	Cleanup and recovery
Corrosion, internal	0	Onshore Pipeline	0	0	0	420,000	0.499	0.952	$9,228	$90,605
Third party excavatio	1	Onshore Pipeline	0	1	1	420,000	0.767	0.916	$185,353	$63,276
Malfunction of contrc	1	Above ground stor	0	1	1	1,260,000	0.463	0.926	$208,554	$8,582
High winds	1	Offshore Pipeline	1	0	0	840,000	0.200	0.676	$291,660,840	$46,319,959
Incorrect operation	1	Onshore Pipeline	0	1	1	840,000	0.767	0.904	$110,206	$30,488
Third party excavatio	0	Onshore Pipeline	0	0	0	500,000	0.499	0.859	$10,684	$183,502

System Part Involved	Table 5	Table 6	Table 7	Table 8
Above ground storage tank	-0.458	1.201	--	-0.283
Offshore Pipeline	-0.497	0.586	--	0.139
Onshore Pipeline	0.885	-0.367	--	0.405
Other	0.215	-0.631	--	0.175
Pump/meter station	-0.145	-0.789	--	-0.437

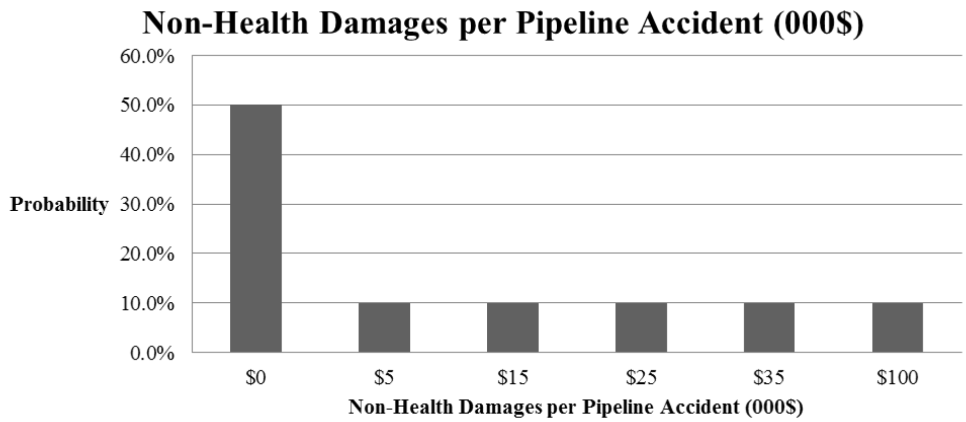
Variable	Table 5	Table 6	Table 7	Table 8
Intercept	-0.89	7.626	1.514	8.671
Logged gallons lost	--	0.192	--	0.245
High consequence area	--	1.059	0.582	1.094
Offshore	--	3.502	--	2.533
Ignition	1.198	1.828	--	--
Explosion	--	--	--	-2.116

5.3 DISTRIBUTION OF VALUES FOR OTHER DAMAGES

The Restreppo *et al*. model predicts $0 cost for approximately 50% of events, while the Office of Pipeline Safety data indicate that 32 out of 37 CO_2 pipeline accidents from 2002 to 2009 had no emergency response, remediation or public/private damages. Of the remaining five CO_2 pipeline accidents, the maximum total damages for the specified categories was $66,530. The Restreppo *et al*. model suggests similar damages for spill characteristics likely associated with a potential Jewett pipeline accident.

This model is used to develop a distribution of potential non-health damages per event (see Figure 5-4).

Figure 5-4. Range of Non-Heath Damages per Pipeline Accident



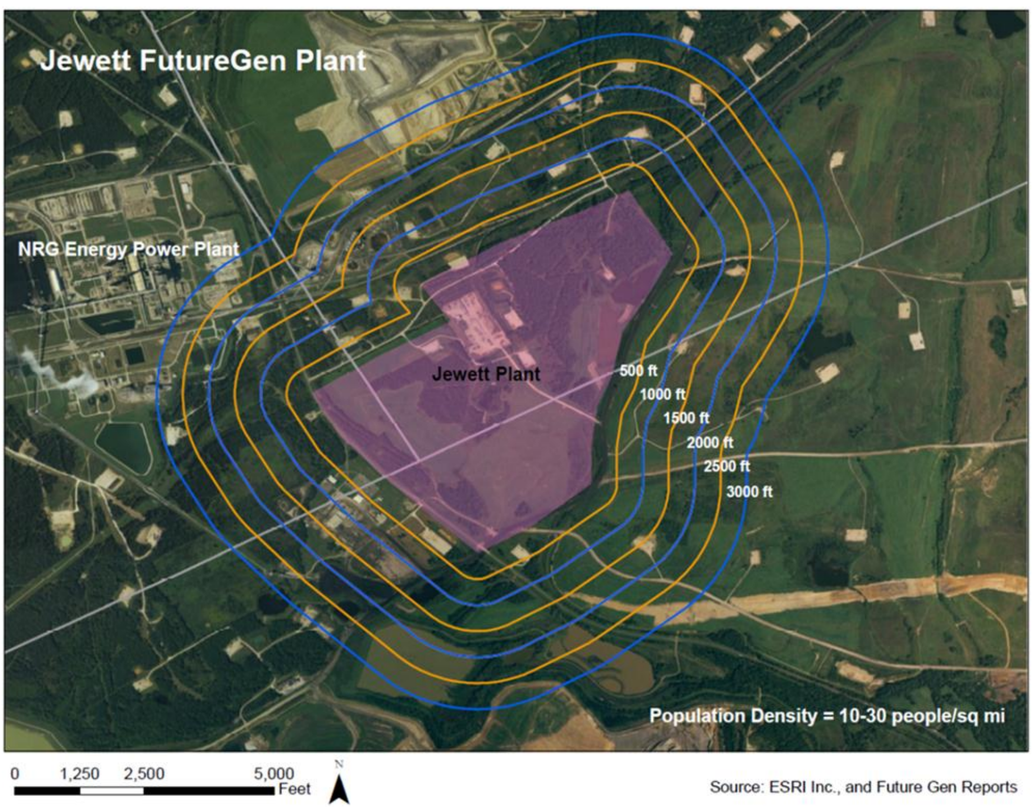
CHAPTER 6 | JEWETT PLANT SITE EVENTS

This Chapter discusses the data available to support the estimation of damages for events at the plant and the results of the Monte Carlo analysis for plant site events. The Chapter begins by summarizing key characteristics of the Jewett plant that may influence the magnitude of potential damages. It then summarizes the types of plant events considered and estimate plume distances associated with these types of events. It concludes by discussing potential damages associated with these events.

6.1 JEWETT PLANT SITE CHARACTERISTICS

The siting of the Jewett Plant is a key factor in determining the type and severity of plant site events. If accidents occur, rural plant location limits potential damages. A map of the Jewett plant site is presented in Figure 6-1.

Figure 6-1. Map of Jewett Plant Site



The plant site (shaded in purple) is approximately 400 acres in size. The plant footprint is expected to be only 75 acres, allowing several hundred feet of open space buffer around the plant itself. There are no residences within 0.3 miles of the proposed plant site, and population densities beyond that radius are very low. One small church, with limited use, is located approximately 0.3 miles north of the northern corner of the proposed power plant site. The plant site is also adjacent to a lignite mine and a power plant.

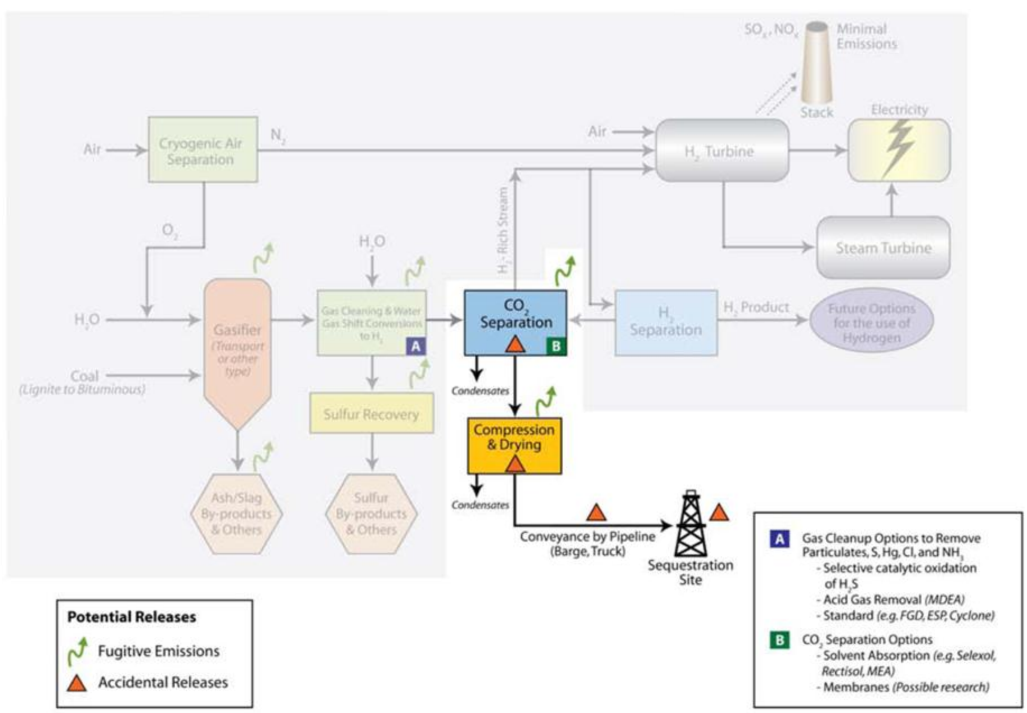
6.2 PLANT SITE EVENTS CONSIDERED

This analysis focuses on events incremental to the carbon capture and sequestration process itself. As highlighted in Figure 6-2, key activities include:

- CO_2 Separation
- Compression and Drying

Quest (2006) is the key data source for FutureGen plant events. Quest evaluates the relationship between coal type and process component manufacturer to accident plume size, but it does not estimate accident probabilities. In addition, while plume distances are estimated, the expected number of effects associated with these plumes is not estimated.

Figure 6-2. Overview of Carbon Capture Process



6.3 GENERIC FUTUREGEN PLANT LAYOUT

The plant footprint and site size affect the potential for public health effects. As noted in Section 6.1, the Jewett plant footprint is approximately 75 acres, with a plant site of 400 acres (see Figure 6-3). Table 5-1 presents the relationship between the site size and the distance to the property line.

Figure 6-3. Schematic of Plant Footprint and Site

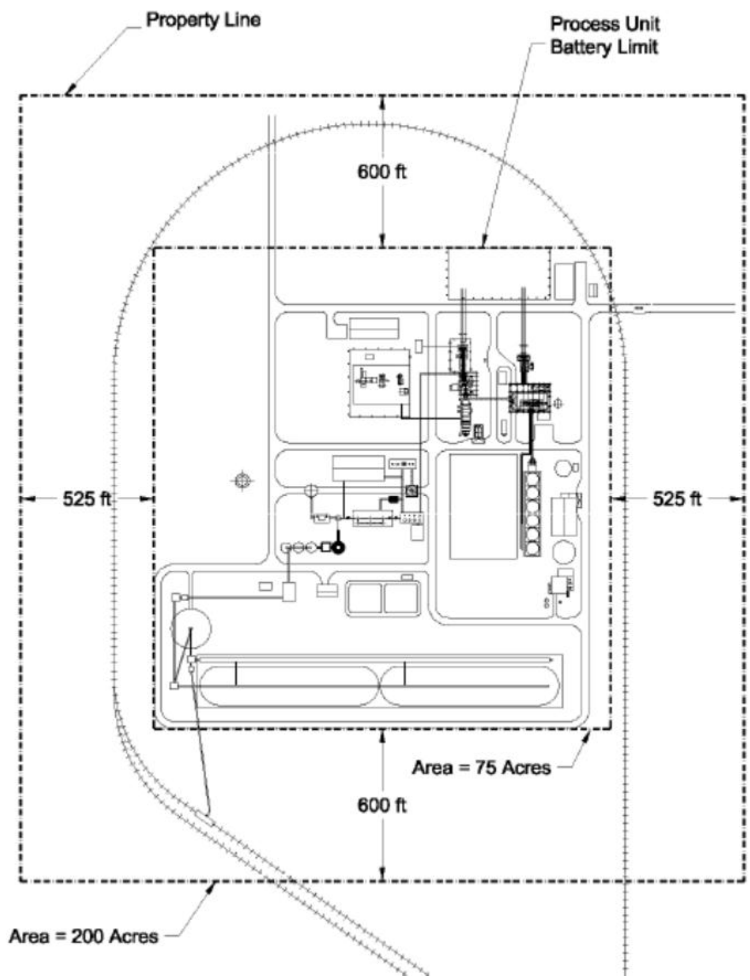


Table 6-1. Relationship between Site Size and Distance to Property Line

Site Size (acres)	Distance to Property Line (feet)
200	1,475
400	2,090
600	2,555

6.4 PLUME DISTANCE ESTIMATES

Quest does estimate potential CO_2, CO and H_2S plume distances in the event that an accident to various plant components occur. As estimated, the CO_2 and CO plumes are considered highly unlikely to extend past plant boundary.

The analysis focuses on accidents at 'CO_2 removing' units. Quest estimates plant accident H_2S plumes will exceed 41 ppmv as far as 1,040 to 3,770 feet from accident location (see Table 6-2). A concentration of 41 ppmv falls between FutureGen irreversible (27 ppmv) and fatal (50 ppmv) thresholds for 15 minute exposures. These plume distances are based on plume maximizing conditions (wind speed 2m/s, Pasquill-Gifford stability F), which occur about 20.8% of the time.

Table 6-2. Plume Distance Estimates

System	Coal	Unit	Release from Process Stream	Endpoint	Distance (ft) to Endpoint
					Public (AEGL-2)
COP	Illinois	Gasifier	Syngas from Quench	CO	3110
COP	Illinois	CO_2 removing	Sour gas to treating	H_2S	1350
COP	Illinois	CO_2 removing	Acid gas to Claus Unit	H_2S	3770
COP	Illinois	Claus	Acid gas to Claus Unit	H_2S	2700
COP	Illinois	Claus	Claus gas from WHB	SO_2	7450
COP	Pittsburgh	Gasifier	Syngas from Quench	CO	3210
COP	Pittsburgh	CO_2 removing	Sour gas to treating	H_2S	1020
COP	Pittsburgh	CO_2 removing	Acid gas to Claus Unit	H_2S	3150
COP	Pittsburgh	Claus	Acid gas to Claus Unit	H_2S	2220
COP	Pittsburgh	Claus	Claus gas from WHB	SO_2	6400
COP	Powder River	Gasifier	Syngas from Quench	CO	3030
COP	Powder River	CO_2 removing	Acid gas to Claus Unit	H_2S	3400
COP	Powder River	Claus	Acid gas to Claus Unit	H_2S	1250
COP	Powder River	Claus	Claus gas from WHB	H_2S	3570

Excerpt from Quest (2006) Table 5-11.

6.5 POTENTIAL HEALTH EFFECTS

Neither Quest (2006) nor the FutureGen Risk Assessment (2007) estimates health effects for releases due to the failure of 'CO_2 removing' equipment. The pipeline rupture scenario at a location immediately adjacent to plant site is the best, readily available proxy for potential human health effects to nearby residents near the plant if CO_2 removing equipment fails.[16]

Under the pipeline rupture scenario, H_2S plumes are estimated to exceed 27 ppmv threshold up to 1,946 feet from the pipeline, assuming averaged weather conditions. In comparison, plant accident H_2S plumes are estimated to exceed a slightly higher

[16] Health effects due to pipeline releases are estimated at discrete points every 300 meters along the entire length of the pipeline.

threshold (41 ppmv) for a greater distance, i.e., possibly as far as 1,040 to 3,770 feet from accident location. However, these plume distances do not account for the buffer zone on plant property and are based on worst case weather conditions.

Readily available information from pipeline rupture scenario at a location immediately adjacent to the Jewett, TX plant suggests that there would be approximately three adverse effects, and no irreversible or fatal effects. These estimates are consistent with the lack of human receptors in the vicinity of the plant.

6.6 OTHER POTENTIAL EFFECTS

Failure of 'CO_2 removing' equipment at the plant will not affect groundwater, will release a negligible amount of CO_2 to the atmosphere, and due to the location of the equipment inside the plant, has a very low potential for causing off-site natural resource, infrastructure or other types of damages.

6.7 EVENT PROBABILITIES

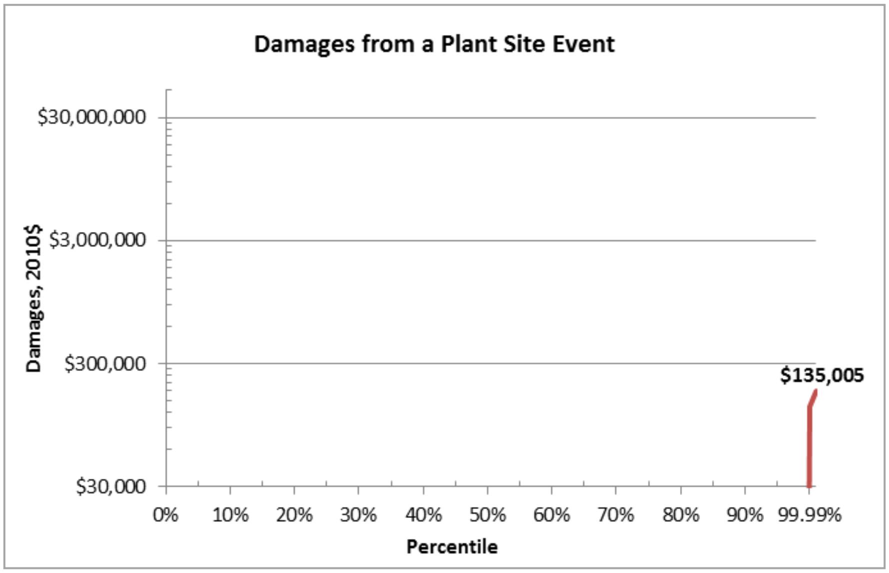
FutureGen analyses do not estimate the annual probability of a failure of 'CO_2 removing' equipment. For the Monte Carlo analysis used in this study, this equipment is expected to have a 5.5-in-100,000 annual chance of failure, conservatively reflecting the highest failure rate identified by the UK Health and Safety Executive.[17]

[17] Event probability based on information provided in Appendix A.

6.8 DAMAGES ESTIMATES

Figure 6-4 presents results for the plant site event scenario. For reasons previously identified, these damage estimates are limited to potential human health damages due to releases of H_2S.

Figure 6-4. Results for the Plant Site Event Scenario



As shown, there is a 99.99% probability that total damages from a plant site event are zero, either because an event doesn't occur or because damages are negligible. At the 50th, 95th, and 99th percentiles, damages are estimated at $0, while at the 99.99th percentile damages are estimated at approximately $135,000. This result is not surprising given the low event probability and relatively low level of impacts expected on those rare occasions an event occurs.

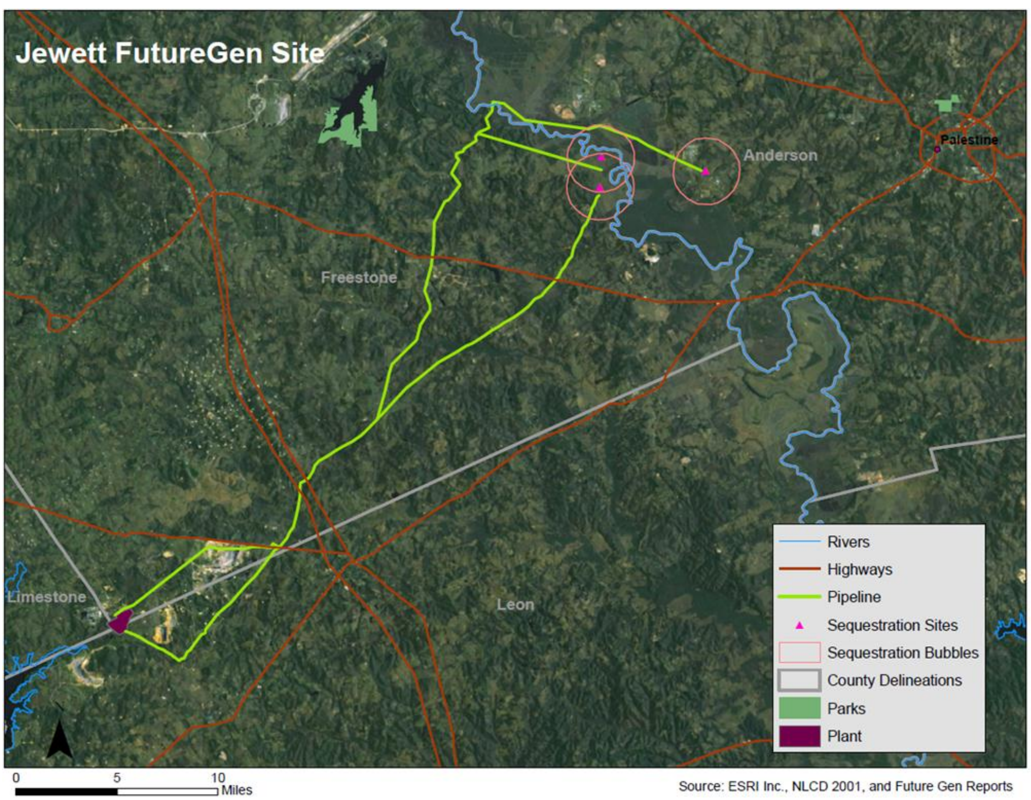
CHAPTER 7 | JEWETT PIPELINE EVENTS

This Chapter develops estimates of damages for pipeline release events. It begins by summarizing key characteristics of the Jewett pipeline that influence the magnitude of potential damages. It then estimates the probability of both a puncture and a rupture event based on data from the FutureGen report and a review of Office of Pipeline Safety accident data. For each forecast event, it then develops a potential number of effects based on the location of the event on the pipeline (e.g., whether a puncture occurs at mile 20 or mile 40). It concludes by estimating damages based on this study's Monte Carlo results.

7.1 JEWETT PIPELINE CHARACTERISTICS

The location, length, siting, and other characteristics of the pipeline are key determinants of the magnitude of potential damages associated with a pipeline event. Figure 7-1 below provides a map of the proposed pipeline for the Jewett, TX site.

Figure 7-1. Map of Jewett Pipeline



Key characteristics of the Jewett pipeline include:

- 59 miles long;
- 19 inch inner diameter;
- Buried approximately three feet deep; and
- Substantial portions utilize existing natural gas pipeline right of way.

Presently, there is very little development near the pipeline itself. Table 7-1 summarizes the frequency of land cover types within 100 meters of the pipeline. Approximately 30% of the area nearest the pipeline is pasture, 20% is forest, and 16% is shrub habitat. In addition, there do not appear to be any significant parks, campgrounds, or other recreational/cultural areas close to the pipeline. The Trinity River is the only water body of note that crosses the pipeline.

Table 7-1. Land Cover Type Within 100 Meters of Pipeline

LAND COVER TYPE	AREA (ACRES)	PERCENTAGE
Water	46	0.8
Developed	437	8.0
Barren	372	6.8
Forest	1,078	19.8
Shrub	888	16.3
Grassland	371	6.8
Pasture	1,634	29.9
Wetland	630	11.5

7.2 PIPELINE EVENT PROBABILITY

FutureGen analyses include two pipeline release scenarios: 1) 'hole-puncture'; and 2) complete severing or rupture.

- The 'hole-puncture' (i.e., 3-inch by 1-inch hole) scenario represents an accidental cut into the CO_2 pipeline transmission pipeline by a 30 to 60 ton excavator.
- The complete severing of the pipeline scenario represents an incident in which a heavy piece of equipment, such as a bulldozer, runs into the transmission pipe or a rail derailment incident in which a portion of a derailed train runs into the buried pipe.

FutureGen analyses assume a five mile section of pipeline would empty under each scenario because safety shut-off valves are located every five miles. Effectively, the puncture and rupture scenarios differ in the rate at which CO_2 and associated substances escape the pipeline. The quantity released is the same under both scenarios.

As previously described, the FutureGen reviewed Office of Pipeline Safety accident data from 1994 through 2006 to develop an estimated probability of a pipeline event. The accident data analyzed by FutureGen identified 31 CO_2 pipeline accidents during this time period. From these 31 accidents:

- DOE categorized the two accidents with the largest carbon dioxide releases (4,000 barrels and 7,408 barrels) as rupture type releases, and the next four highest releases (772 barrels to 3,600 barrels) as puncture type releases.
- FutureGen modeled a pipeline release at Jewett would be about 12,700 barrels (31.5 gallons/barrel).

Based on these data, the FutureGen Risk Assessment assumes a 0.5% and 1.0% annual chance for a pipeline rupture and puncture event at Jewett, respectively. These estimates reflect accident per year per pipeline-mile calculated from the above data, multiplied by length of Jewett pipeline (59 miles).

Our review focused on accident data from 2002 through 2009. Based on this review:

- We calculate an annual CO_2 pipeline incident rate equal 0.00131 per pipeline mile, translating to 0.077 incidents per year for the 59 mile Jewett pipeline (i.e., 7.7% annual chance for an event).
- However, this rate includes all CO_2 pipeline incidents, many of which are very small (approximately half less than 5 barrels).
- From 2002 to 2009, only five out of 37 events involved a release greater than 1,000 barrels (and so of comparable magnitude to the modeled FutureGen pipeline release), translating to 0.01 'comparable' incidents per year for the 59 mile Jewett pipeline (i.e., 1.0% annual chance for an event).
- U.S. natural gas transmission pipeline incident rate (on shore pipelines only) is approximately one-fifth of the CO_2 pipeline rate. U.S. hazardous liquid transmission pipeline incident rate (on shore pipelines only) is approximately twice the CO_2 pipeline rate.

For 'base case' Monte Carlo purposes, IEc adopted the FutureGen pipeline accident probabilities.

7.3 ESTIMATED HUMAN HEALTH EFFECTS

This section estimates the number of potential human health effects for both the puncture and rupture scenarios. These estimates are based on analyses done by FutureGen, and rely on average weather conditions. As a result, the number of potential human health effects may be undervalued. This is discussed in greater detail later in this chapter.

PIPELINE RUPTURE EVENTS

The FutureGen Risk Assessment estimates of the number of health effects caused by a pipeline rupture reflect average wind and atmospheric conditions. Maximum number of health effects per event is presented in Table 7-2.

Table 7-2. Maximum Number of Health Effects for Pipeline Rupture Events

Site	0.51 ppmv H_2S	27 ppmv H_2S	50 ppmv H_2S	30,000 ppmv CO_2	40,000 ppmv CO_2
Jewett	51.8	1.32	1.19	0.47	< 0.5

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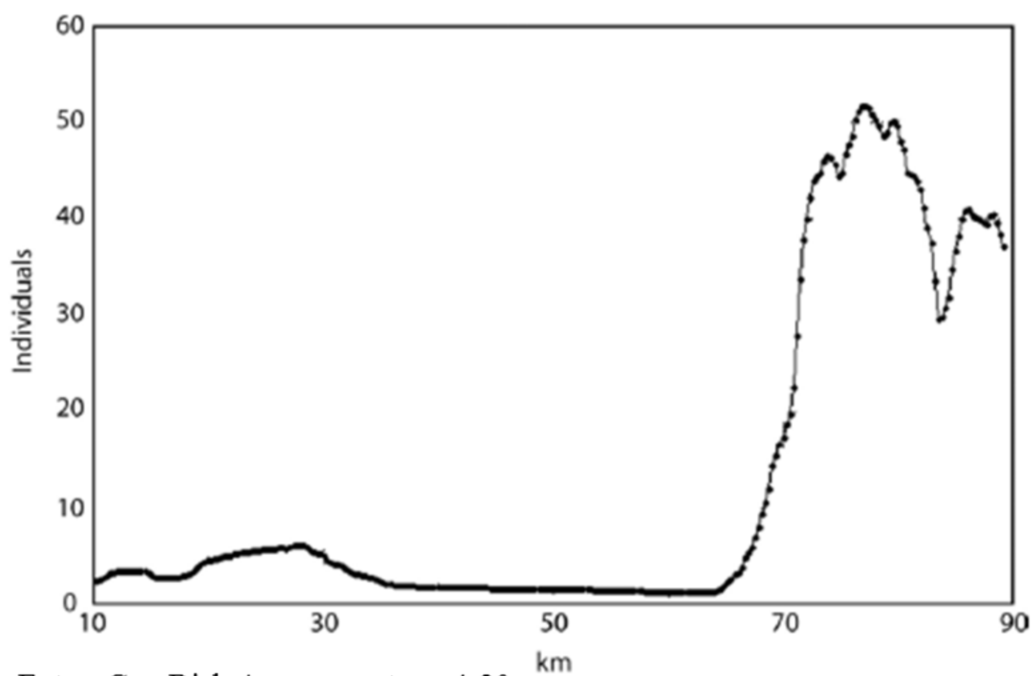
The number of health effects varies by location along the pipeline due to the proximity of the pipeline to various health receptors and population. Figure 7-2 presents the number of adverse health effects (H_2S) by location along pipeline. For Monte Carlo trials that have a pipeline rupture, the model randomly chooses a location and incorporates associated health effects.

Figure 7-2. Number of Adverse Health Effects by Location Along the Pipeline



FutureGen Risk Assessment pg. 4-20

PIPELINE PUNCTURE EVENTS

The FutureGen Risk Assessment estimates of the number of health effects caused by a pipeline puncture reflect average wind and atmospheric conditions. Maximum number of health effects per event is presented in Table 7-3.

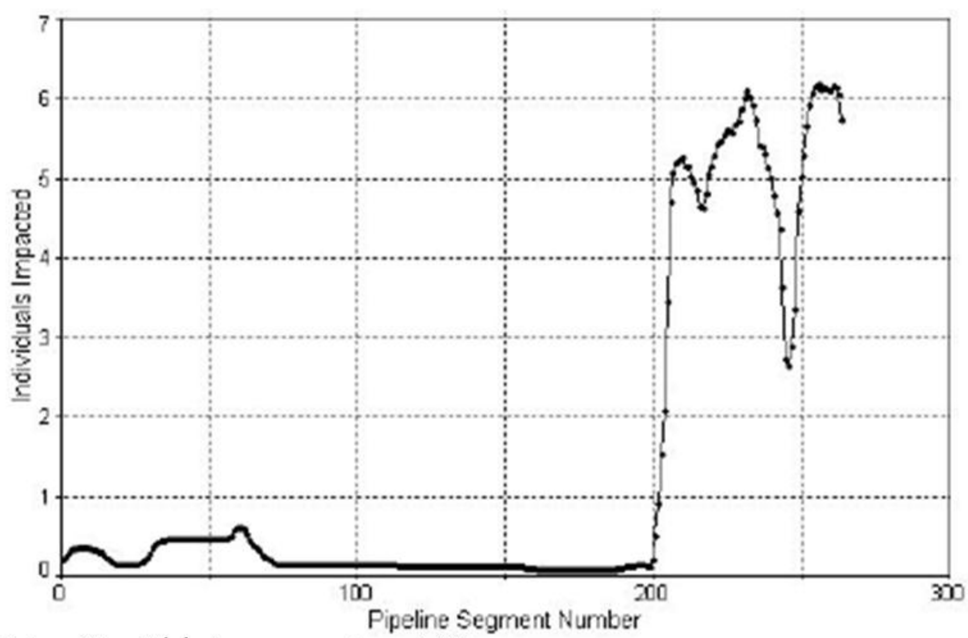
Table 7-3. Maximum Number of Health Effects for Pipeline Puncture Events

Site	0.33 ppmv H_2S	17 ppmv H_2S	31 ppmv H_2S	20,000 ppmv CO_2	70,000 ppmv CO_2
Jewett	6.18	0.076	< 0.08	0.196	< 0.2

FutureGen Risk Assessment pg. C-33

The number of health effects varies by location along the pipeline due to the proximity of the pipeline to various health receptors and population. Figure 7-3 presents the number of adverse health effects (H_2S) by location along pipeline. For Monte Carlo trials that have a pipeline puncture, the model randomly chooses a location and incorporates associated health effects.

Figure 7-3. Number of Adverse Health Effects by Location Along the Pipeline



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IMPLICATIONS OF FUTUREGEN USE OF AVERAGED WEATHER CONDITIONS

FutureGen human health effects estimates reflected averaged weather conditions. This assumption does not allow for the possibility of lower probability, higher consequence events that can occur under certain wind and atmospheric conditions. As shown in Table 7-4, weather conditions can vary at the Jewett site. Jewett experiences calm conditions (F02), which can represent the worse case weather conditions, approximately 1.3% of the time.

Table 7-4. Jewett Wind Rose

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

Data on plume distances under these varying wind and atmospheric conditions are not available for the ‘base case’ model. As shown in Table 7-5, FutureGen does break out plume distances by atmospheric stability class for co-sequestration analysis, but not for the ‘regular’ analysis. Available data do not allow these co-sequestration results, which assume a higher concentration of H_2S in the stream, to be applied to the ‘base case’. By presenting averaged results, FutureGen dampens variability in health effects estimates.

Table 7-5. Plume Distances for the Co-Sequestration Analysis

Stability Class	F	A	A	B	B	C	D
Wind Speed	2 m/sec	1 m/sec	2 m/sec	3 m/sec	4 m/sec	6 m/sec	8 m/sec
Wind Rose	20.8 %	6.5 %	8.7 %	27.9 %	14.3 %	13.4 %	8.4 %
H_2S Criteria: 0.51 ppmv	140 km	16 km	13 km	21 km	18 km	29 km	35 km
H_2S Criteria: 27 ppmv	14 km	2.1 km	1.5 km	2.1 km	1.8 km	2.6 km	2.8 km
H_2S Criteria: 50 ppmv	10 km	1.5 km	1.1 km	1.5 km	1.3 km	1.8 km	2.0 km
H_2S Criteria: 100 ppmv	6.9 km	1.0 km	0.76 km	1.0 km	0.9 km	1.3 km	1.4 km

7.4 OTHER EFFECTS

Pipeline release events also are assigned CO_2 leakage and 'other' damages, as described in Chapters 4 and 5, respectively. Groundwater impacts are not plausible for this type of event.

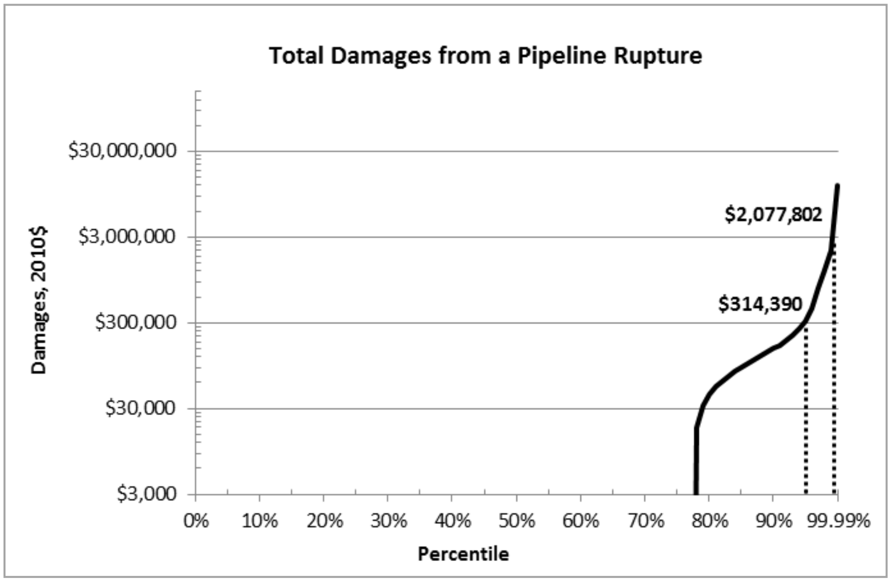
7.5 DAMAGE ESTIMATES

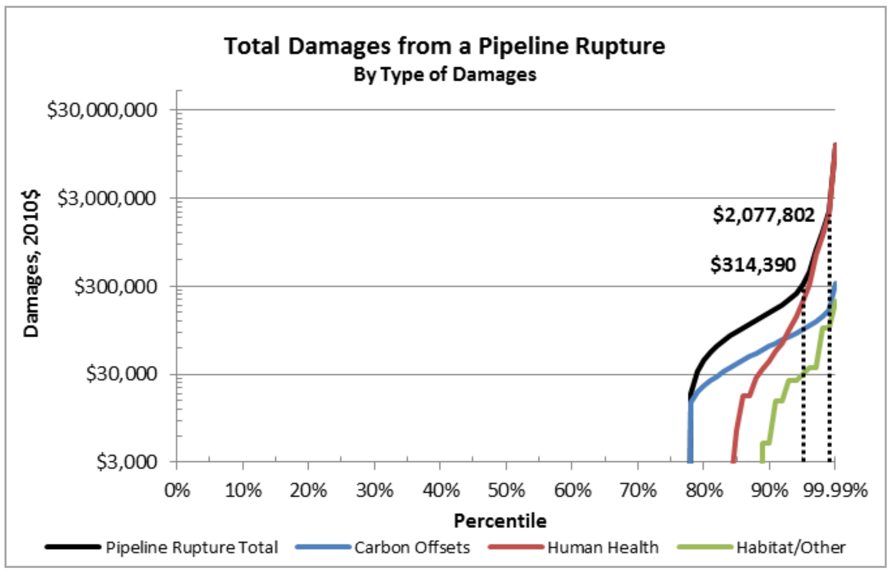
This section consolidates the information in the preceding sections to develop estimates of potential damages for both the puncture and rupture scenarios.

PIPELINE RUPTURE DAMAGES

Figure 7-4 presents results for the pipeline rupture scenario. As shown, there is a 78% probability that damages from a pipeline rupture will be zero, either because a rupture doesn't occur, or because damages are negligible. At the 50th percentile, damages are estimated to be $0, while at the 95th percentile, damages are estimated to be approximately $314,000. These estimates are primarily driven by CO_2 leakage; that is, every time a release event occurs, all of the CO_2 in the affected 5 mile section of pipeline (1,290 tonnes) is assumed to be released to the atmosphere. The CO_2 offset price assigned to each release in this study's Monte Carlo model will range between $10 and $321 per tonne, resulting in CO_2 leakage damages of between approximately $12,900 and $414,100 per event.

Figure 7-4. Results for the Pipeline Rupture Scenario

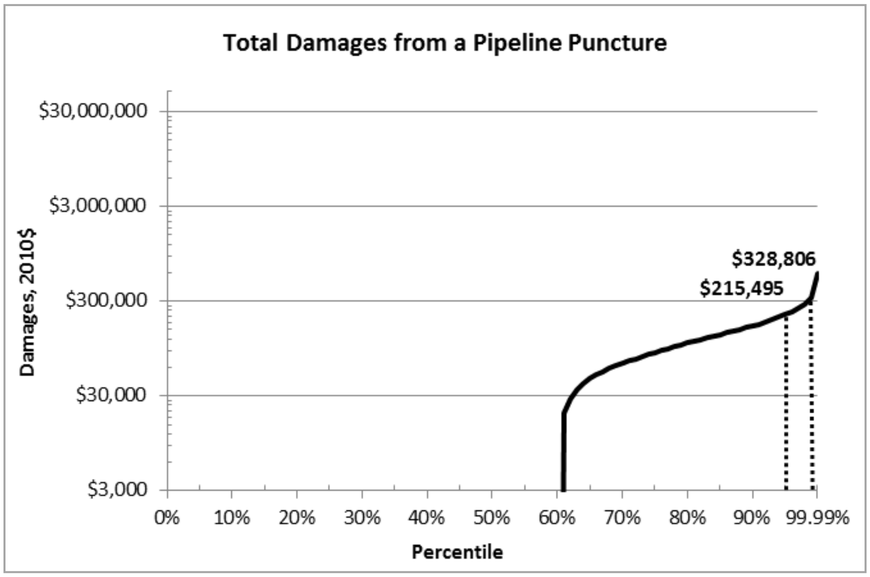


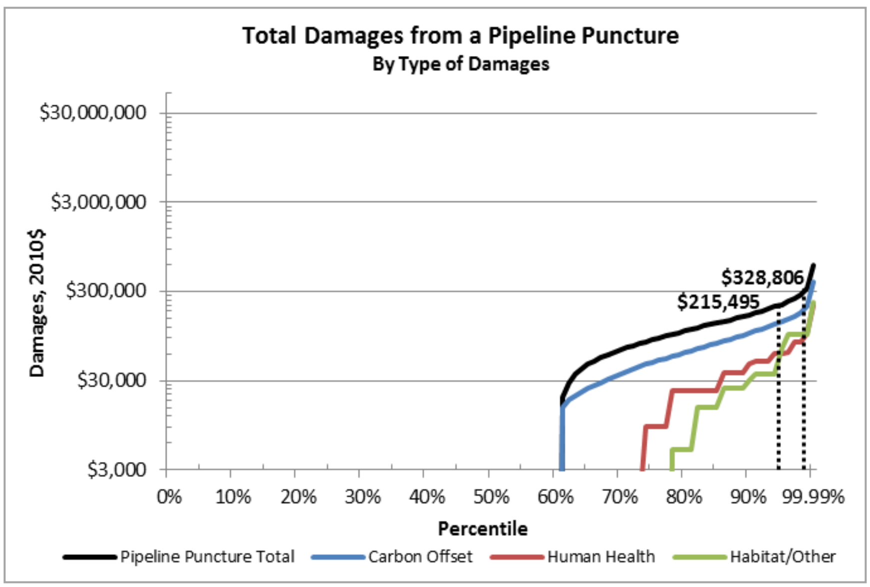


PIPELINE PUNCTURE DAMAGES

Figure 7-5 presents results for the pipeline puncture scenario. As shown, there is a 61% probability that damages from a pipeline puncture will be zero, either because a puncture doesn't occur, or because damages are negligible. At the 50th percentile, damages are estimated to be $0, while at the 95th percentile, damages are estimated to be approximately $215,000. These estimates also are primarily driven by CO_2 leakage, for the same reasons described for the rupture scenario.

Figure 7-5. Results for the Pipeline Puncture Scenario





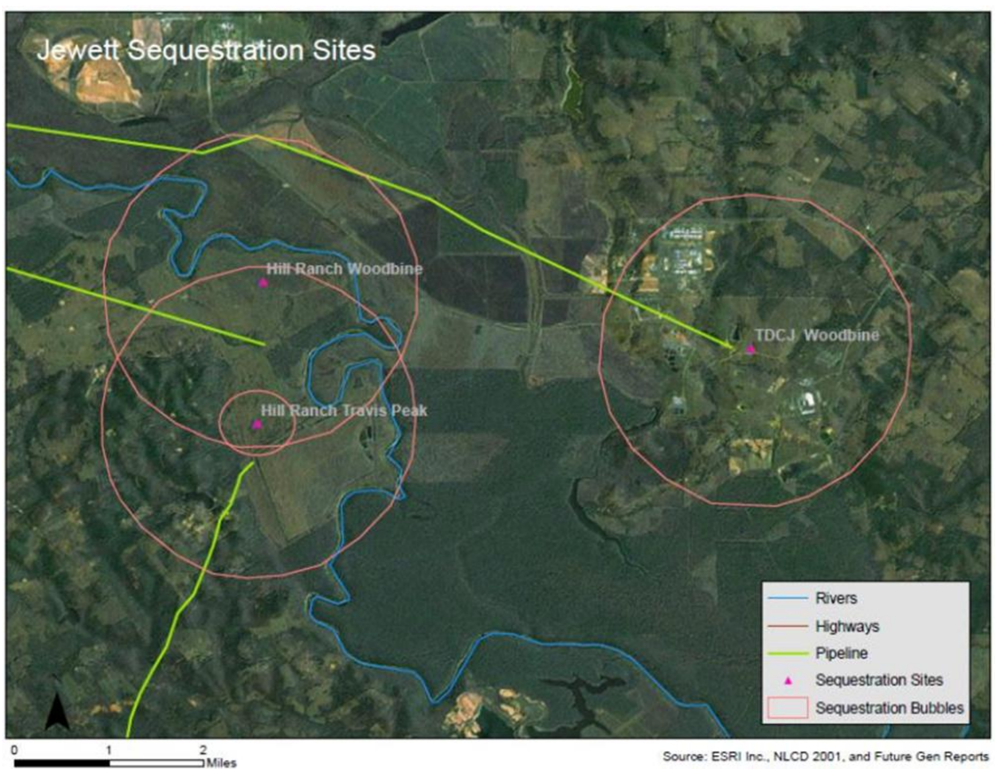
CHAPTER 8 | JEWETT SEQUESTRATION SITE EVENTS

This Chapter describes the approach, inputs and draft Monte Carlo damages estimates for potential releases at the sequestration site, including releases at the injection well or deep oil & gas/other pre-existing wells near the projected sequestration plume. The Chapter first provides an overview of key characteristics of the sequestration site at Jewett. It then summarizes the types of sequestration site events considered in the FutureGen report, and concludes by developing a range of potential damages estimates associated with these events.

8.1 JEWETT SEQUESTRATION SITE CHARACTERISTICS

As with pipeline and plant events, the siting of the sequestration site is a key factor in determining the type and severity of sequestration site events. If an event occurs, the proximity of the sequestration site to population receptors may impact the extent of health effects observed. A map of the Jewett sequestration sites is presented in Figure 8-1.

Figure 8-1. Map of Jewett Sequestration Sites



The Jewett sequestration sites are located in a rural area approximately 33 miles northeast of the plant site. Each of the three wells would have injection depths of approximately 1 mile, with a plume radius of up to 1.7 miles per well. Two of the proposed CCS injection well sites are located about 16 miles east of the Town of Fairfield in Freestone County, about 60 miles east of Waco. The third proposed CCS injection well site would be located about five miles east on Texas Department of Criminal Justice property in Anderson County, which is about 16 miles west of the City of Palestine.

Presently, the proposed sequestration site is forest and grassland, with limited use for ranching purposes. There are few residences. The exceptions are Texas Department of Criminal Justice facilities located directly over the proposed CCS plume. According to FutureGen, injection would occur on a private ranch (i.e., Hill Ranch) and on adjoining state property managed by the Texas Department of Criminal Justice.

8.2 SEQUESTRATION SITE EVENTS CONSIDERED IN FUTUREGEN

Sequestration site events considered in FutureGen reflect a variety of release mechanisms and pathways. These mechanisms and pathways are summarized in Table 8-1.

Table 8-1. Summary of Sequestration Site Release Scenarios

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

Table 8-2 on the following page summarizes event probabilities for the various release scenarios. Based on site-specific analysis, FutureGen finds rapid leakage through caprock at the Jewett, TX site to be so improbable (i.e., 2-in-10 billion annual chance of occurrence), that it does not further consider this type of event in its risk assessment. Similarly, FutureGen analyses indicate that potential releases through existing or induced faults are expected to be extremely unlikely (2-in-100 million annual chance of occurrence). For Monte Carlo valuation purposes, these event types are assigned $0 in damages.

Table 8-2. Event Probabilities by Release Scenario for Jewett, TX Site

Release Scenario	Release Likelihood (annual)
Pipeline Events	
Pipeline Rupture	1-in-200 (0.5%)
Pipeline Puncture	1-in-100 (1.0%)
Sequestration Site Events	
Wellhead Equipment Rupture	6-in-100,000 (0.006%)
CO_2 Injection Well Leak	3-in-100,000 (0.003%)
Other Well Leak	7-in-100 (7.0%)
Rapid Leakage through Caprock	2-in-10 billion (0.00000002%)
Slow Leakage through Caprock	4-in-100,000 (0.004)%
Release through Existing, Induced Faults	2-in-100 million (0.000002%)
Source: FutureGen Risk Assessment Table 6-11	

8.3 HUMAN HEALTH EFFECTS

With respect to the potential for human health impacts, based on site-specific analysis FutureGen finds that some event types result in constituent concentrations well below those needed to harm human receptors. That is, a release results in such low concentration that exposure does not necessarily lead to harm/damages. To determine which types of events may result in sufficient constituent concentrations to cause harm human health, FutureGen calculates risk ratios (estimated exposure concentration divided by threshold concentrations needed to cause harm). These risk ratios are presented by release scenario in Table 8-3. FutureGen quantifies potential human health effects for events with risk ratios greater than (or close to) 1. Events with risk ratios less than 1 are assigned $0 human health damages, assuming that, even if they occur, estimated exposure concentrations are insufficient to cause that type of harm.

As shown in Table 8-3, only three types of release scenarios have estimated human health risk ratios greater than 1. These events reflect the slow release of H_2S either through the injection well, deep oil & gas well, or through other, poorly constructed wells.

Table 8-3. Human Health Risk Ratios by Release Scenario

Release Scenario	Gas	General Populace Risk Ratios			
		Rapid Release		Slow Release	
Plume Footprint		Risk Ratio	Distance (feet [meters]) to No Effects Level	Risk Ratio	Distance (feet [meters]) to No Effects Level
Upward leakage through caprock and seals, gradual failure and slow release	CO_2	NA	NA	0.000008	above reservoir
	H_2S	NA	NA	Not released	
Release through existing faults due to effects of increased pressure	CO_2	NA	NA	0.0004	above reservoir
	H_2S	NA	NA	0.3	above reservoir
Release through induced faults due to effects of increased pressure (local over-pressure)	CO_2	NA	NA	0.0002	above reservoir
	H_2S	NA	NA	0.2	above reservoir
Upward leakage through the CO_2 injection well(s)	CO_2	0.07	near well	0.006	above reservoir
	H_2S	0.8	near well	**4**	**745 (227)**
Upward leakage through deep oil and gas wells	CO_2	0.07	near well	0.006	above reservoir
	H_2S	0.8	near well	**4**	**745 (227)**
Upward leakage through undocumented, abandoned, or poorly constructed wells (days)	CO_2	0.07	near well	0.006	above reservoir
	H_2S	0.8	near well	**4**	**745 (227)**

8.4 GROUNDWATER IMPACTS

At the Jewett, TX site, groundwater damages within the 100-year period evaluated by this analysis are most likely (by far) to arise from leaks in deep oil & gas/other pre-existing wells in the sequestration area. As indicated in Table 8-2, the annual likelihood of a release from these types of wells at the Jewett, TX sequestration location is estimated to be 7%, i.e., three orders of magnitude greater than releases from wellhead equipment or injection wells. In addition, these wells likely are located throughout the sequestration area, potentially closer to areas for which water rights have not been secured by the project sponsor compared to the more 'central' location of injection wells that are well within areas for which the project sponsor has obtained water rights.

Other types of potential sequestration site events (see Figures 8-1 and 8-2) have a negligible likelihood of contributing to potential groundwater damages at the Jewett, TX site within the 100 year period for this analysis.

Therefore, this study assigns potential groundwater damages to the 'other well' release scenario at the sequestration site. As described in Chapter 3, if an 'other well' release event occurs as part of the Monte Carlo trials in this study, damages are assumed to include the costs necessary to stop the release, and costs necessary to address the impacts of the release to groundwater and groundwater services.

8.5 CO_2 LEAKAGE

As indicated in Chapter 4, the following bounding estimates are used in the Monte Carlo analysis:[18]

- If an injection well release occurs during the operational period (2011 – 2060), the Monte Carlo analysis randomly assigns a release volume to the atmosphere between 0.1 and 16.5 tonnes of CO_2;
- If an injection well release occurs between 2061 and 2110, the Monte Carlo analysis randomly assigns a release volume to the atmosphere between 0.6 and 99 tonnes of CO_2;
- If an 'other well' release occurs at any time in the analysis period (2011 – 2110), the Monte Carlo analysis randomly assigns a release volume to the atmosphere between 99 and 5,400 tonnes of CO_2.

Other sequestration site release events within the 100 year period of analysis have low probabilities and/or atmospheric release volumes, resulting in a negligible contribution to potential CO_2 leakage damages.

8.6 OTHER EFFECTS

As described in Chapter 5, other effects are assigned to sequestration site events that could result in the release of sequestered constituents to the surface in non-negligible amounts (i.e., well releases and the failure of aboveground equipment at the sequestration site).

8.7 DAMAGES ESTIMATES

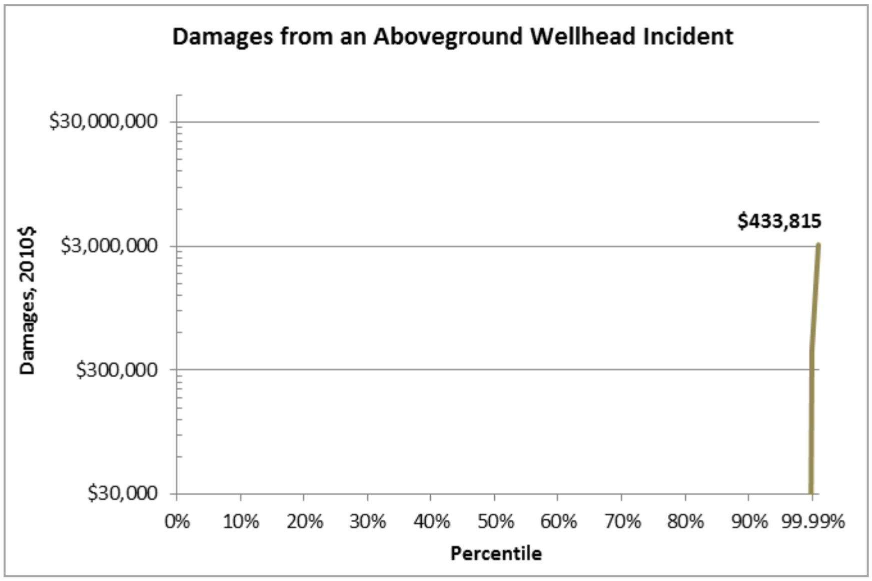
This section summarizes potential damages associated with three types of sequestration site events (aboveground wellhead incident, injection well incident and 'other well' incident) that have the potential to cause non-negligible damages within the 100-year analysis period.

DAMAGES FROM AN ABOVEGROUND WELLHEAD INCIDENT

Estimated damages from an aboveground wellhead incident are presented in Figure 8-2. Due to a very low annual event probability (6-in-100,000), damages at the 50th, 95th, and 99th percentile are all \$0. At the 99.99th percentile, damages are estimated at \$0.4 million. Damages primarily arise from potential human health effects due to H_2S.

[18] See Appendix A.

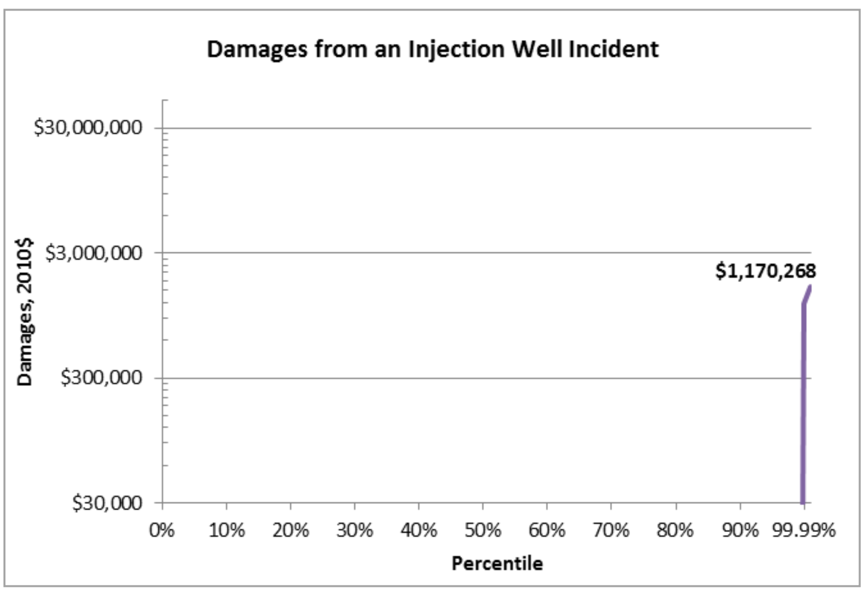
Figure 8-2. Damages from an Aboveground Wellhead Incident



DAMAGES FROM AN INJECTION WELL INCIDENT

Estimated damages from an injection well incident are presented in Figure 8-3. Due to a very low annual event probability of three in 100,000, damages at the 50th, 95th, and 99th percentile are all $0. At the 99.99th percentile, damages are estimated at $1.2 million. Damages primarily arise from potential human health effects due to H_2S.

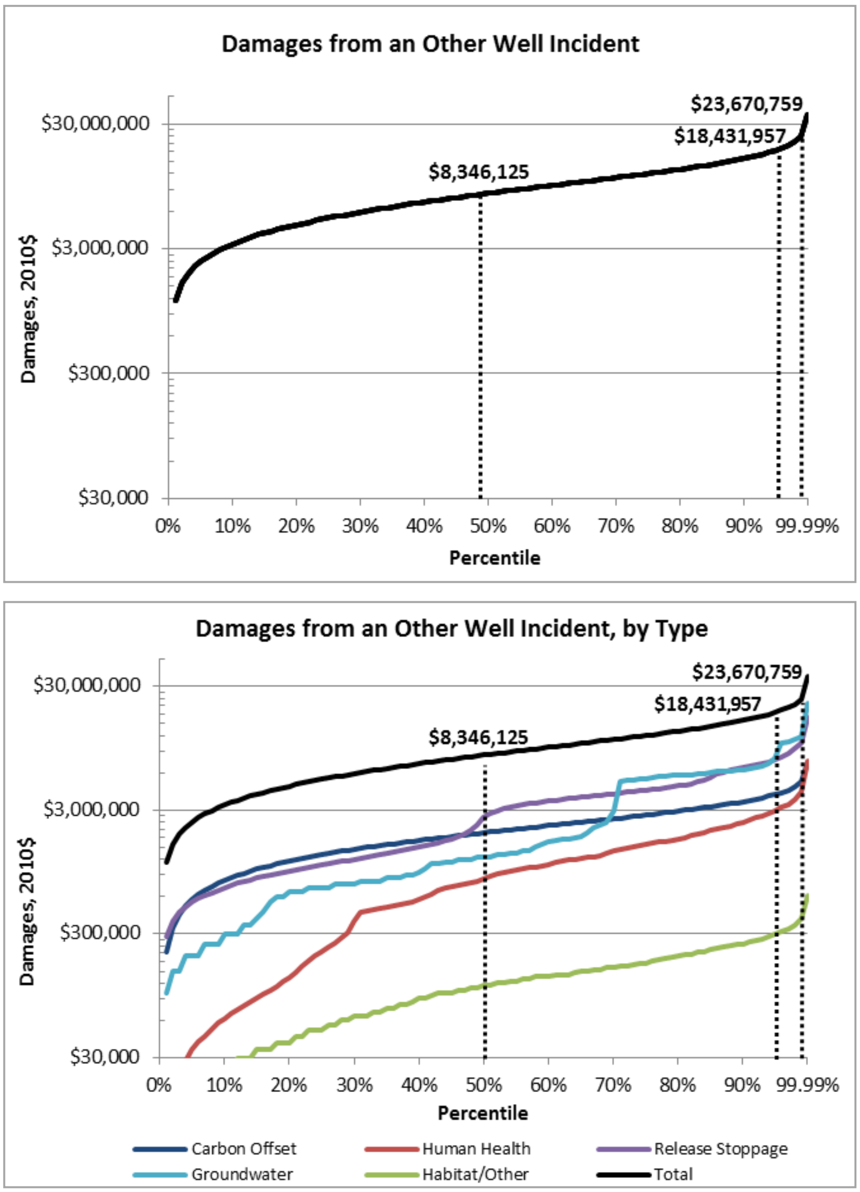
Figure 8-3. Damages from an Injection Well Incident



DAMAGES FROM AN OTHER WELL INCIDENT

Estimated damages from an other well incident are presented in Figure 8-4. By far, this incident type is the single biggest driver of potential damages for the Jewett, TX CCS operation. As a shown, 50th percentile damages are estimated at $8.4 million, with 95th percentile damages estimated at $18.4 million. As shown in Figure 8-4, several types of damages contribute substantially to the total, including groundwater, CO_2 leakage and human health effects.

Figure 8-4. Damages from an Other Well Incident



CHAPTER 9 | CONCLUSIONS AND UNCERTAINTIES

The Monte Carlo approach used in this study provides an analytically rigorous foundation for understanding and managing prospective risks that could arise from CCS projects. The application of this model to a 'realistic' site-specific project, e.g., Jewett, TX FutureGen site, provides successful proof of concept that estimates of monetized damages with associated probabilities can be developed on a site-specific basis for CCS projects.

A key consideration that is reaffirmed by the results from this study is the importance of site location. Specifically, estimated damages are driven by the composition of the CCS plume, the operating structure of the plant, the integrity of the pipeline and site-specific geology. Notably, changes in these risk categories can vary damages estimates by orders of magnitude. Accordingly, results from this study suggest that well-sited, well-operated CCS projects have a relatively small potential for damages, but sound site selection and site-specific monitoring are essential.

Deriving estimates of prospective damages for the Jewett, TX CCS project necessitates that this study impute a variety of assumptions, each of which is associated with varying degrees of uncertainty. Specifically, the damages estimates discussed herein rely in substantial part on the FutureGen Risk Assessment and EIS analyses, both of which were subject to significant public review and comment. In general, the FutureGen analyses apply conservative assumptions, which are more likely to overstate the potential for damages when applied without modification in this study.

As described throughout this document, FutureGen analyses do not provide all of the inputs needed to estimate potential financial consequences if one or more releases occur at the plant, pipeline and/or sequestration portions of the project. We relied on publicly available information to address these additional data needs wherever possible, supplemented by expert professional judgment, as well as communications with industry and trade association experts.

With respect to the key conclusions and drivers of this analysis and associated results, we make the following observations, specific to the Jewett, TX site evaluated as proof of concept:

- **Overall, estimated total damages are approximately \$8.5 million (50th percentile) and \$18.6 million (95th percentile)** – These estimates include all potential adverse events over the 100-year analysis period, and are expressed in 2010\$. These estimates translate to approximately \$0.17 (50th percentile) and \$0.37 per tonne of CO_2 sequestered (50 million tonnes of CO_2 are expected to be sequestered at the Jewett, TX site);

- **Potential releases at oil & gas/other wells in the sequestration site area are responsible for over 95% of estimated total damages** – At the Jewett, TX site there are believed to be dozens of deep oil & gas wells and potentially other old wells. FutureGen analyses assign release probabilities to those wells (i.e., 7-in-100 annual chance of a release incident) that are multiple orders of magnitude higher than any other type of release event at the plant or sequestration site, contributing substantially to the prominence of this potential damages category.[19] Several types of potential damages contribute substantially to this total, including the cost of actions to: stop the release; address groundwater contamination; pay for offsets to address CO_2 leakage; compensate for human health damages; and (much less significantly) address habitat/other damages.

- **Potential damages associated with other types of sequestration site events are negligible** – Estimated damages for aboveground wellhead incidents and injection well incidents are \$0 for both 50th and 95th percentile cases, reflecting their extremely low event probabilities, i.e., 3-in-100,000 annual probability for injection well releases and 6-in-100,000 annual probability for aboveground wellhead releases;

- **Potential damages associated with plant site events are negligible** – Estimated damages for plant site releases are \$0 for both 50th and 95th percentile cases, reflecting their extremely low event probabilities, i.e., 5.5-in-100,000 annual probability;

- **Potential damages associated with pipeline events are low** – Estimated damages for pipeline rupture events are \$0 for 50th percentile and approximately \$0.3 million for 95th percentile cases. Estimated damages for pipeline puncture events are \$0 for 50th percentile and approximately \$0.2 million for 95th percentile cases. Although the likelihood of pipeline rupture and puncture events are reasonably likely to occur during the 50 year operational period (annual probabilities of 1-in-200 and 1-in-100, respectively), if an event occurs the extremely rural setting severely limits potential human health damages, the amount of CO_2 in the affected 5 mile section of pipeline (in between safety shutoff valves) is relatively low (1,290 tonnes) and the potential for ecological/other damages is limited.

- **If there were no H_2S in the sequestration stream, total estimated damages would be approximately 10% - 15% lower -** Although H_2S is the primary driver of human health risks in this analysis, the extremely rural location for plant, pipeline and sequestration operations severely limits potential human health damages, minimizing the added impact of H_2S.

[19] Pipeline punctures or ruptures are the next most common type of release (annual probabilities of 1-in-100 and 1-in-200, respectively), but for reasons described elsewhere are associated with much smaller potential monetary damages.

With respect to key uncertainties, we make the following observations specific to the Jewett, TX site evaluated:

- **Estimated damages associated with CO_2 leakage are highly uncertain** – The potential volume of CO_2 released to the atmosphere if an adverse event occurs, and the potential cost ($ per tonne) associated with such releases, are both highly uncertain. For uncertainty analysis purposes, we note that the 'base case' Monte Carlo model CO_2 leakage damages estimates at the sequestration site are approximately $2.0 million (50th percentile) and $4.0 million (95th percentile).

  To address CO_2 offset pricing uncertainty, the Monte Carlo model includes a relatively broad range of unit costs for CO_2 leakage; that is, between approximately $10 and $320 per tonne depending on the year. Based on currently available information and forecasts, it is difficult to envision offset prices exceeding this range. However, it is possible that CO_2 emissions remain unregulated in the future, resulting in no cost to project proponents for CO_2 releases to the atmosphere. In such a scenario, there would be no CO_2 leakage damages.

  With respect to volume uncertainty, in the 'base case' Monte Carlo model, potential leakage volumes at the sequestration site range between 99 tonnes and 5,400 tonnes. For sensitivity analysis purposes, if the model were changed to assume that each sequestration site leakage event released 50,000 metric tonnes to the atmosphere (instead of a randomly selected volume between 100 and 5,400 tonnes) 50th and 95th percentile damages estimates for CO_2 leakage would increase to approximately $36.6 million and $67.7 million, respectively using 'base case' Monte Carlo CO_2 offset pricing assumptions.

- **Potential groundwater damages are uncertain, but likely constrained by site-specific factors** – This study includes a series of bounding calculations designed to broadly assess potential groundwater damages arising from CCS at the Jewett, TX site. A more detailed assessment of site-specific damages arising from potential impacts to groundwater would require data that are not readily available for the Jewett, TX site, and a commitment of resources beyond the scope of this analysis.

  Nevertheless, readily available information indicates that there are several site-specific factors that act to limit the potential magnitude of damages at the Jewett, TX sequestration location, including but not limited to:

  - Prior to the sequestration project moving forward, project sponsors likely would exercise their existing options to purchase groundwater rights in the sequestration area;
  - Groundwater surrounding the Jewett, TX sequestration site currently is not used for commercial, industrial, or other purposes;
  - The sequestration site and surrounding area has very few residences;

- Publicly available groundwater sampling data from the area suggest a high likelihood that carbonate minerals in the matrix exceed 1%, providing a natural buffering capacity that substantially limits the potential for pH-related impacts; and
- Inexpensive point-of-use treatment technologies are readily available for the types of impacts that might occur.

In light of these factors, readily available site information and expert professional judgment, the Monte Carlo analysis assigns damages to 'other well' release events in the following manner: \$50,000 (75% probability); \$500,000 (20% probability); or \$5,000,000 (5% probability). Given the considerations noted above, it is difficult to envision 'per-event' damages exceeding the range utilized. However, the percentages assigned to each portion of the assigned damages range also are uncertain. For sensitivity analysis purposes, changing the damages distribution percentages to 50% (damages of \$50,000), 30% (damages of \$500,000) and 20% (damages of \$5,000,000) increases sequestration site groundwater damages from \$1.3 million to \$6.7 million (50^{th} percentile) and from \$7.9 million to \$20.2 million (95^{th} percentile).

- **FutureGen use of averaged atmospheric conditions could understate potential 'upper end' estimates of human health effects** – The Monte Carlo analysis uses FutureGen estimates of human health impacts 'as is', and as previously noted those estimates reflect averaged atmospheric conditions. While averaged conditions likely provide a reasonable estimate of 'most likely' impacts, that approach can lead to understatement of 'upper end' effects if a subset of atmospheric conditions could lead to higher plume concentrations, longer plume durations and/or plumes directed towards areas with higher populations densities. Publicly available information from FutureGen analyses is not sufficient to plausibly quantify the potential significance of this factor, although the highly rural setting for the Jewett, TX plant, pipeline and sequestration site likely limits the potential magnitude of understatement.

- **FutureGen estimates of sequestration site event probabilities are used 'as is' in the Monte Carlo model, and FutureGen does not quantify the potential magnitude of underlying uncertainties** – FutureGen estimates of sequestration site event probabilities are based on evaluation of site-specific data, industrial and natural analogs and expert judgment. While the underlying uncertainty in these estimates is not quantified, in some cases FutureGen identifies ranges for event probabilities (e.g., other well releases). In such cases, the Monte Carlo model conservatively uses the highest event frequency within the range (rather than the midpoint or low end) and therefore may be more likely to overstate than understate potential damages.

- **FutureGen estimates of pipeline event probabilities are used 'as is' in the Monte Carlo model, and likely have a relatively low level of uncertainty** – FutureGen estimates of pipeline failure frequencies are based on a substantial database of pipeline failure incidents maintained by the U.S. Office of

Pipeline Safety. The existence and direct relevance of this event frequency data suggests a relatively low level of uncertainty for pipeline event probabilities.

- **FutureGen does not estimate plant event probabilities, estimates used in the Monte Carlo model are based on information in published technical literature and expert judgment** – While there is uncertainty associated with this parameter, failure of plant equipment like that used for CO_2 removal purposes is rare**.** Given the low population density around the Jewett, TX plant, the event failure frequency used in the Monte Carlo model (5.5-in-100,000 annual chance) would have to understate event frequency by at least a factor of 5 before potential plant site event damages would become something other than a negligible contributor to ‘most likely’ and ‘upper end’ damages for the Jewett, TX plant.

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APPENDIX A | KEY DATA ASSUMPTIONS

This report uses estimated probabilities and magnitudes of risks as reported in the FutureGen 1.0 risk assessment for the Jewett, Texas project (Jewett). As indicated in the report, there are certain instances where the FutureGen risk assessment (FGRA) for Jewett either insufficiently characterizes or omits the estimate of probability and/or magnitude of certain risks. The sponsor group determined that the missing elements were important to test the model, gain a sense of the order of magnitude of potential impacts, and to gain insight into the full array of potential damages that could arise from a CCS project. Given limited resources, the sponsor group undertook a review of missing information and developed best estimates based on additional written papers and industry experience. Under normal conditions for a 'real' project, additional effort would be needed to develop actual site specific parameters for the missing data.

This Appendix describes the missing data to be assessed, the process for developing each assumption, and the final assumptions of probability or magnitude of specified risks used in the analysis. These assumptions are presented to ensure transparency. It is important to note that the assumptions in this Appendix have not been reviewed by FutureGen and are not put forward as assessments for the Jewett site. Rather, they are assumptions that appear to be in a reasonable range of likelihood and are acceptable to the sponsor group for the sole purpose of testing the model and exploring potential results.

BACKGROUND

Based on the preliminary review of readily available information, IEc consulted with the sponsor group to estimate values for six parameters that were either insufficiently characterized (e.g., reported in qualitative terms) or not addressed in FutureGen Risk Assessment information:

1. An annual likelihood that CO_2 separation or compression & drying equipment and/or the associated piping would rupture.
2. A forecast of future U.S. unit values (i.e., $ per ton) for CO_2 through Year 2110.
3. An estimated duration and flux of potential releases to groundwater from a deep well release of CO_2 prior to its detection (and subsequent action to stop the release).
4. An estimated duration and flux of potential releases to the atmosphere from a deep well release of CO_2 prior to its detection (and subsequent action to stop the release).
5. The carbonate mineral content of the Carrizo-Wilcox or Queen City aquifer matrix in central Texas.

6. An estimated cost to stop a release from a deep well extending 10,400 ft below surface (not including potential groundwater treatment costs).

What follows is a description of the sources of information consulted and, where useful, a summary of the discussion points raised in selecting a useable assumption for each area above.

1. AN ANNUAL LIKELIHOOD THAT CO_2 SEPARATION OR COMPRESSION & DRYING EQUIPMENT AND/OR THE ASSOCIATED PIPING WOULD RUPTURE.

The sponsor group sought publicly available reports indicating the annual percent chance of rupture and asked industry members within the group to validate that reported ranges were reasonably consistent with their experience.

The assumptions used in the Carbon Capture Sequestration Valuation Study ('CCSVS') were based on a report released through the Health and Safety Executive (HSE) of the United Kingdom in 2006. The report was prepared by Clive Nussey and is entitled: 'Failure frequencies for major failures of high pressure storage vessels at COMAH sites: A comparison of data used by HSE and the Netherlands.'

The report categorizes ruptures by hole size: small hole, large hole, and catastrophic release. Table 4 on page 10 of the report provides the following HSE estimates of annual probability of failure and these were used in the CCSVS analysis:

TYPE OF FAILURE	ANNUAL % CHANCE OF RUPTURE
Catastrophic	$2\text{-}6 \times 10^{-6}$
Large Hole	5×10^{-6}
Small Hole	55×10^{-6}

This report can be found online at: http://www.hse.gov.uk/comah/highpressure.pdf.

2. A FORECAST OF FUTURE U.S. UNIT VALUES FOR CO2 THROUGH YEAR 2110.

The sponsor group felt that projections of future prices for CO_2 would be a sufficient proxy for CO_2 unit values. Further, the sponsor group did not feel qualified to unanimously endorse any specific projection as being more likely than any other. That said, a majority of sponsor group members were in favor of using projections developed by economist William Nordhaus in 2010 and published in an article entitled: 'Economic aspects of global warming in a post-Copenhagen environment,' in Proceedings of the National Academy of Sciences, 107(26): 11721-11726 (and available online at: www.pnas.org/cgi/doi/10.1073/pnas.1005985107).

The article and additional information about the RICE models used by Dr. Nordhaus are also available on the following website: http://nordhaus.econ.yale.edu/RICEmodels.htm. In this use of the model, the economically optimal emission reductions path leads to a peak in atmospheric concentration of CO_2 at just under 600 ppm CO_2 in around 2080, before stabilizing at around 500 ppm CO_2 in 2200. The corresponding years and modeled dollar values for this path were used in the CCSVS analysis and are reprinted in the following table:

YEAR	OPTIMAL/600 PPM (LOW)	LIMIT TO 2 DEGREES (HIGH)
	$/TONNE CO_2	$/TONNE CO_2
2015	10.28	21.49
2025	17.46	38.58
2035	24.12	61.45
2045	32.21	95.50
2055	41.85	144.45
2065	53.15	201.31
2075	66.30	273.04
2085	81.40	321.71
2095	98.49	253.46
2105	117.43	197.30
2115	137.95	193.21

3. AN ESTIMATED DURATION AND FLUX OF POTENTIAL RELEASES TO GROUNDWATER FROM A DEEP WELL RELEASE OF CO_2 PRIOR TO ITS DETECTION.

4. AN ESTIMATED DURATION AND FLUX OF POTENTIAL RELEASES TO THE ATMOSPHERE FROM A DEEP WELL RELEASE OF CO_2 PRIOR TO ITS DETECTION.

The assumptions for both sets of fluxes were developed together and so the method is reported here for both data points.

Step 1: Identify Release Scenarios, Probabilities and Flux.

The FutureGen risk assessment for the Jewett project contained three tables describing site release scenarios, event probabilities by release scenario, and of those events, and the predicted annual flux from those events (the tables have been reproduced below). Since these tables do not utilize the same events or contain similar information for all events, the first step required the development of a list of release scenarios and the associated probability and flux.

TABLE 6-1. SUMMARY OF SEQUESTRATION SITE RELEASE SCENARIOS

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

TABLE 2. EVENT PROBABILITIES BY RELEASE SCENARIO FOR JEWETT, TX SITE

RELEASE SCENARIO	RELEASE LIKELIHOOD (ANNUAL)
Pipeline Events	
Pipeline Rupture	1-in-200 (0.5%)
Pipeline Puncture	1-in-100 (1.0%)
Sequestration Site Events	
Wellhead Equipment Rupture	6-in-100,000 (0.006%)
CO_2 Injection Well Leak	3-in-100,000 (0.003%)
Other Well Leak	7-in-100 (7.0%)
Rapid Leakage through Caprock	2-in-10 billion (0.00000002%)
Slow Leakage through Caprock	4-in-100,000 (0.004%)
Release through Existing, Induced Faults	2-in-100 million (0.000002%)
Source: FGRA Table 6-11	

TABLE 4. FUTUREGEN RISK ASSESSMENT TABLE 5-8, PP 5-41 TO 5-46 WITH STUDY ANALYSIS

SITE	MECHANISM	ANNUAL FLUX IF EVENT OCCURS	
		MINIMUM (MT/YR)	MAXIMUM (MT/YR)
Jewett	Leakage via Upward Migration through Caprock due to Gradual and slow release	0	4,918
	Leakage via Upward Migration through Caprock due to catastrophic failure and quick release	NA	NA
	Leakage through existing faults due to increased pressure (regional overpressure)	118	3,526
	Release through induced faults due to increased pressure (local overpressure)	24	705
	Leakage into non-target aquifers due to unknown structural or stratigraphic connections	2,350	79,910
	Leakage into non-target aquifers due to lateral migration from the target zone	28,928	867,845
	Leaks due to deep CO_2 wells, high rate	11,000	11,000
	Leaks due to deep CO_2 wells, low rate	200	200
	Leaks due to deep O&G wells, high rate	11,000	11,000
	Leaks due to deep O&G wells, low rate	200	200
	Leaks due to undocumented deep wells, high rate	11,000	11,000
	Leaks due to undocumented deep wells, low rate	200	200

Six scenarios were used:

1. Rapid release through cap rock.
2. Gradual release through cap rock.
3. CO_2 injection wells.
4. Oil & Gas wells.
5. Undocumented wells.
6. New and Induced faults.

Step 2: Assume Detection Levels and Timing

In order to assume a volume of released CO_2, the group used an assumption about the amount of released CO_2 that could be detected through monitoring. Assumed detection levels were based on the assumed sensitivity of the monitoring equipment and the frequency of monitoring. A default was developed based on anecdotal information collected from project operators and researchers suggesting a detection level of .3TPD is a detection level (meaning smaller amounts of leakage would not be detected).

Step 3: Assume Movement to Near Surface Waters and Atmosphere

The paper: 'Detection of CO_2 leakage by eddy covariance during the ZERT project's CO2 release experiments,' by Jennifer L. Lewicki, George E. Hilley, Marc L. Fischer, Lehua Pan, Curtis M. Oldenburg, Laura Dobeck, and Lee Spangler modeled movement of CO_2 released in the subsurface. The model suggested there would be some attenuation of released CO_2 in the rock formation as it migrated to the surface. Some of this CO_2 would be released into near-surface groundwater and some CO_2 would migrate all the way to the atmosphere. This basis approach was applied as a convention for subsurface releases from closed wells or through formations. The convention was to assume that 0.01% of seepage reaches groundwater and 10% of that reaches the atmosphere. Releases from operational wells were assumed to migrate quickly to the surface and then be released to the atmosphere.

Applying these steps to the six release events suggests the following:

1. Rapid release through cap rock.

Because there is no estimate of flux for this scenario in the FGRA, this pathway has not been analyzed. An option would be to use the FGRA probability for some initial period of years (perhaps 20) and assume that 50% (or some other percentage) reaches both groundwater and atmosphere. With no clear basis or consensus regarding such assumptions, it was decided not to develop this scenario.

2. Gradual release through cap rock.

A. Years 1-50 (operational period): Assume that there is subsurface monitoring and surface monitoring that takes a 30 day average. Assume detection level of 0.3 T/day and maximum flux of 13.5TPD per FGRA. Assume it take 3 months to correct after detection (for a total of 120 days).

   Minimum = 120D*0.3T = 36 T

   Maximum = 120D*13.5T = 1,620 T

B. Years 50-100 (Closure period): Assume that there is subsurface monitoring and surface monitoring that takes a 6 month / 180 day average. Assume detection level of 0.3 T/day and maximum flux of 13.5TPD per FGRA. Assume it take 3 months / 90 days to correct after detection (for a total of 270 days).

   Minimum =270D*0.3T = 81 T

   Maximum = 270D*13.5T = 3,645 T

C. Groundwater flux: estimate 0.01% reaches groundwater:

   Operational: Min = 0.01%*36T = 0.004 T // Max = 0.01% *1,620T = .16T

   Closure: Min = 0.01%*81T = 0.01 // Max = 0.01% *3,645T = 0.36T

D. Atmospheric flux – assume 10% of GW impact reaches the atmosphere

   Potential for greater movement through wells, less impact on water

3. CO_2 injection wells

A. Operational wells – assume that there are sensitive detection levels, continuous monitoring, max 30 days to control;

   Min: use 0.1 T from In Salah report

   Max: use min flux from FGRA of .55 TPD = 30 D * .55 TPD = 16.5 T

B. Closed wells – assume detection sensitive but 6 months (180D) to control;

   Min: use 0.1 T from In Salah – 180D * 0.1TPM = 0.6 T

   Max: use min flux from FGRA of .55 TPD = 180 D * .55TPD = 99 T

4. Oil & Gas (O/G) wells

Assume same leakage / detection volume as CO_2 injection wells but that all O/G wells in project area are like closed wells. FGRA gives this class of wells a higher probability of occurrence – This should perhaps be altered given the regulatory requirements for AOR but was not for the analysis.

Min: use min flux from FGRA of 180D * .55 TPD = 99 T

Max: use max flux from FGRA of 180 D * 30 TPD = 5,400 T

5. Undocumented wells

These wells are covered in the other well category which has a higher probability of occurrence. Since they are undocumented, there may not be as rapid detection. However, since they are undocumented and therefore difficult to make accurate assumptions about, and given AOR requirements, it was decided to omit these wells from the analysis.

6. New and Induced faults

FGRA assigns these a very low probability. The group agreed with an assumption that such releases would be found in the first years of operation and should not be a problem after injection ceases. Assume quick detection but up to 6 months to control.

> Min: since FGRA min flux is 0.07 TPD – a level we believe is undetectable; use Min detectable flux (GCCSI) of .3 TPD * 180 D = 55 T
>
> Max: use max flux from FGRA of 9.6 TPD * 180 D = 1,728 T

5. THE CARBONATE MINERAL CONTENT OF THE CARRIZO-WILCOX OR QUEEN CITY AQUIFER MATRIX IN CENTRAL TEXAS.

This value relates to the potential buffering capacity of the rock formation into which potentially leaked CO_2 would migrate. The buffering capacity provides insight into the amount of potentially leaked CO_2 that could migrate to the surface, impacting near surface ground water (including drinking water) or being released to the atmosphere. This value is determined regionally or for geologic formations.

Expert geologists were consulted regarding the geologic area near Jewett and they pointed to a paper published by El Sevier in 1987, entitled 'Diagenetic evolution of Cenozoic sandstones, Gulf of Mexico sedimentary basin.' This paper provides a peer reviewed estimate of range of the mineral content in the area of 0% to 4%. It was determined that 2% would be acceptable for purposes of the CCSVS analysis.

The paper is available through El Sevier:
'Diagenetic evolution of Cenozoic sandstones, Gulf of Mexico sedimentary basin'
Lynton S. Land, Kitty Lou Milliken, Earle F. McBride
Department of Geological Sciences, University of Texas at Austin, Austin, TX 78713 U.S.A.
Received 27 October 1986. Available online 22 April 2003.
http://dx.doi.org/10.1016/0037-0738(87)90033-9

It can also be found online at:
http://www.sciencedirect.com/science/article/pii/0037073887900339

6. AN ESTIMATED COST TO STOP A RELEASE FROM A DEEP WELL EXTENDING 10,400 FT BELOW SURFACE (NOT INCLUDING POTENTIAL GROUNDWATER TREATMENT COSTS).

The sponsor group consulted the well workover cost assumptions in a report entitled: '2008 – The Economic Impact of New Mexico's Oil and Gas Industry,' by Jay Lillywhite and C. Meghan Starbuck (available online at: http://www.energyadvancesnewmexico.com/files/NM_Economic_Impact.pdf) to develop a range of estimates that were further tested by informally consulting industry experts. The report suggested an average annual cost of roughly $15/foot for subsurface repair in wells that were about 8,000 feet deep. In consulting with industry, we further developed this estimate to account for the age of the well, and for normal and rare damage. The final estimate is included in the table below:

RELATIVE DAMAGE	DOLLAR ESTIMATE	INCIDENCE
Average Damage	$50,000 – 300,000	90%
High End	$2M – 3.65M	10%

SUMMARY OF PROPOSED CCS VALUATION PARAMETERS				
PARAMETER DESCRIPTION		UNIT	VALUE	PRIMARY DATA SOURCE
1	Annual likelihood that CO_2 Separation or Compression & Drying equipment/associated piping would rupture	% chance of rupture, annually	2-6 x10^{-6} for catastrophic 5 x 10^{-6} for large hole 55 x 10^{-6} for small hole	U.K. HSE Report on High Pressure Vessel Failure
2	Forecast of future U.S. unit values for leaked CO_2 through Year 2110	$/ton	Use the 600 ppm scenario with prices ranging from $10.28 to $137.95 over 100 yrs	William Nordhaus // RICE Model
3	Estimated duration and flux of potential releases to groundwater from a deep well release of CO_2 prior to its detection (could be a point estimate, range or a distribution)	Flux (tons/unit time) and Duration (time)	See discussion above	See discussion above
4	Estimated duration and flux of potential releases to atmosphere from a deep well release of CO_2 prior to its detection (could be a point estimate, range or a distribution)	Flux (tons/unit time) and Duration (time)	See discussion above	See discussion above
5	Carbonate mineral content of Carrizo-Wilcox or Queen City aquifer matrix in central Texas (~60 miles east of Waco, TX)	% of matrix	Range: 0% to 4% Use 2% for analysis	Report: Diagenetic Evolution Of Cenozoic Sandstones, Gulf Of Mexico Sedimentary Basin
6	Estimated cost to stop a release from a deep well extending 10,400 ft below surface (not including potential groundwater treatment costs, which will be addressed separately)	$ per well release	Average case: $50-300K High end (rare cases) $2-3.65M – per industry review Per discussion: Assume 90% occurrences are average and 10% are high cost	Consult with industry members of sponsor group and review report: The Economic Impact of New Mexico's Oil and Gas Industry

APPENDIX B | MONTE CARLO MODEL AND SCENARIO SUBMODULE DESCRIPTIONS

This appendix provides the technical description of the Carbon Capture and Sequestration Monte Carlo model of damages presented in this report. It is intended that the following mathematical description of the Monte Carlo model provide, in combination with the tables of discrete probability distributions for random variables listed in the main text, the blueprint necessary to understand the calculations underlying results and conclusions herein.

EVENT SCENARIOS

The full plant damage model is composed of multiple sub-modules of independently modeled damage-producing event scenarios. The events are modeled as either 50-year or 100-year time series based on whether the specific event is solely related to active operation of the plant or, otherwise, continues after the 50-year lifespan of active operations. There is an independent annual probability of each event. A full list of the six event scenarios appears below.

Event Scenarios Modeled for 50 Years of Active Plant Operations

1. Pipeline Puncture
2. Pipeline Rupture
3. Aboveground Wellhead Release
4. Plant Site Event

Event Scenarios Modeled for 100 Years of Active and Post-Closure Plant Operations

5. Injection Well Leakage
6. Other Well Leakage

COMPONENTS OF DAMAGE

Each scenario includes sub-modules independently calculating the various components of total scenario damages. As detailed in the scenario-specific descriptions below, total event scenario damages consist of either all or a subset of the following components.

1. Health Damages
    a. By chemical

i. H_2S
ii. CO_2

b. By severity
   i. Temporary
   ii. Irreversible
   iii. Fatal

2. Ecological damages
3. Release Stoppage Costs
4. Carbon Offset Costs
5. Groundwater Damages

CARBON PRICE CALCULATION

As part of the Carbon Offset Costs sub-modules, the carbon price is the lone random variable shared between the various event scenarios. All other random variables, regardless of being drawn from identical probability distributions (e.g., health damage values, environmental damage vales, etc.), are selected separately for each event scenario and sub-module. Because the carbon price would be identical for events occurring in a given year, it is an input into all Carbon Offset-containing scenarios.

The carbon price in dollars per tonne $\boldsymbol{p_t}$ in year t is a random variable selected from the uniform probability distribution $\boldsymbol{U}(\boldsymbol{min_{p_t}}, \boldsymbol{max_{p_t}})$ with minimum price in year t of $\boldsymbol{min_{p_t}}$ and maximum price in year t of $\boldsymbol{max_{p_t}}$. The table of annual carbon price minimum and maximum values is provided in the report text.

PIPELINE PUNCTURE SCENARIO

The total Pipeline Puncture damages $\boldsymbol{D_p}$ are calculated as,

$$\boldsymbol{D_p} = \sum_{t=1}^{50} \boldsymbol{E_{p,t}}(\boldsymbol{V_{p,t}} + \mathbf{1290}\boldsymbol{p_t} + \sum_{c}\sum_{m} \boldsymbol{N_{p,c,m,t}}\boldsymbol{H_{p,c,m,t}})$$

For:

Health effect category values $\boldsymbol{m} = \{\boldsymbol{temporary}, \boldsymbol{irreversible}, \boldsymbol{fatal}\}$

Chemical categories $\boldsymbol{c} = \{\boldsymbol{CO_2}, \boldsymbol{H_2S}\}$.

Where:

$\boldsymbol{E_{p,t}}$ is the random variable signifying the occurrence of a pipeline puncture event in year t with a value taken from the Bernoulli distribution such that $\mathbf{Pr}(\boldsymbol{E_{p,t}} = \mathbf{1}) = \mathbf{1} - \mathbf{Pr}(\boldsymbol{E_{p,t}} = \mathbf{0}) = \boldsymbol{e_p} = \mathbf{0.01}$ and $\boldsymbol{e_p}$ is the annual probability of a pipeline puncture event;

$\boldsymbol{V_{p,t}}$ is the random variable totaling the dollar value of ecological damages for a pipeline puncture event in year t with a value taken from the ecological damages discrete probability distribution table;

$\boldsymbol{p_t}$ is the random variable signifying the dollars per tonne of carbon released in year t (as described above);

$\boldsymbol{N_{p,c,m,t}}$ is the random variable counting the number of pipeline puncture health effects due to chemical c in health effect category $\boldsymbol{m}$ in year t with a value taken from the discrete probability distribution table;

$\boldsymbol{H_{p,c,m,t}}$ is the random variable representing the dollar value of each pipeline puncture health effect due to chemical c in health effect category $\boldsymbol{m}$ in year t with a value taken from the discrete probability distribution table.

PIPELINE RUPTURE SCENARIO

The total Pipeline Rupture damages $\boldsymbol{D_r}$ are calculated as,

$$\boldsymbol{D_r = \sum_{t=1}^{50} E_{r,t}(V_{r,t} + 1290p_t + \sum_{c}\sum_{m} N_{r,c,m,t}H_{r,c,m,t})}$$

For:

Health effect category values $\boldsymbol{m} = \{\boldsymbol{temporary, irreversible, fatal}\}$

Chemical categories $\boldsymbol{c} = \{\boldsymbol{CO_2, H_2S}\}$.

Where:

$\boldsymbol{E_{r,t}}$ is the random variable signifying the occurrence of a pipeline rupture event in year t with a value taken from the Bernoulli distribution such that $\mathbf{Pr}(\boldsymbol{E_{r,t}} = \mathbf{1}) = \mathbf{1} - \mathbf{Pr}(\boldsymbol{E_{r,t}} = \mathbf{0}) = \boldsymbol{e_r} = \mathbf{0.005}$ and $\boldsymbol{e_r}$ is the annual probability of a pipeline rupture event;

$\boldsymbol{V_{r,t}}$ is the random variable totaling the dollar value of ecological damages for a pipeline rupture event in year t with a value taken from the discrete probability distribution table;

$\boldsymbol{p_t}$ is the random variable signifying the dollars per tonne of carbon released in year t (as described above);

$\boldsymbol{N_{r,c,m,t}}$ is the random variable counting the number of pipeline rupture health effects due to chemical c in health effect category $\boldsymbol{m}$ in year t with a value taken from the discrete probability distribution table;

$\boldsymbol{H_{r,c,m,t}}$ is the random variable representing the dollar value of each pipeline rupture health effect due to chemical c in health effect category $\boldsymbol{m}$ in year t with a value taken from the discrete probability distribution table.

ABOVEGROUND WELLHEAD RELEASE SCENARIO

The total Aboveground Wellhead Release damages $\boldsymbol{D_a}$ are calculated as,

$$\boldsymbol{D_a} = \sum_{t=1}^{50} \boldsymbol{E_{a,t}}\left(\sum_{m} \boldsymbol{N_{a,m,t}} \boldsymbol{H_{a,m,t}}\right)$$

For health effect category values $\boldsymbol{m} = \{\boldsymbol{temporary}, \boldsymbol{irreversible}, \boldsymbol{fatal}\}$,

Where:

$\boldsymbol{E_{a,t}}$ is the random variable signifying the occurrence of an aboveground wellhead release event in year t with a value taken from the Bernoulli distribution such that $\mathbf{Pr}(\boldsymbol{E_{a,t}} = \mathbf{1}) = \mathbf{1} - \mathbf{Pr}(\boldsymbol{E_{a,t}} = \mathbf{0}) = \boldsymbol{e_a} = \mathbf{0.0000606}$ and $\boldsymbol{e_a}$ is the annual probability of an aboveground wellhead event;

$\boldsymbol{N_{a,m,t}}$ is the random variable counting the number of aboveground wellhead release health effects due to H_2S in health effect category $\boldsymbol{m}$ in year t with a value taken from the discrete probability distribution table;

$\boldsymbol{H_{a,m,t}}$ is the random variable representing the the dollar value of each aboveground wellhead release health effect due to H_2S in health effect category $\boldsymbol{m}$ in year t with a value taken from the discrete probability distribution table

PLANT SITE EVENT SCENARIO

The total Plant Site Event damages $\boldsymbol{D_s}$ are calculated as,

$$\boldsymbol{D_s = \sum_{t=1}^{50} E_{s,t}(N_{s,t}H_{s,t})}$$

Where:

$\boldsymbol{E_{s,t}}$ is the random variable signifying the occurrence of a plant site event in year t with a value taken from the Bernoulli distribution such that $\boldsymbol{\Pr(E_{s,t} = 1) = 1 - \Pr(E_{s,t} = 0) = e_s = 0.000055}$ and $\boldsymbol{e_s}$ is the annual probability of a pipeline puncture event;

$\boldsymbol{N_{s,t}}$ is the random variable counting the number of plant site temporary health effects due to H_2S in health effect category $\boldsymbol{m}$ in year t with a value taken from the discrete probability distribution table;

$\boldsymbol{H_{s,t}}$ is the random variable representing the dollar value of each plant site temporary health effect due to H_2S in health effect category $\boldsymbol{m}$ in year t with a value taken from the discrete probability distribution table.

INJECTION WELL LEAKAGE SCENARIO

The total Injection Well Leakage damages $\boldsymbol{D_i}$ are calculated as,

$$\boldsymbol{D_i = \sum_{t=1}^{100} E_{i,t}(V_{i,t} + C_{i,t}p_t \ + N_{i,t}H_{i,t})}$$

Where:

$\boldsymbol{E_{i,t}}$ is the random variable signifying the occurrence of an injection well leakage event in year t with a value taken from the Bernoulli distribution such that $\boldsymbol{\Pr(E_{i,t} = 1) = 1 - \Pr(E_{i,t} = 0) = e_i = 0.00003}$ and $\boldsymbol{e_i}$ is the annual probability of an injection well leakage event;

$\boldsymbol{V_{i,t}}$ is the random variable totaling the dollar value of ecological damages for an injection well leakage event in year t with a value taken from the discrete probability distribution table;

$\boldsymbol{C_{i,t}}$ is a random variable totaling the volume in tonnes of carbon released by the injection well leakage event in year t selected from the uniform probability distribution

$$\boldsymbol{U\begin{cases}(0.1, 16.5), if\ t \leq 60\\ (0.6, 99), if\ t > 60\end{cases}}$$

with minimum volume of either 0.1 or 0.6 tonnes depending on the value of year t, and maximum volume of either 16.5 or 99 tonnes depending on the value of in year t;

$\boldsymbol{p_t}$ is the random variable signifying the dollars per tonne of carbon released in year t (as described above);

$\boldsymbol{N_{i,t}}$ is the random variable counting the number of injection well leakage temporary health effects due to H_2S in year t with a value taken from the discrete probability distribution table;

$\boldsymbol{H_{i,t}}$ is the random variable representing the dollar value of each injection well leakage temporary health effect due to H_2S in year t with a value taken from the discrete probability distribution table.

OTHER WELL LEAKAGE SCENARIO

The total Other Well Leakage damages $\boldsymbol{D_o}$ are calculated as,

$$\boldsymbol{D_o = \sum_{t=1}^{100} E_{o,t}(V_{o,t} + C_{o,t}p_t\ + G_{o,t} + S_{o,t} + N_{o,t}H_{o,t})}$$

Where:

$\boldsymbol{E_{o,t}}$ is the random variable signifying the occurrence of an other well leakage event in year t with a value taken from the Bernoulli distribution such that $\boldsymbol{\Pr(E_{o,t} = 1) = 1 - \Pr(E_{o,t} = 0) = e_o = 0.07}$ and $\boldsymbol{e_o}$ is the annual probability of an other well leakage event;

$\boldsymbol{V_{o,t}}$ is the random variable totaling the dollar value of ecological damages for an other well leakage event in year t with a value taken from the discrete probability distribution table;

$\boldsymbol{C_{o,t}}$ is a random variable totaling the volume in tonnes of carbon released by the other well leakage event in year t selected uniform probability distribution $\boldsymbol{U(99, 5400)}$ with minimum volume of 99 tonnes and maximum volume of 5,400 tonnes;

$\boldsymbol{p_t}$ is the random variable signifying the dollars per tonne of carbon released in year t (as described above);

$\boldsymbol{S_{o,t}}$ is the random variable signifying the leakage stoppage costs in dollars in year t selected from the nested Bernoulli and uniform probability distributions

$$\boldsymbol{Pr\left(U_{S_{o,t}} = U(50000, 50000)\right) = 1 - Pr\left(U_{S_{o,t}} = U(2000000, 3650000)\right) = 0.9}$$

where $\boldsymbol{U_{S_{o,t}}}$ is the uniform probability distribution of $\boldsymbol{S_{o,t}}$.

$\boldsymbol{N_{o,t}}$ is the random variable counting the number of other well leakage temporary health effects due to H_2S in year t with a value taken from the discrete probability distribution table;

$\boldsymbol{H_{o,t}}$ is the random variable representing the dollar value of each other well leakage temporary health effect due to H_2S in year t with a value taken from the discrete probability distribution table.