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Low-Probability High-Consequence (LPHC) Failure Events in Geologic Carbon Sequestration Pipelines and Wells: Framework for LPHC Risk Assessment Incorporating Spatial Variability of Risk

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Abstract

If Carbon dioxide Capture and Storage (CCS) is to be effective in mitigating climate change, it will need to be carried out on a very large scale. This will involve many thousands of miles of dedicated high-pressure pipelines in order to transport many millions of tonnes of CO_2 annually, with the CO_2 delivered to many thousands of wells that will inject the CO_2 underground. The new CCS infrastructure could rival in size the current U.S. upstream natural gas pipeline and well infrastructure. This new infrastructure entails hazards for life, health, animals, the environment, and natural resources. Pipelines are known to rupture due to corrosion, from external forces such as impacts by vehicles or digging equipment, by defects in construction, or from the failure of valves and seals. Similarly, wells are vulnerable to catastrophic failure due to corrosion, cement degradation, or operational mistakes. While most accidents involving pipelines and wells will be minor, there is the inevitable possibility of accidents with very high consequences, especially to public health. The most important consequence of concern is CO_2 release to the environment in concentrations sufficient to cause death by asphyxiation to nearby populations. Such accidents are thought to be very unlikely, but of course they cannot be excluded, even if major engineering effort is devoted (as it will be) to keeping their probability low and their consequences minimized. This project has developed a methodology for analyzing the risks of these rare but high-consequence accidents, using a step-by-step probabilistic methodology. A key difference between risks for pipelines and wells is that the former are spatially distributed along the pipe whereas the latter are confined to the vicinity of the well. Otherwise, the methodology we develop for risk assessment of pipeline and well failures is similar and provides an analysis both of the annual probabilities of accident sequences of concern and of their consequences, and crucially the methodology provides insights into what measures might be taken to mitigate those accident sequences identified as of concern. Mitigating strategies could address reducing the likelihood of an accident sequence of concern, or reducing the consequences, or some combination. The methodology elucidates both local and integrated risks along the pipeline or at the well providing information useful to decision makers at various levels including local (e.g., property owners and town councils), regional (e.g., county and state representatives), and national levels (federal regulators and corporate proponents).

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1. Introduction

If Carbon dioxide Capture and Storage (CCS) is to be effective in mitigating climate change, it will need to be carried out on a very large scale. For example in the U.S., with transportation sector emissions (e.g., gasoline- and diesel-fueled cars and trucks) beyond the reach of current capture technology, CCS needs to target stationary sources such as U.S. coal and natural gas power plants that collectively emit approximately 3 Gt CO_2/year (U.S. EIA, 2015). For perspective, 3 Gt/year is approximately the same mass as the annual water that is produced during oil and gas production in the U.S., most of which is reinjected (Veil and Clark, 2011; Smit et al., 2014, Table 8.1.1). Thus the future buildout of CCS infrastructure in terms of pipelines and injection wells can be envisioned as being approximately the same size as the U.S. upstream oil and gas production and transportation infrastructure. Dooley et al. (2009) project that an effective CCS mitigation approach to climate change could entail construction of between 11,000 and 23,000 additional miles (18,000 to 37,000 km) of dedicated CO_2 pipelines in the U.S. before 2050, with each pipeline from source to sink on the order of tens of miles. Dooley et al. (2009) point out further that the demand for CO_2 pipeline capacity for CCS will unfold relatively slowly and in a geographically dispersed manner as capture facilities are built, storage sites are licensed, and pipelines are planned and built.

The pipelines that link large power plant CO_2 capture facilities with geologic carbon sequestration (GCS) sites will need to transport millions of tonnes of CO_2 per year. For example, a 1000 MW coal-fired power plant produces approximately 8 Mt CO_2/yr (Mt/yr = million tonnes per year), while a natural gas-fired power plant produces approximately 4 Mt CO_2/yr. Because of the large compressibility of CO_2 and relatively large molecular weight (44 g/mole), high-pressure CO_2 pipelines can transport large amounts of CO_2. For example, a buried onshore CO_2 pipeline operating at ambient soil temperature conditions of 12 ºC and a pressure of 110 bar can carry 3 or 20 Mt CO_2/yr for pipe diameter of 16 in (41 cm) or 30 in (76 cm), respectively, easily capable of supporting CCS from a large power plant (Skovholt, 1993).

Once a large CO_2 pipeline reaches a GCS site, multiple injection wells will likely be utilized for accessing the deep subsurface sequestration or storage reservoirs. The number of wells needed is controlled primarily by the injectivity (kg of CO_2 injected per unit of pressure rise) of the well. If reservoir permeability and capacity are high, a single well could sustain an injection rate of more than 1 Mt CO_2/year for a decade or more. On the other hand, if permeability or reservoir thickness is low, multiple wells may be needed to accommodate the CO_2 delivered by the pipeline in order to avoid excessive pressure rise in the reservoir. Regardless of reservoir properties, one or more observation wells may also be required, and in many cases (e.g., depleted hydrocarbon reservoirs) numerous pre-existing wells, some abandoned and plugged, will be present within the projected CO_2 underground plume footprint.

The combination of a new and large onshore transportation and well infrastructure for CCS involving high-pressure CO_2 entails hazards for human health, pets, livestock, terrestrial fauna, the environment, and natural resources quite apart from the subsurface storage risks which are the subject of other studies (e.g., Oldenburg et al., 2009). Pipelines are known to rupture due to corrosion, external forces such as impacts by vehicles or digging equipment, and by defects in construction (e.g., bad welds) or failure of valves and seals. Similarly, wells are vulnerable to catastrophic failure due to corrosion or operational mistakes that fail to counter fluid pressure in the well. Many pipeline and well failures are headline stories due to their potential impacts on human health and the environment. For example, the 2010 San Bruno natural gas pipeline disaster in California killed eight people and destroyed 38 homes (Richards, 2013). And emissions from the 2010 Macondo oil well blowout in the Gulf of Mexico (e.g., Crone and Tolstoy, 2010) and the recent Aliso Canyon natural gas well blowout in California (Conley et al., 2016) are just two examples of large-scale releases from well blowouts. Despite these very visible and catastrophic failures, transportation of hazardous materials, and use of wells for subsurface injection and extraction of fluids, are proven technologies and widely accepted by society. Nevertheless, large-scale transportation and injection of CO_2 entail some unique risks. For example, CO_2 is much denser than air (ρ_{CO2} = 1.8 kg/m^3, ρ_{air} = 1.3 kg/m^3 at standard conditions), and will tend to fill topographic lows upon release prior to dispersing with ambient air, in a way that depends on the local topography and weather. Although the common assumption is that CO_2 is inert and impacts to human and animal health are therefore limited to those due to oxygen displacement, CO_2 is in fact physiologically active and causes cognitive and respiratory impacts at surprisingly low concentrations (Satish et al., 2012; Rice, 2014; NIOSH, 2016). In addition, unlike the deep reservoirs into which CO_2 is injected for storage, the transportation and well infrastructure will be located in the biosphere and can be in close proximity to people, their pets, livestock, and terrestrial fauna including endangered species, which makes accidents and leakage events potentially very severe.

Given the potential for very high-consequence failure scenarios involving CO_2 pipelines and wells, e.g., pipeline ruptures and well blowouts that result in large CO_2 releases with potential for fatalities, it is essential that risk assessment approaches be developed to understand such risks and to provide information to help decision-makers to evaluate ways to mitigate these risks. This imperative is motivated not only by the need to minimize fatalities, injuries, economic losses, and environmental impacts, but also by the need to avoid loss of public trust in the safety and effectiveness of CCS, without which much worse climate change impacts will occur as the world supports growth in energy consumption with fossil fuel sources even as renewable sources grow (IEA, 2016).

In this report, we first review the state-of-the-art in risk assessment of low-probability-high-consequence (LPHC) events and then go on to describe our proposed risk assessment framework that addresses the key features of CO_2 pipelines and wells. This framework is designed to clearly identify cost-effective risk mitigation options from complex systems that will allow engineers and operators to efficiently reduce the risk of geologic carbon sequestration infrastructure. Reducing risk is vital for public acceptance of CCS, a critical technology for avoiding the worst effects of climate change.

2. Scope and Objectives

Although good design, siting, engineering/construction, operation, accident management/mitigation, maintenance, and monitoring are effective at reducing both the likelihood and the consequences of CO_2 pipeline and well failure scenarios, there is always residual risk in large industrial endeavors. Despite following best practices governed by industrial consensus codes and standards and government regulations that reduce both the likelihood of major accidents and their consequences, even in the best of all worlds, major accidents cannot be entirely prevented. To be blunt, "accidents will happen," despite the goal of safety engineering to preclude them.

The residual risk: The "residual risk" is not an abstract concept, but a descriptive term alluding to the potential for specific large accidents (with specific consequences) that remain as threats after all regulations, industry codes and standards, and best practices have been followed. To analyze the residual risk, therefore, means to analyze these specific accidents, and that means analyzing them one-by-one, or at least in sensibly defined groups of similar accident scenarios.

The probabilistic nature of the analysis: Such an analysis is, by its nature, intrinsically probabilistic. This is because there is uncertainty and ranges of likelihoods and consequences are possible. For example, different accident types, and indeed the different individual accident scenarios within a type, all have different likelihoods of occurring – specifically, different annual frequencies of occurring. (An annual frequency is defined as the probability of occurrence in one year.) A major differentiator among these accidents must be their different annual frequencies.

Following this logic further, for a given accident type -- which is generally analyzed by studying a group of similar accidents – there is a spectrum or range of consequences, meaning that not all such accidents will produce the exact same consequences. Therefore, an analysis of the consequences, conditional on the accident having occurred, must also be intrinsically probabilistic in nature, to capture the spectrum of consequences in a useful way rather than simply characterizing the consequences of all of the accidents in a group as identical.

Scope of the analysis herein: The project to date has focused on two classes of potential accidents:

a) accidents arising from a major rupture of a high-pressure CO_2 pipeline, and

b) accidents arising from a leaking well at a geologic carbon sequestration site, with a focus on so-called blowout scenarios.

The principal objective of this project is to recommend a framework methodology for describing, analyzing, and evaluating various LPHC accident scenarios involving pipelines and wells that accompany the deployment of a widespread CCS system.

A successful methodology must accomplish each of the following:

1) The methodology must enable the identification of each broad category of scenarios -- one example of such a category is the set of those pipeline-rupture accidents arising when a large vehicle crashes into and breaches the pipeline, while another example is the set of those accidents arising from a sudden breach and release caused by long-term pipeline corrosion or weld failure. Analogous corrosion and collisions can also occur to wells and wellheads resulting in failure.

2) The methodology must enable the screening out of those specific accident scenarios (or subsets of them) that are not important to risk, using defined criteria. The screening out can be because the annual frequency is below some predetermined cutoff, or because the consequences are too low to be considered important, or some combination of low likelihood and low impact.

3) For those scenarios (or subsets) that cannot be screened out, the methodology must guide the analyst through a series of analysis steps to enable working out each scenario's likelihood and its consequences.

4) For each scenario not screened out above, the results of the analysis must be useful to decision-makers. Specifically, the analysis must enable a decision maker either to support a conclusion that a given scenario carries with it an acceptable risk, or (if the risk is judged not acceptable) to enable the identification of potential mitigating strategies that could reduce either the likelihood or the consequences of those scenarios. Decisions about such mitigating strategies are the heart of risk management, enabling the risk to be reduced to acceptable levels or even well below acceptable levels, as required by policies outside the scope of the analysis itself.

5) The methodology must require that the analyst identifies the major uncertainties that could compromise the usefulness of the results, identifies the sources of those uncertainties and what is known about them, and describes how the uncertainties might be reduced (if possible) if the decision-maker so requires.

6) The methodology and its results must be useful in identifying gaps in the knowledge base or the data base, or gaps in the various analysis methodologies, that could be addressed through a research program or literature/data review.

What the methodology will not do: The methodology itself, as outlined here, cannot provide the following:

- It is outside the scope of the methodology to provide guidance concerning at what levels the residual accident risk is acceptable, in terms of either a scenario's probability, or its consequences, or its "risk," however estimated. Acceptability will be judged by regulators, project operators, other stakeholders, or local, regional, or national populations and their representatives.

- It is outside the scope of the methodology to specify a screening-out level for the scenarios under study. In typical risk analyses of complex engineered systems, it is common to attempt to retain all accident scenarios whose overall risk is within about one order of magnitude of the scenarios representing the largest risks. (Alternatively, one might retain all scenarios whose overall likelihood is within about one order of magnitude of the likelihood of the most likely ones, and similarly for the scenarios with consequences within about an order of magnitude of those with the largest consequences. However, depending on how large the uncertainties are, the retention of even more (smaller-risk) scenarios may be warranted.

- Although the scope of the methodology includes identifying various different mitigating strategies, if a given accident scenario's risk is judged to be "unacceptable," the criteria used for choosing among the possible mitigation approaches is outside the scope here. Those criteria and that choice must be based on value judgments which are always very specific to the individual decision at-hand and to the entity (regulator, project operator, other stakeholder, or the local population and their representatives) making the decision.

3. Background and Prior Work

3.1 Low-Probability High-Consequence Failures

The Boston Squares representation of risk tolerability plots consequences on one axis and likelihood on the other axis, creating an *x*-*y* graph with high risk in the upper right-hand corner and low risk in the lower left-hand corner. Assuming the convention that likelihood is plotted on the abscissa (x-(horizontal) axis), the ranges of likelihood relevant to typical risk assessments are from 10^{-6}/yr to 10^{-4}/yr. The reason for this commonly accepted range of likelihoods within which risk assessment is carried out is that failure or accident scenarios more likely that 10^{-4}/yr are usually not acceptable, and scenarios less likely that 10^{-6}/yr are usually considered acceptable (Bouder et al., 2007, p. 98). Within this range of potentially acceptable risks, consideration must be given to consequences as plotted on the ordinate (*y*-axis). As shown in Figure 1, failure scenarios with combined likelihood-consequence products above the red line would be considered high risk and potentially unacceptable, while scenarios plotting below the red line might be considered acceptable. We show in Figure 1 another region, that of the LPHC scenarios which are very high consequence and very low likelihood. Examples of LPHC accident scenarios relevant to GCS might include events like catastrophic earthquakes that would totally destroy CO_2 infrastructure leading to large-scale CO_2 surface plumes and fatalities. Certain more limited pipeline and well blowout scenarios in the vicinity of people also fall into this category of LPHC events.

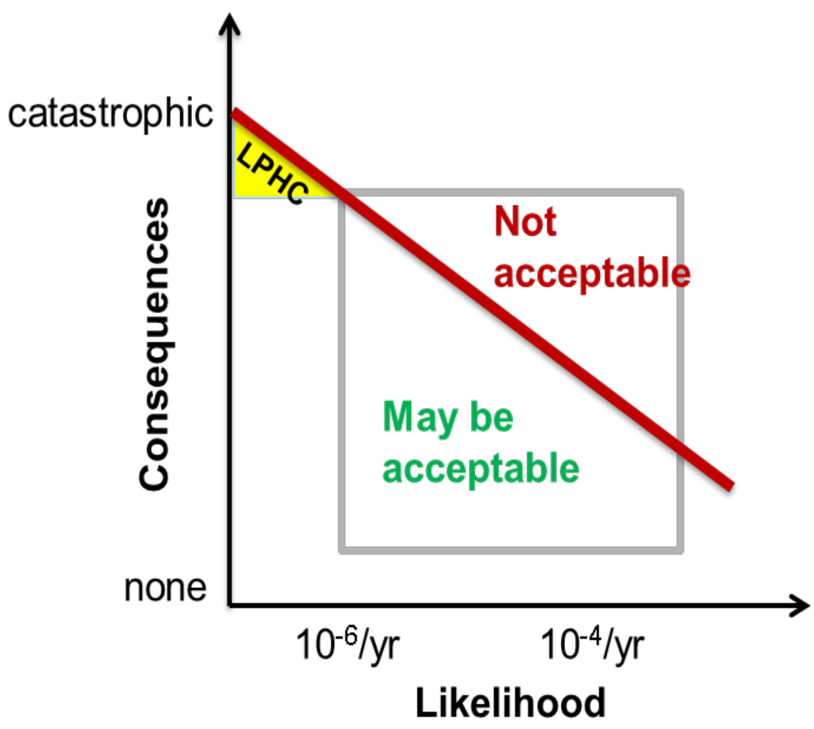

Figure 1. *Generalized Boston Squares representation of risk showing normal ranges of likelihood and consequences (gray outline) and the LPHC region that is the focus of this report.*

There are a number of terms used in risk assessment that have very specific meanings in the risk assessment context. In order to avoid confusion, we present below in Table 1 a glossary of some key terms and their specific meanings as we will use them herein.

Table 1. *Definitions of key terms.*

Hazard	Potential negative effects associated with a component or system failure
Failure scenario	Sequence of events surrounding a component or system malfunction with resulting negative effects or costs
Accident scenario	Failure scenario, sometimes called an "accident sequence"
Consequence	Impact, or quantified negative effect of a failure scenario
Likelihood	Probability per year or quantitative or semi-quantitative chance (or expected frequency) of occurrence of the failure scenario
Risk per year	Consequence × Likelihood
Risk endpoint	Value (e.g., health, safety, non-degradation) to be protected
Threat	Qualitative potential for a failure scenario to affect something
Vulnerability	Qualitative potential for something to be affected by a failure scenario
FEP-scenario approach	Features, Events, and Processes, a method to aid in generating a complete and accurate set of failure scenarios

3.2 General Approaches for LPHC Risk Assessment

The assessment of the risk arising from a complex engineered system requires the analysis of individual accident sequences, each of which contributes to the risk but differently, depending on the likelihood of the sequence and its consequences. Although an analysis of this type was recognized as desirable early in the history of safety engineering, and while the analysis of the likelihood and of the consequences of an individual accident sequence was considered feasible, the general conclusion early-on was that in practice it was not feasible to identify all of the large number of accident sequences that might arise in a complex engineered system. This was especially thought to be true for those accident sequences that were understood to occur very rarely (with very low annual probability), even if those same accident sequences often were associated with very large consequences. This is, of course, problematic because it is precisely those types of rare but large-consequence (LPHC) accident sequences that are often the most worrisome both to the facility's owners/operators and to the public,

This impasse was broken by the success of the first such comprehensive analysis, the 1973-1975 "Reactor Safety Study," (NRC, 1975) performed under the guidance of Professor N. Rasmussen of MIT, which was published by the US Nuclear Regulatory Commission and which studied the risks from accidents arising from two large nuclear power reactors. Today, that study is widely praised as a truly ground-breaking piece of technical work; it was imaginative, thorough, and comprehensive. However, the study was controversial at the time within the risk-analysis community, principally because its published uncertainties in the numerical risk numbers were thought to have been underestimated. Nevertheless, within a very few years the engineering community as a whole had embraced the study's methods as fully feasible. This led to the use of the methods to evaluate risks arising from a number of other complex engineered systems, including the risk of a disaster in manned space-flight, the risk of major offsite releases from petroleum refineries, the likelihood that a deep geological repository designed to dispose of radioactive waste might not do so effectively, and an understanding of how likely and consequential might be major accidents at large offshore oil-drilling platforms.

Note that these risk-assessment methods, whose central feature is identifying accident sequences, are intrinsically probabilistic, because the only way to sort accident sequences sensibly is by quantifying the annual probability of each along with the spectrum of uncertain consequences arising from each.

- an identification of all of the important accident sequences that might arise, or at least all of them that cannot be screened out as having either very low likelihoods or very low consequences (or some combination);
- a delineation of the events and processes that combine to form each sequence, including the initiating failure, subsequent failures of equipment, subsequent human errors, and the like;
- a quantitative analysis of the annual probability of each accident sequence, usually using event-tree or fault-tree methods; *(Note that a discussion of these accident-analysis trees is found later in this report, in Section 5.)*
- an analysis of the consequences arising from each sequence, expressed in terms of whichever of several end-point(s) are most relevant – damage to the facility, releases of hazardous materials to the environment, injuries or fatalities to onsite workers or to offsite populations, etc.
- an analysis of which contributors to the important accident sequences, or more broadly, which features of the facility's design and operation, contribute most to the risk.

There is a rich literature describing both the methodologies used and the risk-analysis studies performed with these methodologies. That literature is too extensive to cite here. Suffice it to note that there are fault-tree-event-tree methods commonly used for sequence quantification and estimation of likelihood of sequences of rare events. And the technical analysis approaches to quantify the consequences, e.g., by modeling and simulation, of an individual accident sequence are all fully feasible. Although we adopt a fault-tree approach for estimating likelihood of the rare event in the example of Section 5, we note that there are other methodologies (*similarity judgment*, *importance sampling*, and *time to event*) for estimating the likelihood of rare events as described in Appendix 1.

In some analyses there are important uncertainties in the quantified risk numbers, often because there is insufficient real-world data and experimental information to support the quantification. Even in those cases, however, important insights can be derived, often simply by the identification of the important accident sequences and of the equipment failures and human errors that contribute to them, even if the quantification itself is only approximate.

It is these risk-analysis methods that form the technical foundation of the CO_2 pipeline and well risk assessment methodology outlined in this report.

3.3 General CO_2 Pipeline Risk Assessment

From the earliest studies of CCS, CO_2 pipeline risks were acknowledged as a critical issue (e.g., Skovholt, 1993; Kruse and Tekiela, 1996; Gale and Davison, 2004; Barrie et al., 2004). More recently, causes of pipeline failure have been reviewed (e.g., Bilio et al., 2009), and significant efforts are being made to develop approaches for onshore pipeline risk assessment, yet no overall CO_2-specific framework has emerged (Koornneef et al., 2010; McGillivray et al., 2014). The most recently published work on CO_2 pipeline risk assessment focuses heavily on consequence modeling (e.g., Lisbona et al., 2014) rather than on likelihood estimation (e.g., McGillivray et al., 2014). The reasons for this are probably that (i) CO_2 pipeline failure-rate statistics are sparse because CO_2 pipeline experience is limited, and (ii) much more sophisticated modeling capabilities exist for simulating CO_2 discharge from the pipe (e.g., Mahgerefteh et al., 2006), dispersion from pipelines (e.g., Mazzoldi et al., 2008; Witlox et al., 2014), and coupled discharge and dispersion (Mazzoldi et al., 2013; Mazzoldi and Oldenburg, 2013), and researchers prefer to demonstrate capabilities rather than highlight gaps and limitations. To the extent the studies emphasizing atmospheric dispersion have considered likelihood in their risk assessments, they have used the limited available failure rates from pipeline industry statistics (e.g., van den Brand and Kenter, 2009; Vendrig et al., 2003) to quantify failure likelihood.

3.4 General CO_2 Well-Failure Risk Assessment

Well failure has been widely recognized as the main vulnerability to storage integrity of geologic storage sites (Celia et al., 2006; Gasda et al., 2004; Duncan et al., 2008). Much of the concern for well failure has been that well cement would be vulnerable to reaction leading to degradation in sealing capability, but in fact research is showing that well cement reacts with CO_2 but remains sealing in the presence of CO_2 (e.g., Kutchko et al., 2009; Crow et al., 2010; Carey, 2013). Nevertheless, concern for well cement integrity remains, and leakage pathways outside of casing are particular concerns for older abandoned wells. But such leakage is most likely to be relatively slow and result in secondary accumulations, e.g., following leak-off into thief zones.

In the context of LPHC risk assessment, the blowout scenario is our focus. Skinner (2003) has reviewed the increasing number of CO_2 injection projects for enhanced oil recovery (EOR) and highlighted the unique properties of CO_2 that increase blowout likelihood, namely the corrosivity of CO_2-water mixtures, enormous decompression that accompanies supercritical to gaseous phase transitions, and associated cooling with potential for dry-ice and hydrate formation, among others. Several locally high-profile CO_2 blowouts have occurred with large fines paid by operators (Amy, 2013). Lynch et al. (1985) provide an excellent review of the experiences in killing a CO_2 well blowout at Sheep Mountain. Lynch et al. describe a breach blowout (CO_2 coming out numerous vents in the ground in the vicinity of the well), chunks of dry ice blowing out of the ground, and the difficulty in killing the well. This is the kind of LPHC event that our framework is designed to address.

As for risk assessment of well blowouts, the likelihood of these rare events has been studied by analogy to oil wells under steam injection for enhanced recovery by Jordan and Benson (2009) who found the rate is approximately 1 in 1000 to 1 in 10,000 wells depending on well type and that this rate has decreased over time presumably because well construction methods have improved. As for consequence modeling, numerical simulation capabilities for estimating CO_2 blowout flow rates and physical properties of CO_2 throughout the well during blowouts have been developed and demonstrated (Pan et al., 2011). And finally, Porse et al. (2014) have reviewed data on well blowouts in Texas including consequences on health and safety in comparison to public perception of the health risk of CO_2 releases (Porse et al., 2014).

3.5 The Need for LPHC Risk Assessment Methodology

Our conclusion from reviewing the literature on CO_2 pipeline and geologic carbon sequestration well risk assessment is that prior work has not balanced efforts on quantifying both likelihood and consequences particularly for LPHC events, and as such has left the community with reduced clarity on how risk mitigation can be accomplished. In particular, we believe breakthroughs in quantifying and mitigating risk can be achieved by considering the spatial component of pipeline risk (i.e., where the failure occurs) represented conceptually by the convolution of population density along the pipeline and the local radius around the pipe failure within which harm can occur. The overall risk of failure at a specific location along the pipe is then the product of this convolution and the likelihood of the scenario. Expanding the risk assessment to the full length of the pipeline involves integrating all of the potential risks along the pipeline, as we will explain fully below.

4. Proposed Framework for Point-Source Releases of CO_2

4.1 Introduction

The methodology we have developed for performing the analysis of low-probability-high-consequence accidents has 10 elements. Each is introduced below, first in tabular form (Section 4.2) and then followed by a brief description (Section 4.3). The brief descriptions are then followed by a detailed element-by-element description and discussion (Section 4.4), which is the "meat" of this report and which is intended to be guidance for the analyst.

The methodology has been developed for application to <u>a specific pipeline or injection well situation</u>. Specifically, all that follows <u>assumes</u> that <u>a specific analysis problem has been identified</u>, for example a CO_2 pipeline of specified design traversing a given route, or a specific CO_2 injection well with defined features including characterization of nearby populations. The methodology is suitable for analyzing LPHC accident scenarios arising from either an existing installed pipeline or well, or one that has been planned but not yet installed.

As part of the basis for this analysis, the analyst using this methodology needs specific information about the toxicity of CO_2 at different concentration levels. If the endpoint of the risk analysis is human fatalities, the concentration of CO_2 that produces those fatalities will be needed. If non-fatal injuries or other effects are the endpoint(s) of the risk analysis, corresponding information about the CO_2 levels that can produce those effects will be needed. The development of this information is outside the scope of the methodology here.

Fortunately, the state-of-knowledge about the toxicity of CO_2 is excellent (e.g., Rice, 2014). As noted, even very short-term exposure to high enough concentrations can be fatal. We assume here that the endpoint of concern is fatalities to the nearby population, but the methodology can be applied to other endpoints too, meaning for exposures to CO_2 concentrations lower than fatal ones.

4.2 Brief Description of Each Methodology

Figure 2 shows a flow-chart description of the steps, while Table 1 provides a very brief description, element-by-element, of each step. We present in Section 4.3 an abbreviated description in the text of each element.

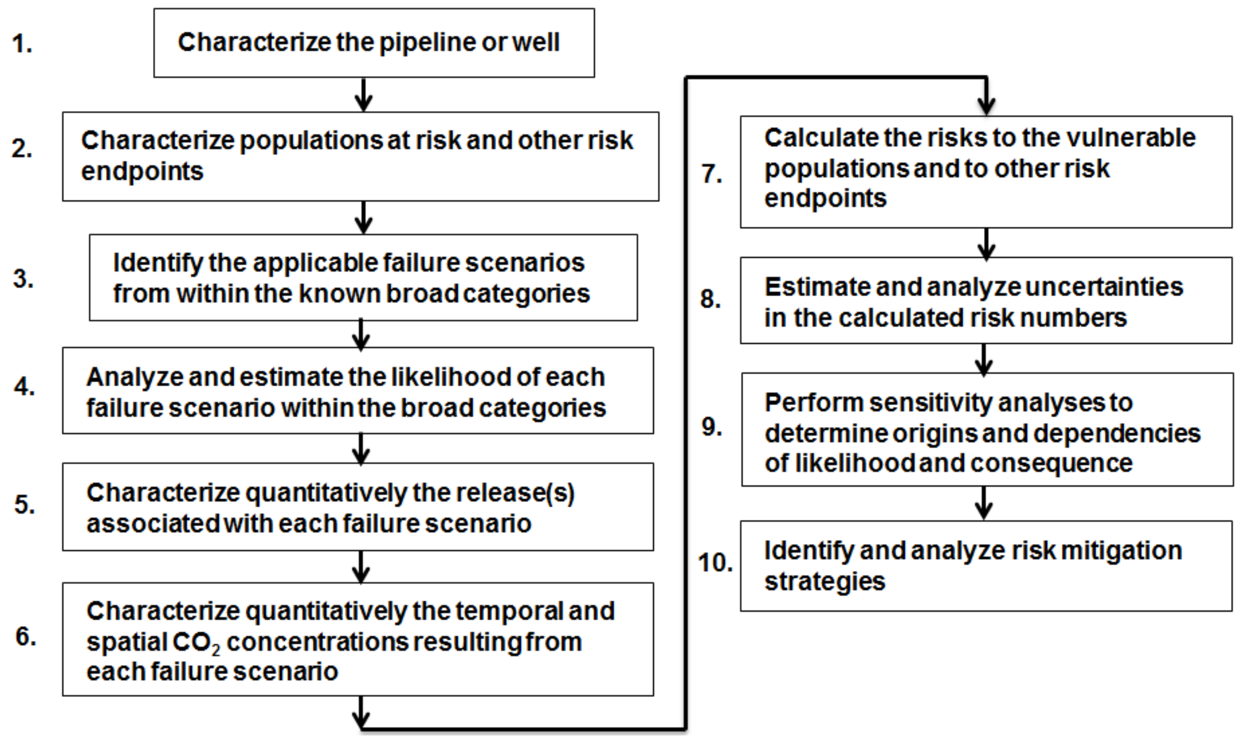

Figure 2. *Flow chart showing the steps of the proposed LPHC risk assessment methodology.*

Table 2. *Methodologies and their descriptions.*

Methodology Element	Brief Description
#1	Characterize the pipeline or the injection well including those design features that are relevant to the accidents to be studied
#2	Characterize the populations at risk, and other risk endpoints
#3	Identify the broad categories of accident scenarios, and the applicable accident scenarios within each of the broad categories
#4	Analyze and estimate the likelihood of each accident scenario within each scenario category
#5	Characterize quantitatively the release(s) associated with each accident scenario (e.g., rate of release, amount released, character of the release)
#6	Characterize quantitatively the temporal and spatial CO_2 concentrations resulting from each accident scenario
#7	Calculate the risks (likelihood × consequences) to the vulnerable populations and to other risk endpoints
#8	Describe and analyze the uncertainties in the risk numbers
#9	Perform sensitivity analyses to determine the origins and dependencies of likelihood and consequences
#10	Identify and analyze risk mitigation strategies

4.3 Brief Description of Each Methodology Element in Text Form

<u>Methodology Element #1a (pipeline)</u>

Characterize the pipeline: its route, features of the route that could contribute to accident vulnerabilities (exposed sections, river crossings, crossing major tectonic faults, proximity to populations, proximity to sensitive habitats, etc.), the pipeline's design and operational features, CO_2 carrying capacity, etc. Those design features that are relevant to the accidents to be studied must also be identified.

<u>Methodology Element #1b (injection well)</u>

Characterize the well: its location, features of the location that could contribute to accident vulnerabilities (wellhead exposure above ground, thrust or normal faults at depth, subsidence, etc.), design and operational features, CO_2 capacity, etc. Those design features that are relevant to the accidents to be studied must also be identified.

<u>Methodology Element #2</u>

Identify and characterize the potential population at risk, specifically by the population's proximity to the CCS activity being analyzed, and also by the population's capability to shelter or evacuate if those capabilities are credited in the analysis. Also, identify and characterize any other risk endpoints of interest, such as pets, livestock, terrestrial fauna, the environment, and natural resources.

Methodology Element #3

Identify the broad categories of accident scenarios that could lead to CO_2 releases of concern and the applicable accident scenarios within each of the broad categories.

Methodology Element #4

For each accident scenario within each scenario category, analyze and estimate the likelihood of the scenario (probability per year or annual frequency). This quantification can be approximate at first, subject to further analysis if appropriate. This analysis is intrinsically probabilistic in character.

Methodology Element #5

For each accident scenario, characterize and quantify the potential CO_2 release – (for example, the rate of release, the amount released, the character of the release). Again, this quantification can be approximate at first, subject to further analysis if appropriate. This analysis must capture the variabilities and uncertainties, and hence it is intrinsically probabilistic in character.

Methodology Element #6

Concerning the release, characterize quantitatively the temporal and spatial concentrations resulting from each failure scenario. This analysis must capture the variabilities and uncertainties, and hence it is intrinsically probabilistic in character.

Methodology Element #7

Analyze the "risk" to nearby populations arising from the release. (If other risk endpoints are of interest, such as pets, livestock, terrestrial fauna, the environment, and natural resources, then the risk to these must also be analyzed here.) This is in terms of the likelihood multiplied by the consequences. This requires specifying how the risk is to be characterized (fatalities or other endpoints). This risk may vary depending on whether any population protective actions (sheltering, evacuation, etc.) are considered. This analysis is intrinsically probabilistic in character.

Methodology Element #8

Describe and then analyze the uncertainties in the bottom-line risk results, and the sources of those uncertainties.

Methodology Element #9

Perform sensitivity analyses, as appropriate, to determine the extent to which the analysis results and insights are sensitive to each the various important assumptions, inputs, or phenomenological models.

Methodology Element #10

Identify and analyze appropriate and feasible mitigation strategies that, if deployed, could reduce the risk. Some mitigation strategies might reduce the likelihood of the risk, while others might reduce the consequences. Still others might reduce the uncertainty, which can be of great value by itself. Still other strategies might involve trade-offs – reducing one risk aspect while increasing another.

4.4 Detailed Description of Each Methodology Element for a Point Source

In this section, we cover the analysis of a CO_2 release from a single point source. The CO_2 release from an injection well is intrinsically from a point source, of course. For the pipeline, covering as it does an extended distance which could be tens or even hundreds of kilometers long anywhere along which the source that could be, developing an analysis of the overall risk means performing an integration of potential releases at various points over the full length of the pipeline. We describe here an analysis of a point source--for a pipeline, this means a breach at a specific point along the pipe, arising for whatever reason. Below, in Section 4.5, the methodology for performing an integration along the length of a pipeline will be discussed.

Methodology Element #1

For a pipeline: Characterize the pipeline: its route, features of the route that could contribute to accident vulnerabilities (exposed sections, river crossings, crossing major tectonic faults, proximity to populations, proximity to sensitive habitats, etc.), the pipeline's design and operational features, CO_2 carrying capacity, etc. Those design features that are relevant to the accidents to be studied must also be identified.

For an injection well: Characterize the well: its location, features of the location that could contribute to accident vulnerabilities (exposure above ground, wellhead exposure above ground, thrust or normal faults at depth, subsidence etc.), design and operational features, CO_2 capacity, etc. Those design features that are relevant to the accidents to be studied must also be identified.

The supposition here is that a specific pipeline or injection well is being analyzed. The pipeline has a route, and the injection well has a specific location. Either case has a design (including operational features) and, if it has been built already, then it has operating data.

The detailed features that require characterization are, of course, directly linked to the types of accident scenarios to be analyzed. The characterization in detail of these features must be linked to the accident scenario types being considered, which are identified in Methodology Element #3. (As an example, consider the scenario group "pipeline damage from a truck crashing off the road and into the pipeline" as presented in Section 5. The crucial pipeline feature relevant to this scenario group is the location of those few places where the pipeline is both adjacent to a road and exposed at or near the surface.)

Methodology Element #2

Identify and characterize the potential population at risk, specifically by the population's proximity to the CCS activity being analyzed, and also by the population's capability to shelter or evacuate if those capabilities are credited in the analysis. Also, identify and characterize any other risk endpoints of interest, such as pets, livestock, terrestrial fauna, the environment, and natural resources.

The task here is to identify the locations of the populations living or working close enough to the pipeline or the injection well to be at risk. (If other risk endpoints are of interest, such as pets, livestock, terrestrial fauna, the environment, or natural resources, these must be identified and characterized too.) The identification should be by location with as much accuracy as can easily be mustered. If the location is a business, then the characterization needs to note the fraction of the week or year when the population is present. For residences, assuming almost full occupancy is typically a reasonable approximation. How close is “close enough to the pipeline to be at risk?” This will emerge from the subsequent analysis of potential releases and their fate (Methodology Elements #5 and #6). In that sense, an iteration may be necessary after Elements #5 and #6 have been accomplished.

For the purposes of the remainder of the analysis, the population information should be expressed by latitude-longitude coordinates on the earth’s surface or by something equivalent. A location accuracy within, say, several tens of meters is more than sufficient, given the variabilities and the uncertainties involved. We call the population that is potentially at risk *Pop(x,y)* which has dimensions of population density, e.g., units of #people/km^2.

Methodology Element #3

Identify the broad categories of accident scenarios (Catj) that could lead to large CO_2 releases of concern (R_j) and the applicable accident scenarios i within each of the broad categories j.

We need to begin by emphasizing that this methodology has been developed to perform the analysis of a specific pipeline, meaning a CO_2 pipeline of specified design traversing a given route with well-defined features, or a specific injection well of specified design at a specified location.

Two different steps are involved in this part of the analysis, the identification of the broad categories of accident scenarios and then the identification of the specific features of the pipeline or injection-well design that are relevant to the risk analysis.

In interpreting the phrase “broad categories of accident scenarios,” we have identified the following categories, without claiming that this is a complete list:

Categories of releases from a pipeline:

Cat_1	leaky valve
Cat_2	corrosion or other gradual process attacking the inside of the pipe
Cat_3	corrosion or other gradual process attacking the outside of the pipe
Cat_4	back hoe strikes the pipe
Cat_5	failures of deficient welds, flanges, or other non-corrosion-related components
Cat_6	operator error
Cat_7	nearby explosion
Cat_8	accidental impact by vehicle or aircraft
Cat_9	purposeful impact or sabotage (aircraft, truck bomb, etc.)

Categories of releases from a well:

Cat_1	leaky valve
Cat_2	corrosion or other gradual process attacking the inside of the well
Cat_3	corrosion or other gradual process attacking the outside of the well

Cat_4	failures of deficient welds, flanges, or other non-corrosion-related components
Cat_5	failure of cement to seal casing(s)
Cat_6	operator error, e.g., failure to control pressure
Cat_7	nearby explosion
Cat_8	accidental impact by vehicle or aircraft to the wellhead
Cat_9	purposeful impact or sabotage (aircraft, truck bomb, etc.) to wellhead

The identification process in Element #3 is intrinsically inductive in nature – it is not possible to make a "complete" list of identified scenario categories. In this sense, expert judgment accompanied by an outside peer review should be part of the process.

The second aspect of this Element is, for each category of accident scenarios, to identify the specific features of the specific pipeline or injection-well design and its layout and operations that are relevant to the analysis of the accident risks. Specifically, before the remainder of the analysis can proceed for any given category of accident scenarios, all of the relevant features of the design must be identified and characterized.

The features of the pipeline or injection well that are relevant will differ from one category of accident scenario to the next. Some examples may be illustrative:

(i) As one example, for accidents arising from a backhoe intrusion or from a truck that might crash into the pipeline, the pipeline's location and the strength against rupture impacts from the outside are among the important features to understand. If it is above ground, the support of the pipe in the region of potential impact would be an important feature. The properties of the truck or backhoe are also important, and if a variety of trucks or back hoes are contemplated, then the variability among these needs to be characterized.

(ii) For accidents arising from internal corrosion within either an injection well or a pipeline, the important features are quite different. Among the features of importance are the chemical properties of impurities and/or amount of water mixed with the CO_2, the pipe's or well's pressure and temperature, the electrochemical environment inside the pipe or well, that can either encourage or retard corrosion, and the presence or absence of various types of flaws in the pipe or well. If there is variability in any of these properties, it needs to be sufficiently characterized.

(iii) For accidents that could lead to a large release from an injection well, if corrosion or the failure of components like welds or valves is the cause, then the list of features is very similar to the list just above in (ii) for corrosion in a pipeline. Other important features include the locations of valves, the thickness of the pipe and of the casing, the configuration of the pipe and casing and how it varies vertically, the method of installation, how various elements in the well are supported, and what is known (if anything) about flaws in the system as installed. Again, if there is variability in any of these properties, such variability needs to be sufficiently characterized.

(iv) For accidents arising from operator error, the important information relates to which operator actions are relevant, how an error can produce an accidental release, and what the likelihood is of that error – either as a fraction of all operator actions (say, one error in each 1,000 actions) or as a rate (say, one error every ten years). The "denominator" problem is important here – the analyst needs to consider carefully how many "successes" are in the database along with how many “errors.” There is an entire field of human-factors engineering that has developed techniques for working out such error rates.

The development of the list of important features will likely be difficult unless it is based on either experience performing the relevant analysis for the specific category of accident sequences, or a literature review. Typically, analyses in the literature are an excellent starting point. The information so gathered must be supplemented by whatever site-specific and/or pipeline-specific information might be different than for a “typical” pipeline. However, in the end it is worth noting that *no matter which approach is used, the process is intrinsically inductive in nature*.

Methodology Element #4

For each accident scenario i within each scenario category j, analyze and estimate the likelihood or probability ($Prob_i$) of the scenario (probability per year or annual frequency). This quantification can be approximate at first, subject to further analysis if appropriate. This analysis is intrinsically probabilistic in character.

Two different steps are involved in this part of the analysis:

1) The analyst must first identify (and differentiate) each accident scenario (*i*) within a given release scenario category (Cat_j). As an example, one scenario category is “accidental impact by aircraft.” Within this category *j*, there are many (e.g., *i*) different types of aircraft (large commercials jets, small private planes, military jets, helicopters, etc.) and it is easy to understand why one needs this differentiation, because the likelihood of an airplane crash differs from one category to another.

2a) The next analysis step is to determine if sufficient data exist to quantify the likelihood of the scenario. If so, the data should be used, because they are likely the most reliable and useful way to do the quantification of the endpoint, which is the probability per year.

2b) If adequate data are lacking, another approach must be used. At least two possibilities need to be considered, namely using a fault-tree method or using experts. Guidance on fault-tree methodology can be found in (Vesely et al., 1981), and guidance on use of experts can be found in (Budnitz et al., 1997). An example of a fault-tree approach can be found later in this report.

As noted above, the end point of this analysis step is an annual frequency $Prob_i$ equal numerically to a probability per year. This annual frequency will inevitably have uncertainties, arising from an incomplete database, the variability among similar events within the category, and an incomplete understanding of the phenomena. The analyst has a duty to estimate these uncertainties, even if only approximately, to support the use of the results in decision-making.

Methodology Element #5

For each accident scenario i, characterize and quantify the potential CO_2 release R_i – (for example, the rate of release, the amount released, the character of the release). Again, this quantification can be approximate at first, subject to further analysis if appropriate. This analysis must capture the variabilities and uncertainties, and hence it is intrinsically probabilistic in character.

Please note that in this section we are describing the analysis of a potential CO_2 release R_i from a single identified point source, either a specific injection well or an identified specific location along a pipeline.

To analyze the risk over an entire pipeline, it is first necessary to perform an analysis of release risk arising from each individual segment (dL) over the length (L) of the pipeline. The integrated risk is then developed by performing an integration over the risks arising from the individual segments. This integration is described below in Section 4.5.

It is important to note that both the risk associated with a specific event and the total risk over the entire pipeline are important for pipeline risk mitigation and analysis. For mitigation, understanding the origins of the risk in terms of whether consequences or probability are the main risk driver allows appropriate risk mitigation measures to be identified. As for risk analysis, it is important in mitigation to know the origins of risk at specific locations where the mitigation actions can be taken. For example, if the risk of CO_2 exposure due to corrosion-related failure of the pipe and resulting leakage near a small town is deemed not acceptable, a mitigation might be to reroute the pipeline away from the town to diminish the consequence part of the corrosion failure scenario. On the other hand, for higher level decisions, e.g., on large-scale pipeline routing and design overall, the risk along the whole pipeline is an important consideration for decision-making.

We note further that this element of the methodology is likely to be the most difficult aspect of the entire analysis.

Each accident scenario is characterized by its own release R_i, different from that associated with every other accident scenario. There are differences not only in the amount of CO_2 released, but also in the rate of release, the thermal properties, the duration, the chemical or physical properties of any other gaseous constituents co-released with the CO_2, and the force with which the gas is released. Even within an accident scenario, there will be uncertainties and variabilities.

Several different steps are involved in this part of the analysis, as follows:

1) First, the physical features of the pipeline of injection-well breach must be characterized, in terms of the breach's size, location, and shape. This will determine the way the CO_2 is released – as a jet from a small hole, as a mass moving out of a large breach, as a sheet from a narrow long slit, etc.

2) Second, the pressure and temperature in the pipe or injection well behind the release must be characterized, so that the energy and force with which the internal gas emerges can be calculated.

3) Third, the amount of the release must be characterized. This includes both the total amount of gas, the release's duration, and the driving force, from which the rate of release (amount per unit time) can be derived.

4) If the gas is other than almost pure CO_2, the chemical character of the other constituents, and hence the chemical character of the release as-a-whole, must be characterized.

Many analysis tools (computer codes) exist in the literature that are widely used to perform this type of analysis. They have been benchmarked against experimental data and therefore can provide an acceptable basis for their use in the analysis contemplated here.

The above analysis steps, taken together, can provide the description of the release that is needed to perform the next step in the analysis, Methodology Element #6, which will examine where the released gas will go.

Methodology Element #6

Concerning the release, characterize quantitatively the temporal and spatial concentrations $C_{Ri}(x,y)$ resulting from each failure scenario i. This analysis must capture the variabilities and uncertainties, and hence it is intrinsically probabilistic in character.

As noted above, each accident scenario is characterized by its own release, different from that associated with every other accident scenario. This element of the analysis asks and analyzes, "*Where does the release go?*"

The science of analyzing the dispersion of gases in the environment from a point source is very well developed. Numerous analysis tools (computer codes) exist that embed the appropriate physical phenomena into a full "model," and significant benchmarking against real-world data has provided validation of these models (e.g., Ermak et al., 1982; Hanna et al., 2006). The models can account for the thermal properties of a point-source release, the density (which is important, because CO_2 is heavier than air), the directionality of a release if it emerges with a jet-like character, and the dynamics if the release rate varies over time (e.g., Mazzoldi et al., 2008; 2013).

The analysis tools (models) need to account for the local "weather" (temperature, humidity, wind speed and direction, etc.). The way this is usually done in a probabilistic analysis is to use year-long data and a year-long wind-rose directionality distribution, so that if, for example, the wind is from the south only in the winter, the analysis can account for that fact probabilistically -- these analysis models can work out the probability that the gaseous release will end up in location (x,y) with concentration $C_{Ri}(x,y)$ a certain fraction of the time over the average year.

The models can also deal with the influence of individual buildings if they are large enough to affect things, although it seems unlikely that issues of this type will be important in the analyses contemplated here.

Using these models, the answer to the question, "*Where does the released CO_2 go?*" is a probabilistic distribution of locations and the associated concentrations, accounting for the various features and parameters noted above.

The endpoint of this part of the analysis can be framed as probabilistic concentrations $C_{Ri}(x,y)$ in space over the nearby terrain. These can then be cast into the form of a series of probabilistic "contours" of CO_2 concentration (plotted for example on a map in two dimensions), with contours representing higher concentrations closer to the release point and contours representing lesser concentrations farther away.

A more simplified approach to describing the concentrations of concern arising from a given release R_i is to plot a downstream safety radius ($DSR(x,y)$) which is a circle of radius $DSR(x,y)$ representing the farthest extent in any direction away from the point source that CO_2 concentration could exceed a level of concern. Use of a DSR obviates the need for considering specific wind directions, and allows convenient inclusion of conservatism by simple adjustment of the level of concern.

Methodology Element #7

Analyze the "risk" to nearby populations arising from the release. (If other risk endpoints are of interest, such as pets, livestock, terrestrial fauna, the environment, and natural resources, then the risk to these must also be analyzed here.) This is in terms of the likelihood multiplied by the consequences. This requires specifying how the risk is to be characterized (fatalities or other endpoints). This risk may vary depending on whether any population protective actions (sheltering, evacuation, etc.) are considered. This analysis is intrinsically probabilistic in character.

Assumption: We will assume that the risk endpoint is fatalities due to exposure to CO_2. (If another endpoint has been chosen instead, the analysis will differ but the steps below should be similar.)

If fatality is the endpoint of concern, then the release contour of interest is that corresponding to the concentration leading to fatalities. (Let us suppose this concentration to be 5% CO_2 for the moment.) Then the analysis proceeds by identifying every individual in the local population whose location is inside the 5% concentration contour. (Individuals outside that contour will not suffer a fatality.) This requires overlaying the population location information developed earlier in Methodology Element #2 with the concentration contour of interest

For example, we characterize the population at risk $VulPop_i(x,y)$ along the pipeline as a function of the population $Pop(x,y)$ convolved with the downstream safety radius $DSR_i(x,y)$ for scenario i which is the distance away from the leak that populations could be harmed by high CO_2 concentrations. Mathematically, we can write this as

$$VulPop_i(x,y) = Pop(x,y) * DSR_i(x,y) \qquad (1)$$

where the convolution integral is indicated by the asterisk and is described in Appendix 2. In order to calculate risk, we need to multiply the $VulPop_i(x,y)$ by the likelihood of the $DSR_i(x,y)$ which is a function of the C_{Ri} which is a function of the likelihood (or probability) of R_i which is $Prob_i$. Thus the risk for the event i at a particular location is given by

$$Risk_i(x,y) = VulPop_i(x,y) \times Prob_i \qquad (2)$$

Insofar as there could be a spatially variable $Prob_i$ function rather than the single-value frequency number assumed in Equation 2, there would also be a convolution of $VulPop_i(x,y)$ and $Prob_i(x,y)$ rather than the simple multiplication shown in Equation 2. In Section 4.5, we will present the calculation for the overall or total pipeline risk which involves considering that there are different probabilities and consequences for each of the different potential failure events i along the pipeline.

Protective actions: If no protective actions (like sheltering or evacuation) will occur, then each individual within the high-exposure contour will be one fatality in this analysis. Of course, if sheltering or evacuation will be employed, an analysis of the likelihood of successful mitigation from the protective action(s) must be accounted for too.

Part-time: If certain individuals in the nearby population are only located in the vicinity part-time, then this factor must be accounted for in the analysis. For example, if a retail worker is only on the premises of a store for 40 hours/week, that fact must be included in the analysis as a factor that reduces the (probabilistic) likelihood of the fatality at issue.

Overall probability: The overall likelihood (per year) of a fatality requires factoring in the likelihood per year of the initiating event – the annual frequency of the truck crash or of the leak caused by the operator error or the leaky valve. These frequencies were developed earlier, in Methodology Element #4.

Overall “risk”: If “risk” is measured by the expected value of the number of fatalities per year, then this is calculated by accounting for the number of individuals at risk of fatality and the overall probability of the release being studied.

Example calculation:

a) Suppose the population located within the fatality-concentration contour is 200 individuals.

b) Suppose that half of these are office workers who are present only 25% of the time, whereas the other half live at home and are present essentially all of the time. The “population at risk” is then not 200 but 125:

$$(25\% \text{ of } 100) + (100\% \text{ of } 100) = 125$$

c) Suppose that the annual likelihood of the release of interest is 4×10^{-6} per year.

d) The overall expected number of fatalities per year is

$$(125) \times (4 \times 10^{-6}) \text{ per year} = 5 \times 10^{-4} \text{ per year.}$$

Note that this is a probabilistic number – it is the probability in one year of the scenario that will lead to the 125 fatalities. However, also note that for a single individual living full-time within the contour, the likelihood per year of his/her fatality is 4×10^{-6} /year. For an individual office worker located within the contour, the likelihood per year of fatality is smaller, only 25% of the above, or 1×10^{-6} /year. These are also individual risks, which must be distinguished from risks affecting large populations as calculated above.

If there is important uncertainty in any of these input numbers to the risk calculation, then an integration (a convolution) over the uncertainty range of each of the inputs is required. The methods for accomplishing this are well known.

Methodology Element #8

Describe and then analyze the uncertainties in the bottom-line risk results, and the sources of those uncertainties.

None of the numerical values that enters into the “risk” calculation is known exactly. Hence, there is an uncertainty in both the bottom-line “risk number” and in each of the intermediate numerical values in the analysis. It is very important for the analyst to attempt to characterize the sizes of these various uncertainties, so that their relative importance can be understood. The analyst needs this information, and the ultimate user of the analysis (the “decision-maker”) also needs it.

There are usually at least three sources of uncertainty:

a) First, the “input numbers” are seldom known as well as one would like. The uncertainty can arise from a data base, or from the uncertain knowledge of certain parameters entering into the calculation.

b) Second, there is always some variability in the analysis, due to the fact that the analyst is forced to perform some grouping of similar but slightly different events into a category. An example is that the scenario category “truck strikes pipeline” can involve trucks of different sizes striking the pipeline at different speeds and angles. In principle, one could perform a separate analysis of each truck size, speed, and so on, but in practice this is an unmanageable ensemble. The analyst typically chooses instead to study one truck (or perhaps two or three) but then must assign an uncertainty in the “result” of the analysis arising from the variability in the actual truck population at issue.

c) Third, there can be uncertainty in the analytical model employed. An example is that the analysis of the dispersion of CO_2 after its release typically employs a simpler model (based on uncomplicated local meteorology) than one might use if a highly sophisticated air-dispersion model were necessary. This compromise is used because there is so much uncertainty and variability in the remainder of the analysis that a highly precise dispersion calculation is generally not worth the effort.

The burden on the analyst is to attempt to characterize each of the sources of uncertainty with enough care that the major sources of uncertainty are well identified. (For those sources of uncertainty that are less important – smaller – a less rigorous uncertainty characterization can be sufficient.)

The uses of the uncertainty characterization are several. Among them are:

i) The analyst can do additional work to reduce the most important uncertainties, if judged to be of value. (Sometimes this is not possible, of course, if the dominant issues are variabilities that cannot be reduced.)

ii) The user of the analysis – the decision-maker – can understand how reliable the bottom-line insights are, and why.

iii) The analysis of the potential benefit from various mitigation strategies requires an understanding of how uncertain the insights are, and why.

iv) A decision can be made to gather more data or other information to support a less uncertain analysis.

Methodology Element #9

Perform sensitivity analyses, as appropriate, to determine the extent to which the analysis results and insights are sensitive to each the various important assumptions, inputs, or phenomenological models.

This methodology element involves using the insights from the previous Element (the characterization of uncertainty) to formulate one or more “sensitivity” studies, the objective of which is understanding whether the results and insights are particularly sensitive to certain of the input assumptions, and if so in what way(s).

This is related to uncertainty analysis, but is logically a very different type of analysis. A typical sensitivity analysis might, for example, employ a different phenomenological model for one of the processes under study – a different air dispersion model for the CO_2, or a different corrosion model within the pipeline. Sensitivity analyses of this type can explore what is usually called model-to-model uncertainty.

Another type of sensitivity analysis can study whether the use of certain parameters within the analysis – the strength of the pipeline against rupture or the rate of corrosion within the injection well, for example – would produce different results or insights if that parameter were characterized differently, within the range accepted by experts as a reasonable range.

Still another type of sensitivity study might explore whether the characterization of the "risk" in terms of the product of the likelihood and the consequences would yield different insights if the risk were characterized differently.

Methodology Element #10

Identify and analyze appropriate and feasible mitigation strategies that, if deployed, could reduce the risk. Some mitigation strategies might reduce the likelihood of the risk, while others might reduce the consequences. Still others might reduce the uncertainty, which can be of great value by itself. Still other strategies might involve trade-offs – reducing one risk aspect while increasing another.

This element is more "open-ended" than any of the earlier elements. It relies, however, on the insights from the "risk" analysis (in Element #7), the uncertainty analyses (in Element #8), and the sensitivity analyses (in Element #9).

The identification of feasible mitigation strategies is, by its nature, inductive – it must rely on the insights and imagination of the analyst or the decision-maker. However, the leverage offered by any given mitigation strategy can often be usefully illuminated through the sensitivity analyses and uncertainty analyses performed earlier.

There is little in the way of guidance to be offered about the work undertaken in this Element. Clearly, the analyst must perform whatever studies are needed to explore how much risk reduction, and of which type (lowering the probability? lowering the consequences?) is available.

However, one insight is useful and very much worth mentioning, and it involves reducing uncertainty. As a general matter, risk management involves decisions about uncertain risks. The uncertainty arises, of course, in the analysis. The studies in Elements #8 and #9 (uncertainty analysis and sensitivity analysis) are included as parts of the overall Methodology herein so as to explore these questions. A major consideration for decision-makers is sometimes that there can be value – often major value – in reducing the uncertainty rather than only reducing the risk. Hence a given mitigation strategy might be worth undertaking if it can significantly reduce the uncertainty, even if it doesn't significantly reduce the risk.

4.5 Integration Over the Length of a Pipeline

In Section 4.4 (above), a step-by-step methodology has been described for analyzing the risk arising from potential CO_2 releases from an identified point source, either a specific injection well or an identified specific location along a pipeline.

As noted earlier, to analyze the risk over an entire pipeline, it is first necessary to perform the probabilistic analysis of releases arising from each individual segment over the length of the pipeline, as in Section 4.4. The integrated risk is then developed by performing either a summation or an integration over the risks arising from the individual segments, e.g.,

$$Risk(x,y) = \sum_i VulPop_i(x,y) \times Prob_i \qquad (3)$$

Recall that the $VulPop_i$ was calculated as the convolution of the *Pop* density function and the *DSR* (downstream safety radius) function for an event *i*.

To elaborate on the calculation of total risk, consider the case that the sources of the CO_2 release along the pipeline are several point sources, such as the points near several road bridges where a truck might leave the road and then strike the pipeline. In this case, the “integration” to obtain the total risk is simple – it consists merely of adding the contributions from the various point sources. However, for a pipeline there are also potential sources of releases that are not characterized so simply, such as releases arising from the phenomenon of corrosion.

Corrosion might occur anywhere along the pipeline, although certain individual segments may be more susceptible than other segments for one or another reason, a factor that needs to be understood to support the analysis. Given this, one needs to analyze releases arising from corrosion or similar effects differently than when studying several point sources, because one cannot identify a single “point source” with a single “location” in the same way as for, say, a truck crash.

This manifests itself most obviously in the development of the annual probability (or frequency per year). For a point source, Methodology Element #4 in Section 4.4 directs the analyst to develop an annual probability for that point source. For a distributed (line-type) source, it is necessary to develop an annual probability (or frequency per year) per unit of pipeline length, such as per meter of pipeline. Notice that the units are different.

This annual probability per meter can then be integrated over the length of the whole pipeline to obtain the total risk arising from, say, corrosion. If the likelihood of corrosion differs from one part of the pipeline to another, as might be the case, then this integration requires expressing the annual probability per meter as a numerical function of the location along the pipeline.

So far, this is simple enough. However, the likelihood of a nearby individual suffering a fatality from pipeline releases of CO_2 also requires integration to account for the contributions of different pipeline segments. Again, this is numerically straightforward once the analyst recognizes the need for this integration along the pipeline’s length.

5. Notional Example Application of the Framework for a Pipeline

In this section, we present a notional (neither rigorous nor quantitative) example to illustrate the methodology by describing each step as it would be applied to a hypothetical pipeline.

<u>Element #1a (pipeline)</u>

Characterize the pipeline: its route, features of the route that could contribute to accident vulnerabilities (exposed sections, crossing major tectonic faults, proximity to populations, proximity to sensitive habitats, etc.), the pipeline's design and operational features, carrying capacity, etc. Those design features that are relevant to the accidents to be studied must also be identified.

We consider an accident scenario involving a pair of pipelines that transports CO_2 from a capture source in City A to GCS site B. As shown in Figure 3, the buried pipelines (red) and the main road follow the same route through a mountainous area and both of the pipelines and the road cross a river south of City C. Figure 3 shows a black dot at the location where the pipelines cross the river to represent a pipeline rupture event i (described below), that produces a release with hazardous concentration $C_{Ri}(x,y)$ extending out a distance $DSR(x,y)$ that partially intersects the population in City C.

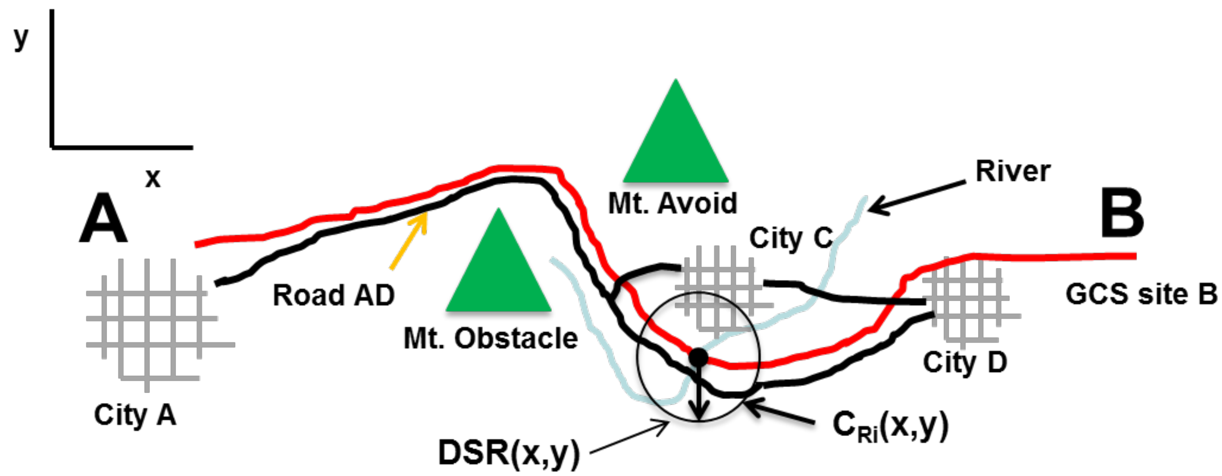

Figure 3. *Conceptual map of a pair of buried pipelines (red curve) that follows a road from City A to GCS site B. Both of the pipelines and the road cross over a river south of City C, a location at which the pipelines are vulnerable to impacts with vehicles that leave the roadway. R_i = release associated with failure scenario i; C_{Ri} = Concentration distribution arising from release i; DSR = downstream safety radius*

<u>Element #2</u>

Identify and characterize the potential population at risk, specifically by the population's proximity to the CCS activity being analyzed, and also by the population's ability to shelter or evacuate if those capabilities are credited in the analysis. Also, identify and characterize any other risk endpoints of interest, such as pets, livestock, terrestrial fauna, the environment, and natural resources.

The risk endpoint here is the local population. City C is a small town located on flat and level ground with a population of 2,000 people living in single-story residences clustered around a main street with small businesses. The city is not far from where the pipelines and the road cross the river as shown in Figure 3.

Element #3

Identify the broad categories j of accident scenarios that could lead to large CO_2 releases of concern and the applicable accident scenarios within each of the broad categories.

The broad categories of accident scenarios with high consequences in this hypothetical case all involve full-bore rupture of the pipeline. This could occur due to external impacts (e.g., vehicles hitting the pipe), massive failure due to corrosion or weld failure, or failure or shifting of pipe supports where the pipe is above ground, for example, due to an earthquake or landslide where the pipe crosses the river. An example of the vulnerability of a pipe as it crosses a river is apparent in Figure 4, which shows two pipelines and a road crossing in close proximity.

Figure 4. *Example of hypothetical CO_2 pipelines crossing a river near a road with potential for truck to crash through guardrail and hit the pipes.*
Source: http://pstrust.org/about-pipelines1/map-of-major-incidents/el-paso/

Focusing on this vulnerable location, we can develop an LPHC failure scenario through the Features, Events, and Processes (FEP) approach. By this inductive approach, the analyst reviews lists of FEPs and identifies relevant FEPs that could combine to create failure scenarios of greatest concern. For the hypothetical case being considered, one very relevant failure scenario can be written as shown in Figure 5, where the various features, events, and processes are identified by color coding.

Feature Event Process

- Near the place where the CO_2 pipeline passes out of the ground for its suspended crossing of a river, a large truck misses the turn just before the bridge and drives off of the road through a guardrail with wood support posts weakened by decades of rot and decay and crashes into the CO_2 pipeline causing a full-bore pipeline rupture.

- Risk per year = likelihood per year X consequence
- Top event = full-bore pipeline rupture
- Contributing factors = unburied pipe, proximity to road, presence of traffic, traffic including large trucks, …

Figure 5. *Example failure scenario with each FEP identified by color coded scheme. Below the failure scenario we define annual risk and identify the top event (see below) and contributing factors to the risk of this failure event.*

<u>Element #4</u>

For each accident scenario i within each scenario category j, analyze and estimate the likelihood of the scenario $Prob_i$ (probability per year or annual frequency). This quantification can be approximate at first, subject to further analysis if appropriate. This analysis is intrinsically probabilistic in character.

Presented in Figure 6 is a fault tree, one of the useful approaches for estimating likelihood of low-probability failure scenarios. (As noted earlier, guidance on fault-tree methodology can be found in (Vesely et al., 1981).) As shown, the top event is the full-bore pipeline rupture. Starting at the bottom, the contributing factors begin with the failure of a truck driver to pay attention to the road, the likelihood of which we estimated for the sake of this example as being 3×10^{-5} /yr, that is, one truck driver in 300,000 trips across the bridge might be expected to be asleep or otherwise unable to negotiate the turn onto the bridge. Note that the two possible situations of truck-driver inattention feed into an OR gate, and their annual likelihoods are additive when combined to estimate likelihood of the truck crashing into the guardrail. Moving up to the next level, in order for the truck to drive off of the road, it needs to crash through the guardrail. We estimate the guardrail as being subject to failure in resisting the force of a truck at 50% given the presence of wooden posts that rot over time (see processes active in the failure scenario as shown in Figure 5).

The truck crashing into the guardrail and the failure of the guardrail to hold the truck result in the truck driving off of the road. Note the likelihood of driving off of the road is one-half the likelihood of hitting the guardrail because both events (hitting guardrail, and guardrail failing) need to occur (AND gate), and the likelihood of both occurring is calculated by multiplying the likelihoods of each event.

So at this point in the fault tree there is a 1.5×10^{-5} /yr likelihood (L_i) of a truck driving off of the road at the river crossing.

What does it take to for the truck to hit the pipe? First the pipe must be above ground, and second, the pipe must be in proximity to the guardrail/road. The likelihoods of these factors are shown in Figure 6, and again, we multiply these likelihoods together to obtain the 3×10^{-6}/yr likelihood that the truck would hit the pipe. Assuming that 90% of the time the pipeline will not be strong enough to resist the impact of the truck, we end up with an overall likelihood of this low-probability event of 2.7×10^{-6}/yr likelihood that a truck will impact the pipe at this location and cause a full-bore rupture.

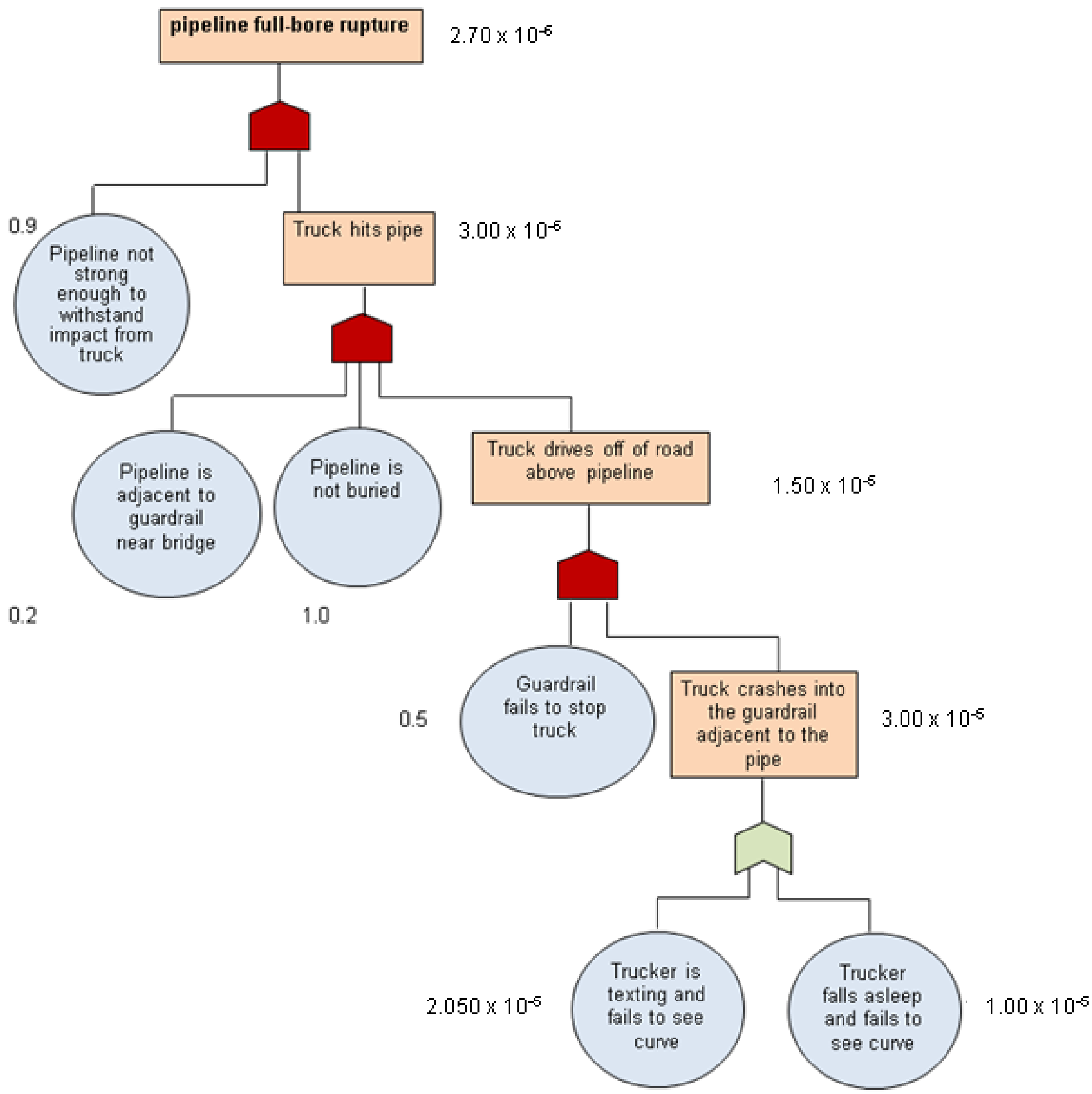

Figure 6. *Example Fault Tree for the accident scenario involving a truck crashing through a guard rail causing a CO_2 pipeline to rupture.*

<u>Methodology Element #5</u>

For each accident scenario, characterize and quantify the potential CO_2 release – (for example, the rate of release, the amount released, the character of the release). Again, this quantification can be approximate at first, subject to further analysis if appropriate. This analysis must capture the variabilities and uncertainties, and hence it is intrinsically probabilistic in character.

Pipeline discharge and decompression following rupture can be modeled using coupled computational fluid dynamics and equation of state models. One example of such a model is the PIPE model (Picard and Bishnoi, 1988). This model calculates flow rates, pressure drop, temperature and related quantities for the entire blowdown of a high-pressure pipeline. The model has options for various gases (e.g., natural gas (CH_4), or CO_2) described by equations of state. Results from the PIPE model for a 16-inch diameter CO_2 pipeline with block-valve (emergency shutoff valve) spacing of 1 km are shown in Figure 7. As shown, the mass flow rate at the outlet (blue curve) reaches its maximum value within the first second after rupture and then declines after less than a second as pressure is released. The main release event occurs over about 100 sec. The temperature declines much more steadily over this period. Interestingly, the velocity of discharge actually increases during this period as pressure decline causes the density to drop, thereby requiring higher gas velocity to transfer the (decreasing) mass leakage. The results of pipe discharge models provide the source term for Element#6 of the risk assessment.

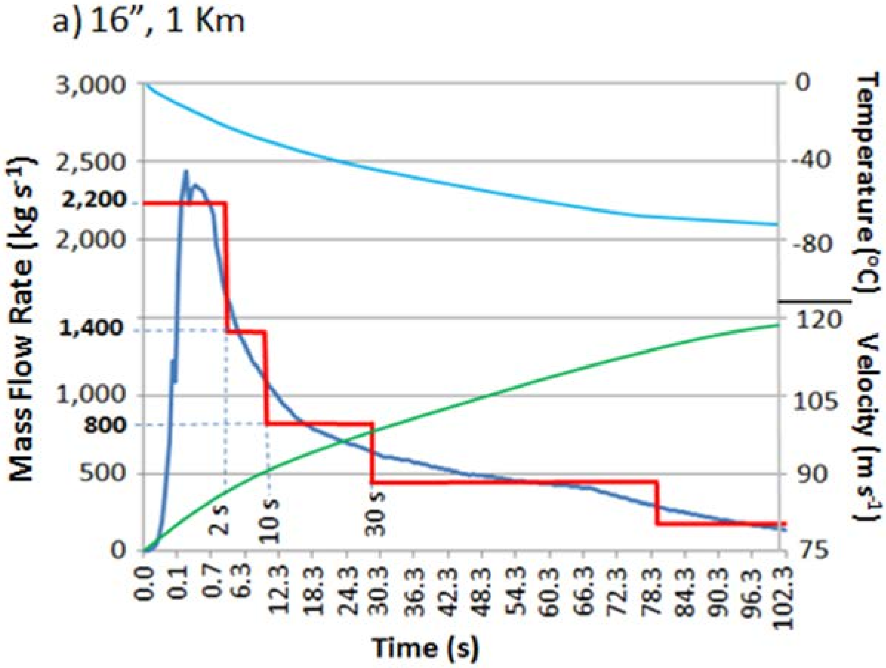

Figure 7. *Model results from the PIPE model (Picard and Bishnoi, 1988) of mass-flow rate, temperature, and velocity of CO_2 escaping from a full-bore rupture of a 16-inch pipeline with 1 km spacing of block valves (emergency shut-off valves). The PIPE model temperature is shown in the light blue curve. The PIPE model mass flow rate is shown in the dark blue curve. The PIPE model velocity is shown in the green curve. The red stair-step curve is the mass flow rate source term used in the CFD simulations of the CO_2 plume dispersion shown in Element #6 (below).*

Methodology Element #6

Concerning the release, characterize quantitatively the temporal and spatial concentrations resulting from each failure scenario. This analysis must capture the variabilities and uncertainties, and hence it is intrinsically probabilistic in character.

Under the scenario considered, a full-bore pipe rupture occurs following the truck crash into the pipe. High pressure CO_2 discharges at large mass-flow rates for the first few minutes at velocities in excess of 100 meters per second (220 miles per hour). This discharge produces a dynamic plume of elevated and potentially harmful CO_2 concentrations. In order to characterize the temporal and spatial concentrations from this scenario quantitatively, CFD models can be used (e.g., Mazzoldi et al., 2013). We present in Figure 8 the results from such a model. Specifically, Figure 8 shows pipeline discharge velocity vectors in a background wind field with velocity 2 meters per second at a height of 10 m blowing left-to-right in Figure 8. As shown, CO_2 gas velocity near the pipe is approximately 100 meters per second diminishing to near-background velocity 150 m away from the pipe.

The associated CO_2 plume concentrations are shown in Figure 8 by the colored wireframes indicating the 250,000 ppmv (red) and 100,000 ppmv (yellow) contours of CO_2 concentration. If the downstream safety length (DSL) is defined on the basis of the 100,000 ppmv concentration contour, the DSL is 230 m for this scenario, occurring at t = 35 s. This kind of modeling coupled with the pipe discharge model can characterize the temporal and spatial concentrations ($C_{Ri}(x,y)$) that inform downstream safety lengths and locations with high likelihood of impacts to health and safety.

The probabilistic aspect of Element#6 arises because of the variability and uncertainty in both the nature of the rupture and all of the environmental characteristics that influence it. For example, the truck may rupture the pipeline but also partially block and deflect the CO_2 discharge. The failure could happen during a calm or very windy day. The exact location may include topography that influences the plume. Clearly there are too many variables and uncertainties to model every possible combination of system properties. While there are many approaches to handling uncertainty and variability in risk assessment, we advocate using approaches that represent uncertainty in practical and defensible ways. For example, one approach is to choose a somewhat conservative concentration to define the DSL, and to make the DSL apply in all directions around the well to account for the fact that the initial discharge and the wind could be in any direction. When we assume the DSL could occur in any direction, we call it a downstream safety radius (DSR). We have taken this approach in our work on the National Risk Assessment Partnership (NRAP) project (Zhang et al., 2016). We note that NRAP's Integrated Assessment Model (IAM) is intrinsically probabilistic to account for variability and uncertainty in leakage risk assessment.

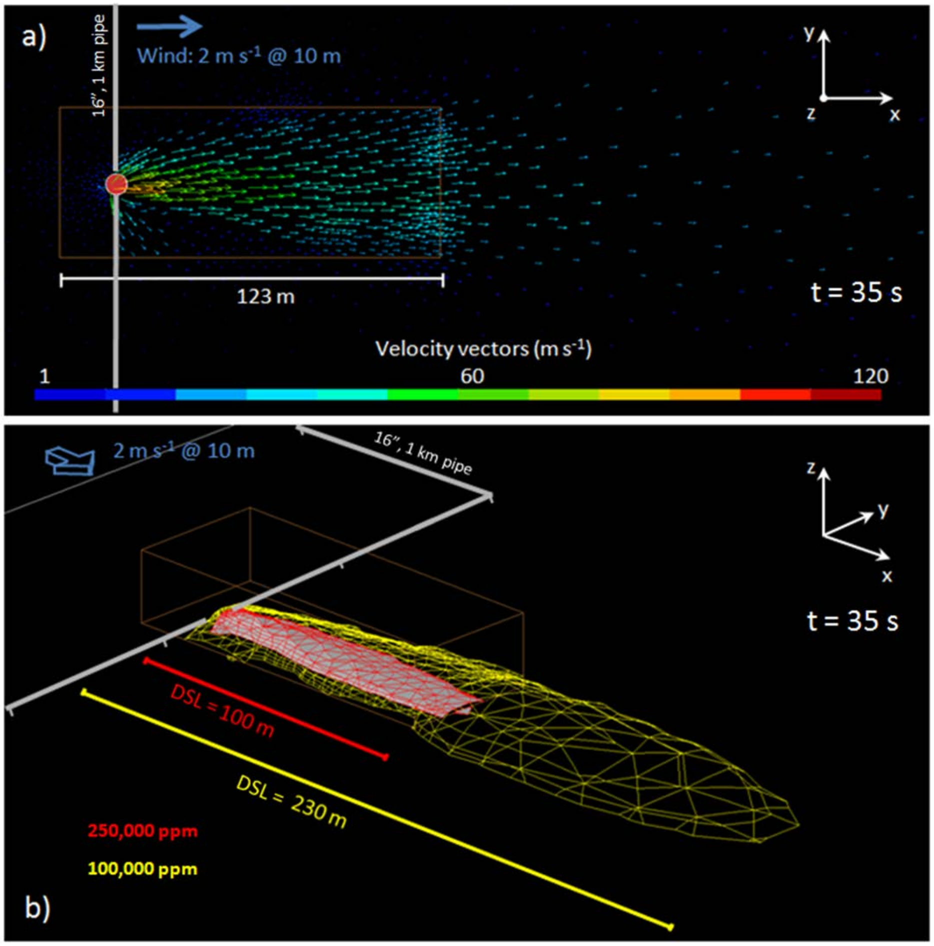

Figure 8. *CFD model results (Mazzoldi et al., 2013) of (a) the velocity of CO_2 escaping from a full-bore rupture of a 16-inch pipeline with 1 km spacing of block valves (emergency shut-off valves), and (b) the contours of 250,000 ppm (red) and 100,000 ppm (yellow) CO_2 concentration, which define downstream safety lengths (DSL). Note that the wind in this simulation is assumed to be aligned with the discharge from the pipe.*

Methodology Element #7

Analyze the "risk" to nearby populations arising from the release. (If other risk endpoints are of interest, such as pets, livestock, terrestrial fauna, the environment, and natural resources, then the risk to these must also be analyzed here.) This is in terms of the likelihood multiplied by the consequences. This requires specifying how the risk is to be characterized (fatalities or other endpoints). This risk may vary depending on whether any population protective actions (sheltering, evacuation, etc.) are considered. This analysis is intrinsically probabilistic in character.

In this element as applied to the scenario under consideration, the main risk arises from inhalation of CO_2 by the nearby population in City C. Because we have not carried out any specific modeling for this example failure scenario, we present here analogous calculations done by Lisbona et al. (2014) who considered the effects of topography on the plume following leakage from a pipeline. As shown in Figure 9, Lisbona et al. (2014) calculated contours of harm with units of cpm/year (chances (of fatality) per million (people) per year). The CO_2 concentration is the underlying cause of the inhalation hazard. Lisbona et al. considered the likelihood of exposure to these elevated CO_2 concentrations by estimating probabilities of various wind directions and weather conditions, and multiplying these probabilities by the likelihood of the pipeline failure. Lisbona et al. (2014) used two different models for simulating the CO_2 concentration plume (dotted and continuous curves) over the variable topography of the site.

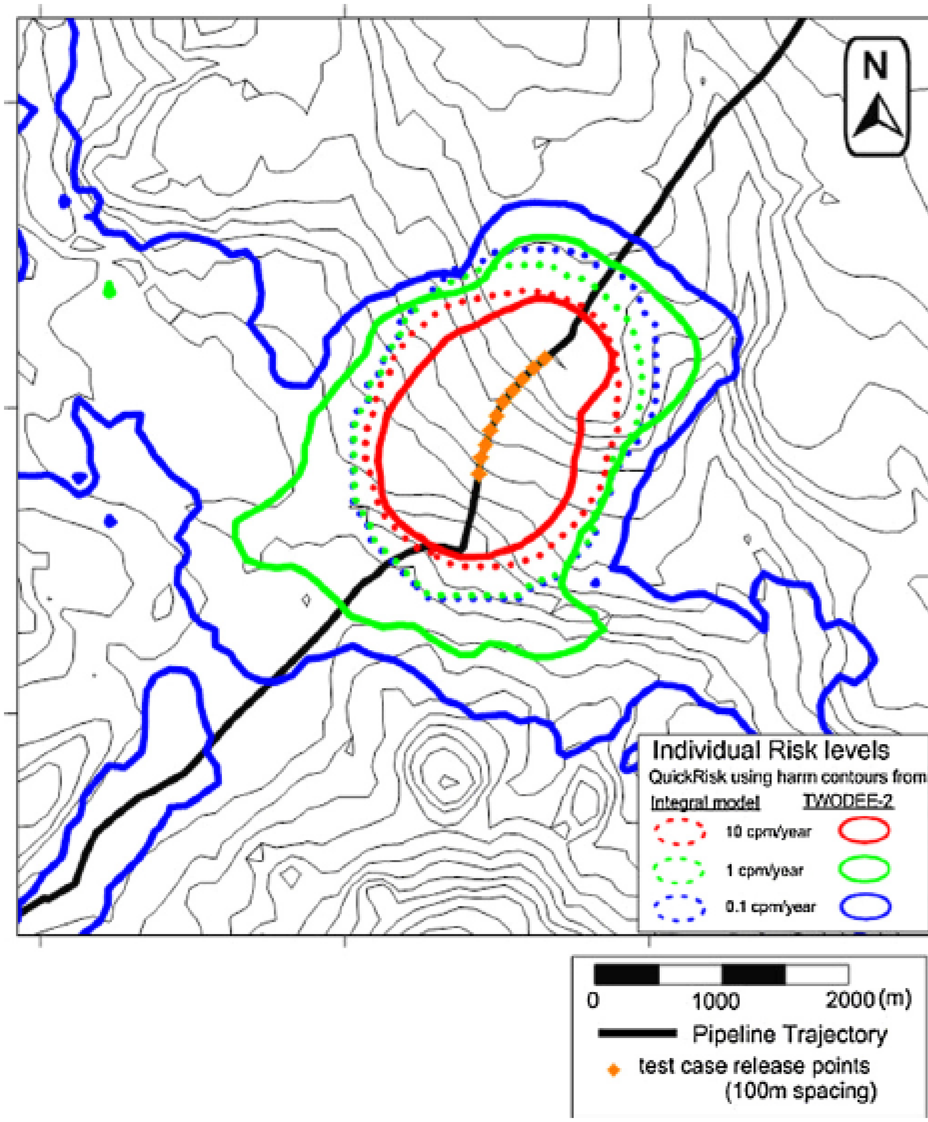

Figure 9. *Contours of potential harm to people from CO_2 inhalation estimated using simulations from an integral model (dashed curves) and the simulator TWODEE-2 (solid curves) from the paper by Lisbona et al. (2014).*

Lisbona et al. (2014) then went a step further and convolved the risk of harm with the population density to estimate the potential fatalities per hectare per year. The result is shown in Figure 10 and represents a very important aspect of pipeline risk assessment. Specifically, because pipelines are spatially extensive and pass over regions with highly variable potential receptors (e.g., through unpopulated areas, cities, under and over roads, etc.), the fact that pipeline rupture risk is spatially variable can be used to make decisions about risk mitigation that optimize risk reduction for a given expenditure. For example, from information such as that in Figure 10, the best locations to implement risk reduction efforts (e.g., increased frequency of block valves, use of audible alarms, burying pipe, etc.) are in the orange areas where risks to people are higher.

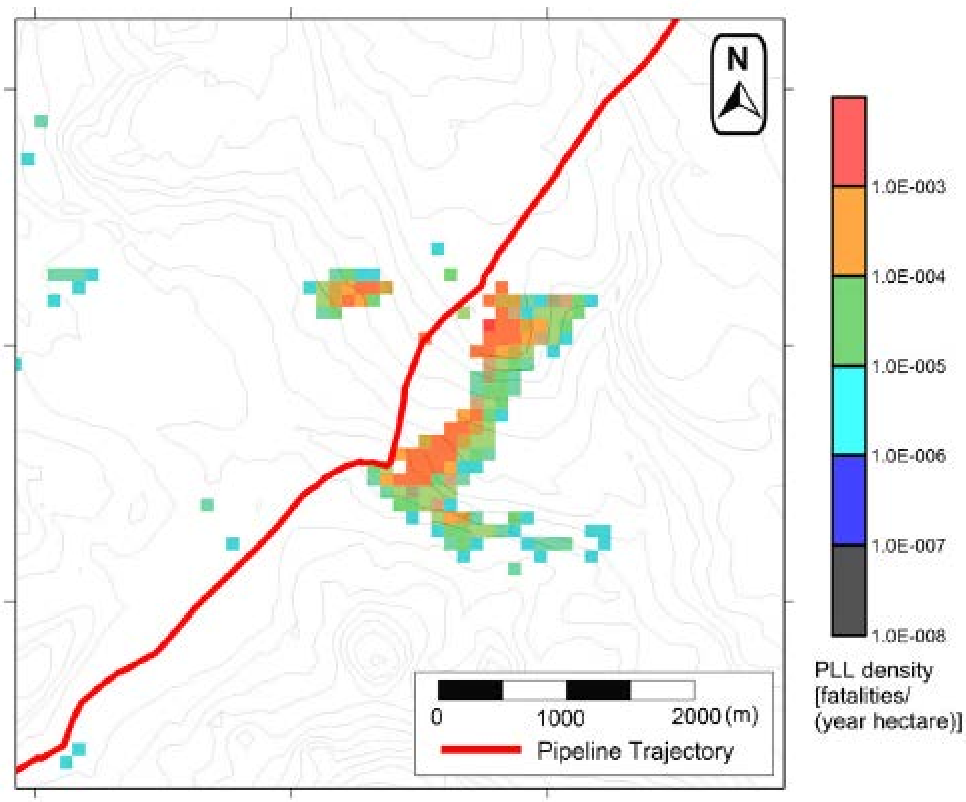

Figure 10. *Contours of projected fatalities from CO_2 inhalation estimated by combining simulation results of potential harm due to CO_2 inhalation with population density from the paper by Lisbona et al. (2014).*

Methodology Element #8

Describe and then analyze the uncertainties in the bottom-line risk results, and the sources of those uncertainties.

For the failure scenario under consideration, we assume that we combine results such as those of Figure 10 with a health hazard model to produce results of harm similar to that of Lisbona et al. (2014) to determine whether or not the residents in City C will be exposed to any concentrations leading to fatalities. In the course of carrying out this assessment of the risk (likelihood × consequences) of a given failure scenario, it is essential that uncertainties and the sources of those uncertainties be analyzed so that decision makers can assess the level of confidence in the risk numbers and the associated insights. For our scenario, there are many large uncertainties on the consequences side of the risk equation, e.g., the location of the rupture, the wind at the time of rupture, the deflection of the initial blast, etc. And there are uncertainties on the likelihood side of the risk equation. Recall that in the fault tree of Figure 6 we used very rough estimates of frequency of occurrence for several contributing events to arrive at an estimated likelihood of the top event. Can the uncertainty in these probabilities be estimated? One reason for presenting both likelihood and consequence estimates along with their product (risk) is to avoid the pitfall of losing the information of which factor is the main risk driver, i.e., is risk dominated by likelihood or by consequences? By presenting this information separately, decision makers can independently evaluate both factors along with the uncertainty inherent in the individual calculations.

In the pipeline rupture scenario presented here, the likelihoods have enormous uncertainty. On the other hand, the calculations of discharge and plume spread, while very accurate for the specified conditions, are uncertain because the exact location of the rupture and the direction of the discharge may be different from that in the model. Case study applications are needed to actually carry out uncertainty quantification (UQ) for particular cases, and to understand the effects on risk numbers of this uncertainty.

Methodology Element #9

Perform sensitivity analyses, as appropriate, to determine the extent to which the analysis results and insights are sensitive to each the various important assumptions, inputs, or phenomenological models.

Closely related to UQ (see Element #8, above) is sensitivity analysis. Simply put, decision makers have great interest in the degree to which various factors and system properties control the estimated risk because such information allows decision makers to efficiently identify how best to reduce risk. For example, in the example scenario here, the assumption of the location of the pipe rupture strongly controls whether or not people in City C will be impacted. Similarly, the assumptions about frequency of trucks leaving the road control the likelihood of the rupture. More subtle sensitivities will arise from a very long list of assumed and measured properties and parameters of the models used to estimate plume dynamics.

Methodology Element #10

Identify and analyze appropriate and feasible mitigation strategies that, if deployed, could reduce the risk. Some mitigation strategies might reduce the likelihood of the risk, while others might reduce the consequences. Still others might reduce the uncertainty, which can be of great value by itself. Still other strategies might involve trade-offs – reducing one risk aspect while increasing another.

The failure scenario described in Figure 5 and the fault tree in Figure 6 reveal several opportunities for risk mitigation. First, from the failure scenario text, we see immediately the problem is that the pipeline is above ground and near the road. Burial of the pipeline and or placement of the pipe farther from the road can virtually eliminate this entire scenario. If these mitigations are not possible, then perhaps a stronger guardrail and/or improvements in the roadway and signage could mitigate the likelihood of the truck leaving the roadway thereby eliminating the contributing events of Figure 5. If none of these mitigations is practical, perhaps the pipe could be double-walled or protected by a secondary barrier where it comes out of the ground. Without going through every possible mitigation option here, it should be apparent from this risk assessment approach that there are numerous mitigation opportunities identified by the analysis. Information on UQ, sources of uncertainty, and costs of mitigations can be combined by the analysts to inform decision making to optimize risk reduction while minimizing cost.

6. Recommendations for Further Work

Review of technical basis for CO_2 pipeline risk assessment

Given that a vast network of CO_2 pipelines, far larger than the ~5000 km currently built in the U.S., will be needed for large-scale implementation of CCS, a review of the technical basis for risk assessment and approval of CO_2 pipelines should be carried out. The main purpose of such a review is to allow experts to evaluate requirements in light of advances that have been made in modeling (e.g., CFD for atmospheric dispersion) and data on reliability and failure. Depending on the findings, requirements for risk assessment could be updated or revised to match the larger network envisioned for CCS.

Case studies and demonstrations

In order to more fully validate and demonstrate the proposed CO_2 pipeline and well failure risk assessment framework presented here, case study applications should be carried out. By case studies, we mean cases with sufficient detail that real scenarios and fault-tree analyses FTA's can be carried out. The cases could be actual planned pipelines, or alternatively existing pipelines upon which the framework could be applied retrospectively. The point is that sufficient details in routing, hazards, vulnerable populations, and sensitive environmental conditions need to be available to realistically verify and demonstrate the usefulness of the framework.

Identify useful models and their applicability to specific conditions

Consequence prediction in the framework involves simulating or modeling CO_2 release and associated transport and dispersion. Such release may occur on very windy days, or on calm days, in mountainous terrain in winter, or in summer in desert environments. In short, there are a wide variety of conditions possible for CO_2 release, and it will be beneficial to identify various specific models that are most appropriate and efficient for various situations. For example, for flat terrain with steady wind, it is possible that much simpler models will suffice than if the release occurs in mountainous terrain with variable topography. In this effort, researchers could create a table that identifies the most appropriate models for different end-member conditions with notes on computational requirements to help practitioners decide which models to use.

Develop coupled models for release and dispersion

To our knowledge, there is no coupled pipeline or wellbore blowout model that is directly coupled to sophisticated atmospheric dispersion simulation capabilities. In our previous work (e.g., Mazzoldi et al., 2013), we manually transferred output from the PIPE model to the PANACHE atmospheric dispersion model. We recommend that development efforts be aimed at directly coupling these two fundamental pipeline process models to ensure that accurate simulation capability exists for high-pressure pipeline failures. This coupling is particularly important in the near-pipeline region where consequences can be very large for nearby populations. Similarly for well blowout scenarios, there are no process-based coupled wellbore flow (e.g., T2Well) and atmospheric dispersion (e.g., PANACHE) models. NRAP has developed a multiple source leakage reduced-order model (ROM), but this is designed for surface leakage rather than energetic pipeline or well blowout scenarios and therefore does not model inertial effects, in addition to other simplifications (Zhang et al., 2016).

Low-energy seepage into subsurface and pipeline backfill

Although most of the discussion about the framework in this report centered on high-energy (e.g., full-bore ruptures) and well blowout scenarios, another class of failure of buried pipelines and wells is shallow subsurface leakage, where for example, corrosion of the pipe or well casing allows incipient and persistent small-scale leakage that is difficult to detect, but nevertheless can lead to serious consequences. We recommend that modeling and simulation be carried out to investigate these scenarios to determine what kinds of surface leakage signals develop, and what kinds of migration pathways, e.g., along pipeline backfill, are possible. The ability to monitor and detect small-scale corrosion-related leakage (before such corrosion compromises the integrity of the whole pipeline or well such that a catastrophic leak develops) would allow remedies to be applied before large-scale failure occurs.

Defensible Fault-Tree Analysis (FTA)

Insofar as likelihood is on equal footing with consequence in estimation of risk, approaches such as FTA deserve equal time and effort in the analysis. We recommend that practitioners carry out thorough FTA and utilize defensible databases or statistical analyses to generate likelihoods of contributing events. Similarly, we emphasize the importance of ensuring that all significant potential failure scenarios are evaluated, a challenge inherent in any inductive approach that relies on experience and expertise in the subject area, along with a certain amount of imagination and objectivity to envision the very unlikely or “unthinkable” failure scenarios and contributing events. Efforts in this area include compiling statistics on various accidental events such as vehicles driving off of roads, airplanes crashing, and backhoes hitting buried pipelines.

Pipeline and well casing corrosion

Because corrosion is a common cause of failure for steel, we recommend that research focus on monitoring and detection along with prevention of corrosion. We realize that this is a huge area of interest and research, but we believe that, especially for the case of wells, monitoring and detection of corrosion can be further developed or more rigorously applied to prevent failures such as the 2015-2016 Aliso Canyon SS-25 well failure in California (e.g., Conley et al., 2016). In the case of wells, the only access is from the inside, which can make it difficult to detect corrosion that is starting from the formation and/or cement outside of the casing. The opposite is true for pipelines, where monitoring is often done outside of the pipe. As for prevention of corrosion, most of the industry experience is with natural gas; attention to corrosion prevention for CO_2 pipelines is needed now so that corrosion can be reduced in future pipeline networks.

Emergency Shut-off (or block) Valves (ESV’s) in pipelines

We have learned that emergency shut-off (or block) valves (ESV’s) in pipelines are used sparingly because of concerns about maintenance and inadvertent actuation. Nevertheless, the attraction of such valves for consequence reduction is obvious and will not escape a skeptical public concerned about reducing risk. Rather than continuing to make the argument that such valves are impractical and unnecessary, we recommend that the weaknesses and shortcomings of such valves be considered an opportunity for improvements in the technology. Simply put, more reliable block valves can certainly be developed and deployed, and research should be directed at these advances so that improved devices become available at competitive costs for future CO_2 pipelines.

Subsurface Safety Valves (SSSV's) in wells

Similar to the emergency shut-off valves in pipelines, subsurface safety valves (SSSV's) are pressure- or flow-rate activated valves that can shut-off flow in a well during blowouts or other uncontrolled flow events. And like ESV's in pipelines, they are rarely deployed, most likely because of reliability problems, specifically false-positive failures (closing when they should not). As with ESV's, we believe the lack of reliability for SSSV's is a huge opportunity for engineers to develop better SSSV's that can be widely installed and counted upon to mitigate risk of well blowouts.

Well-kill modeling for developing better kill strategies

Despite seven attempts at killing the Aliso Canyon natural gas storage facility SS-25 well, it continued to leak methane into the air for nearly four months. The difficulty in killing the well likely arose from the complex geometry of flow paths in the well that prevented the pooling of kill fluid and promoted its atomization and transport up and out of the well entrained with natural gas. Similarly, the Macondo well in the Gulf of Mexico leaked oil and gas for approximately three months after the blowout preventer failed (Oldenburg et al., 2012). We recommend research aimed at modeling and simulation of well blowouts and kill processes in order to understand what kinds of well flow-path geometries are favorable and unfavorable for well-killing. Adequate numerical simulation capabilities exist (e.g., Pan et al., 2011; Pan and Oldenburg, 2014), but new and more powerful wellbore flow simulation capabilities should be developed to address the complex high-Reynolds number and potentially two-phase flow phenomena occurring in wellbore flow.

7. Summary and Conclusions

This report reviews the state-of-the-art of risk assessment of low-probability-high-consequence (LPHC) accidents arising from the deployment of a nationwide network of CCS pipelines and injections wells. The report then goes on to describe a risk assessment framework that addresses the analysis of LPHC accidents that could arise from the deployment of such a network. The framework concentrates on the identification of specific individual accident sequences, for each of which one analyzes both the likelihood (in terms of the sequence's annual frequency) and the consequences (in terms of CO_2 releases and their consequences to public health). Because the individual accident sequences have very different annual probabilities from one to the next, and there is uncertainty in consequences and likelihoods, the analysis methodology is intrinsically probabilistic in character.

This risk assessment framework and the detailed step-by-step methodology that implements it are designed to parse the many factors contributing to risk into clearly identifiable pieces that will allow identification of cost-effective risk mitigation options so that engineers, operators, and policy-makers can efficiently reduce the risks arising from CCS pipeline-and injection-well infrastructure. Reducing risk is vital for public acceptance of CCS, a critical technology for avoiding the worst effects of climate change.

One major conclusion of this report is that the methodology needed for this analysis is fully feasible, and in fact none of the technical analysis work described in the step-by-step guidance contained in the report breaks new ground in terms of methodologies. However, the entire suite of techniques embedded in the step-by-step methodology has never been implemented as a whole to our knowledge.

This leads to another major conclusion of this report, which is that the full realization of the benefits will not occur until there have been a few real-world trials of the approach, as recommended in the "Research Needs" discussion in Section 7.

Finally, it is important to emphasize that the methodology described in this report is, in its application, user-oriented. The users are the decision-makers who will rely on the results and insights from these analyses to make engineering, operational, deployment, investment, and other decisions about these CCS pipeline and injection-well systems. For these users, the insights can provide them with technically sound information about the low-probability high-consequence accident sequences discussed herein. To the extent that the analyses themselves are performed with this user-oriented philosophy at the forefront, the analyses will provide the desired insights to the users. This must be the focus.

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Nomenclature

a, b	Weighting parameters (see App. 1)	
CCS	Carbon dioxide Capture and Storage	
C_{Ri}	Concentration field produced by release R_i	ppmv
DSL	Downstream Safety Length	m
DSR	Downstream Safety Radius	km
EOR	Enhanced Oil Recovery	
ESV	Emergence Shut-off Valve	
f_{ij}	Features in the index and comparison cases (see App. 1)	
FEP	Features, Events, and Processes	
FTA	Fault Tree Analysis	
GCS	Geologic Carbon Sequestration	
IAM	Integrated Assessment Model	
L	Length of pipeline	km
LPHC	Low-Probability High-Consequence	
P_i	Probability or likelihood of scenario i	#occurrences/yr
Pop	Population density	#people/km^2
R_i	Release under scenario i	kg CO_2
$RiskPop_i$	Risk of fatality under scenario i	#fatalities/km^2
ROM	Reduced Order Model	
S_{ij}	Measure of similarity between scenarios i and j (see App. 1)	
SSSV	Subsurface shut-off valve	
UQ	Uncertainty Quantification	
$VulPop_i$	Vulnerable population under scenario i	#people/km^2
t	time	sec, yrs
x	x-coordinate	m
y	y-coordinate	m

Subscripts

i	specific failure scenario index
j	scenario class index

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Appendix 1. Examples of likelihood estimation methods for very rare events

Similarity Judgment

In this approach, it is recognized that a very rare failure scenario *i* may be similar to a failure scenario *j* which has occurred more frequently in the past. Similarity judgment involves estimating factors by which *i* differs from *j*. These factors describe the degree of similarity, which can then be used to estimate the unknown likelihood of *j* relative to the known likelihood of *i*.

For example, suppose that following the experiences of compaction-related well failure at a particular Site A, we want to know the likelihood of well failure at a new Site B with rock that compacts a factor *n* less than at Site A. This factor *n* may be one of many factors that would be used to scale Site A likelihoods to Site B likelihoods.

In general, the very rare failure scenario *i* (index case) may have similar features to those in failure scenario *j* (comparison case) which can be classified as follows:

1. Features in the index case but not in the comparison case, $f_{i,\ not\ j}$

2. Features in the comparison case but not in the index case, $f_{not\ i,\ j}$

3. Features in both cases, $f_{i,j}$

In this case, the similarity can be measured as the count of shared and not shared features using the following formula:

$$S_{ij} = f_{i,j} / [f_{i,j} + a\ f_{i,\ not\ j} + b\ f_{not\ i,\ j}]$$

$$P_{catastrophic\ failure,\ j} = P_{catastrophic\ failure,\ i} \times S_{ij}$$

where *a* and *b* are weighting parameters, the choice of which relies on the analyst's judgment. This similarity judgment approach in practice is only useful where the index and comparison cases are largely similar.

Importance Sampling

The idea behind importance sampling is to analyze event likelihood in samples of the whole population where the event is not rare. For example, consider a well integrity risk assessment where one needs to estimate the likelihood of a rare well-failure scenario. If it happens that this well-failure scenario is more likely in older wells, e.g., those older than 50 years, we can use statistics on the failures of wells older than 50-years to generate a likelihood of failure for this subset of all wells. The likelihood of failure of the whole population of wells can then be estimated by multiplying the likelihood of failure of old wells by the fraction of old wells in the whole population of wells.

Time to Event

Assuming a constant likelihood of occurrence over time (t), the number of consecutive occurrences of an event has a geometric distribution. For a geometric distribution, the probability p of occurrence of rare events can be estimated from the average time to the event as

$$P = 1 / (1 + t)$$

We refer interested readers to the online materials posted by Farrokh Alemi (George Mason Univ.) for further details on likelihood estimation of rare events:
http://openonlinecourses.com/RiskAnalysis/ProbabilityRareEvent.asp
(Accessed 8/26/16),

Appendix 2. Convolution

The convolution of two functions is an integral that expresses the amount of overlap of one function as it is shifted over another function. This abstract concept can be made very clear in the pipeline risk application presented in this report, i.e., to find the population at risk of a pipeline failure. Consider for example the *DSR(x,y)* produced by a full-bore pipeline rupture. The *DSR* represents the radius away from the pipe within which CO_2 concentrations are harmful. Consider next the population density along the pipeline, *Pop(x,y)*. For simplicity, consider idealizing the two-dimensional pipeline of Figure 3 into a one-dimensional pipeline of length L. The *DSR* and *Pop* functions then become *DSR(L)* and *Pop(L)* as shown in Figure A1.1 along with Cities C and D. The convolution of *Pop(L)* and *DSR(L)* will give the fraction of the population impacted by pipeline leakage anywhere along the pipe.

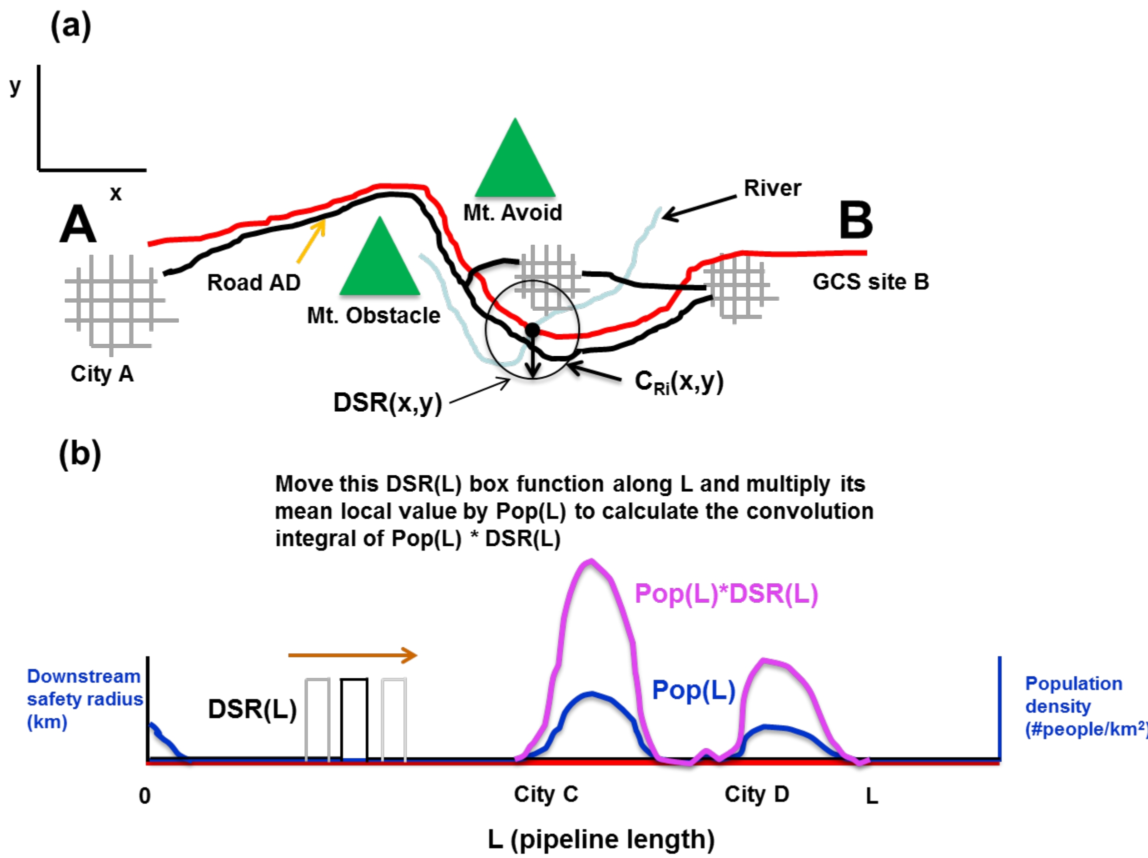

Figure A1.1 *(a) Graphical depiction of the notional pipeline risk scenario repeated from Figure 3 (b) the projected pipeline (red) with the DSR(L) box function (black) and Pop(L) function (blue) shown to illustrate the convolution of DSR(L) with Pop(L) (purple).*