Risk Assessment Framework for Evaluating Low-Probability High-Consequence (LPHC) Failure Scenarios of CO$_2$ Pipelines and Wells

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Large-scale CCS will entail a pipeline transportation network with associated CO$_2$ pipeline hazards

Example hazards of CO$_2$ pipelines include:

Rapid catastrophic rupture (e.g., full-bore or longitudinal fracture) of the high-pressure pipeline can cause potentially fatal blast wave;

Large-scale CO$_2$ leakage displaces oxygen and is toxic at high concentrations;

CO$_2$ is a dense gas that can seep out of the backfill where it may have accumulated from slow incipient leakage out of pinhole leaks or leaky seals and can then migrate into low-lying topography or basements of buildings.
For pipelines and wells, the risk matrix (Boston Squares) is useful, but residual risks (e.g., LPHC scenarios) also need evaluation.

- Adherence to all regulations, industry codes and standards, and best practices in pipeline and well construction and operation can reduce risk to acceptable levels (e.g., below the green line, and within the gray box).
- Yet residual risk always remains, e.g., risk associated with LPHC failure scenarios.
- By their very nature, LPHC scenarios cause concern among the public.
- Decision-makers need technical analysis of LPHC scenarios to address public concern.
Summary of LBNL statement of work

LBNL will analyze and discuss risk (likelihood and consequences) assessment and risk mitigation for two low-probability failure scenarios associated with geologic carbon sequestration (GCS):

1) High-pressure CO₂ pipeline rupture;
2) Leaking wells including blowout scenarios;

LBNL’s treatment of these topics will be in the context of recommending a framework methodology for evaluating low-probability and high-consequence failure scenarios.

The framework we have developed is based on the FEP-scenario approach whereby failure scenarios are generated along with their likelihoods and consequences to estimate risk of the given failure scenarios.

The novelty of our work is in the emphasis on the identification and analysis of individual accident sequences (grouped by type), and the explicit consideration of spatially variable population and resource vulnerability along the pipeline (or as a function of well location), which leads to the potential for targeted risk mitigation and associated cost savings.
Key Definitions in the Context of LPHC Risk Assessment

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, sometimes called an “accident sequence”

Consequence = Impact = quantified negative effect of a failure scenario

Likelihood = Probability per year = quantitative or semi-quantitative chance (or expected frequency) of occurrence of the failure scenario

Risk per year = Consequence x Likelihood per year

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
It is difficult to estimate uncertainty for LPHC failure scenarios

- LPHC scenarios are by definition very rare
- Scenario frequency too low for statistics if failure event(s) are rare

Yet LPHC failure scenarios cannot be ignored—many examples exist

- O-ring on solid rocket booster (rubber brittle at low temperature)
- Fukushima (backup power existed but was flooded by the tsunami)
- Cockpit door lock (installed to keep terrorists out—also kept captain out)
- Macondo Well (Blowout preventer installed to prevent blowouts, but was not able to shear the pipe)
Likelihood of CO₂ pipeline or well failures can be estimated from failure rate data for existing pipelines or from fault tree analysis (FTA).

Frequency or time-to-event for CO₂ pipeline failures

<table>
<thead>
<tr>
<th>Module</th>
<th>Expected failure rate (events per module per year)</th>
<th>Leak every $x$ years, $X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  CO₂ recovery at source</td>
<td>$1.5 \times 10^{-1}$</td>
<td>7</td>
</tr>
<tr>
<td>2  Converging pipelines</td>
<td>$4.6 \times 10^{-3}$</td>
<td>217</td>
</tr>
<tr>
<td>3  Booster station</td>
<td>$4.0 \times 10^{-2}$</td>
<td>25</td>
</tr>
<tr>
<td>4  10 km pipeline</td>
<td>$3.4 \times 10^{-4}$</td>
<td>2.941</td>
</tr>
<tr>
<td>5  Injection well</td>
<td>$1.8 \times 10^{-1}$</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 1. Yearly failure rate summary per module (Vendrig et al., 2003).

From Mazzoldi and Oldenburg, 2011
Consequences of CO\textsubscript{2} pipeline and well failures can be estimated in many different ways:

- Empirical models, lookup tables
- Simple analytical solutions
- Simplified mechanistic models (e.g., SLAB models)
- Computational Fluid Dynamics (CFD) models

CFD simulation results for leakage of a pipeline 16 inch in diameter and 1 km length (Mazzoldi et al., 2012).

Fig. 4a. CO\textsubscript{2} leakage perpendicular to the direction of the pipe creates a wind field as shown.

Fig. 4b. Surface contours at two concentrations (100,000 and 250,000 ppm) used to define the Downstream Safety Length (DSL) reached by CO\textsubscript{2} plumes.
A useful abstraction from models of plume dispersion is the downstream safety length (DSL).

Figure 6. DSLs of plumes of $[\text{CO}_2] = 250,000$ ppm. Values depend primarily on pipeline diameter, secondly on pipeline length – accounting for the atmospheric conditions considered (Mazzoldi et al., 2012).
Shock waves generated by the sudden expansion of the gas are a serious hazard

- Velocity of the escaping gas is limited to its speed of sound in choked conditions.
- The actual release velocity just downstream from the rupture is equal to the speed of sound plus the speed of the gas particles driven by the rapid expansion into ambient air.
- In this extremely fast process, pressure gradients do not have the time to develop and the energy is dissipated through the creation of a spherical pressure front that expands radially from the broken end of the pipe (Schardin, 1954; Stoner and Bleakney, 1948).
- This sudden expansion is analogous to a blast-front (the front of the shock-wave) caused, for instance, by an explosion of TNT.
- The energy generated by the explosion can be estimated by comparing the actual effects of the explosion (or the measured blast-front amplitudes at given distances from the detonation center) with the experimentally measured effects (or blast-front amplitudes) of determined masses of TNT charges (Kleine et al., 2003).
- The dissipation of the pressure blast will be approximately linear with distance from the breach and dependent on the energy of the initial shock front.
- The pressure blast front, while short-lived (hundredths of a second) and limited in space to the immediate vicinity (on the order of meters) of the catastrophic rupture, can be fatal to anyone in its path.
- 5 psi blast overpressure ruptures eardrums in 1% of people, 45 psi in 99% of people (Zipf and Cashdollar, 2007).
- Threshold for lung damage is 15 psi (Zipf and Cashdollar, 2007).
- 55-65 psi overpressure is fatal to 99% of people (Zipf and Cashdollar, 2007).
There are many potential causes of pipeline failure

- Corrosion or other failure of material or flange or valve
- Flaw in construction (bad weld)
- Error in operation (over-pressurizing)
- Impact breach (backhoe, vehicle, airplane, meteorite)
- Loss of support (landslide, subsidence, river crossing support failure, etc.)
- Earthquake (shear or tensile failure)
- Tornadoes
- Flood currents

http://www.energyjustice.net/content/new-kind-pipeline%E2%80%A6-co2
Many mechanisms of well failure have been identified

- Wellbore integrity relies on cement, steel, and pressure control.
- In the LPHC context, well integrity also relies on protection of the wellhead, e.g., from impacts of vehicles or airplanes etc.

From Gasda et al. (2004) Env. Geol. (Dan Magee, Alberta Geol. Survey)

CO₂ spread as a dense plume from the December 2015 blowout in Seminole, TX

- 8 Dec. 2015, Seminole, TX
- CO₂ injection well with casing problems
- H₂S was emitted with CO₂
- 500 people evacuated from their homes over 2 sq mi area

http://www.oaoa.com/inthepipeline/oil_news/article_06cd14ac-9dfe-11e5-b4d7-e3ca1e967954.html?mode=image&photo=1
There are many examples of natural gas pipeline and well failures

- A large natural gas storage well at the Aliso Canyon natural gas storage facility suffered a blowout October 2015 to February 2016.
- Cause appears to be corrosion in the steel casing at a depth of 440 ft.

- In addition, a large natural gas pipeline in Pennsylvania exploded in April 2016.
- Cause appears to be corrosion arising from a "possible flaw" in materials used to coat welded joints of the 30-inch pipeline installed in 1981.
FEP-Scenario Pipeline Example 1

Source: http://pstrust.org/about-pipelines1/map-of-major-incidents/el-paso/
**Scenario Example 1**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Event</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

- Identify key event of the failure scenario
- Determine series of things that must happen for that event to occur
- Some things rely on other things happening (AND gate)
- Other things may happen more than one way (OR gate)
- Estimate likelihood of each thing happening
- Total likelihood is the sum over the OR gates of the product of all likelihoods calculated assuming AND dependencies
- Index $j$ refers to AND gates, and $i$ refers to OR gates:

\[ P_{\text{catastrophic failure}} = \sum_{i} \prod_{j} p_{i,j} \]
Top Event (from FEP analysis):
pipeline full-bore rupture

Initiating processes:
Trucker not paying attention
Ineffective guardrail
Pipeline above ground near guardrail
Pipeline not strong enough to withstand impact

AND gate:

OR gate:
Time to Event

• Assuming constant likelihood of occurrence over time, number of consecutive occurrences has a geometric distribution.

• If geometric distribution, probability of occurrence of rare event can be estimated from the average time to the event

\[ p = \frac{1}{1+t} \]
## Time to Event

<table>
<thead>
<tr>
<th>ISO 17799 word</th>
<th>Frequency of event</th>
<th>Calculation</th>
<th>Rare probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible</td>
<td>Once in a decade</td>
<td>$1/(1+3649)$</td>
<td>0.0003</td>
</tr>
<tr>
<td>Very low</td>
<td>2-3 times every 5 years</td>
<td>$2.5/(5\times365)$</td>
<td>0.0014</td>
</tr>
<tr>
<td>Low</td>
<td>$\leq$ once per year</td>
<td>$1/(364+1)$</td>
<td>0.0027</td>
</tr>
<tr>
<td>Medium</td>
<td>$\leq$ once per 6 months</td>
<td>$1/(6\times30+1)$</td>
<td>0.0056</td>
</tr>
<tr>
<td>High</td>
<td>$\leq$ once per month</td>
<td>$1/(30+1)$</td>
<td>0.0333</td>
</tr>
<tr>
<td>Very high</td>
<td>$\geq$ once per week</td>
<td>$1/(6+1)$</td>
<td>0.1429</td>
</tr>
<tr>
<td>Extreme</td>
<td>$\geq$ one per day</td>
<td>$1/1$</td>
<td>1</td>
</tr>
</tbody>
</table>
Similarity Judgment

• Very rare Failure Scenario $i$ may be similar to Failure Scenario $j$ which has occurred in the past

• Similarity judgment involves estimating factors by which $i$ differs from $j$

• These factors describe degree of similarity

• E.g., suppose that, following the experiences at a particular Site A of compaction-related well failures, someone wants to know likelihood of well failure at a new field 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 new site likelihoods.
Similarity Judgment

• Very rare Failure Scenario i (index case) may have similar features to those in Failure Scenario j (comparison case) which has occurred in the past

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

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

3. Features in both cases, \( f_{i,j} \)

Then similarity can be measured as the count of shared and not shared features using the following formula:

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

\[
P_{\text{catastrophic failure, } j} = P_{\text{catastrophic failure, } i} * S_{ij}
\]
Importance Sampling

- Analyze event likelihood using samples where the event is not rare

- E.g., we could consider likelihood of well integrity failure in wells older than 50 years. Then we could extrapolate that likelihood of failure to the whole set of wells by multiplying likelihood by the fraction of wells older than 50 years.
Putting it all together: A new framework that emphasizes LPHC events

- Considers spatial variability in vulnerable populations or resources along the length of the pipeline or adjacent to the wellhead
- Uses FEP-scenario approach to ensure consideration of all relevant failure scenarios
- Estimates likelihood per year of failure scenarios and their consequences
- Estimates consequences, e.g., downstream safety lengths
- Convolves locations where concentrations are hazardous with locations of populations or other valuable resources to estimate consequences as a function of space
- Multiplies the above with the likelihood per year of the failure scenario to estimate risk per year as a function of location
- Considers uncertainty in the above estimates
- Uses results to focus risk mitigation at specific locations for cost-effective risk reduction
Assumptions for CO₂ pipeline and well failure risk assessment framework

We assume the following are known a priori from broad studies of CO₂ risk assessment and pipeline and well experience to date:

• Hazards (e.g., concentration of concern) of CO₂ are known and critical thresholds of potential impacts to humans are defined, e.g., 100,000 and 250,000 ppmv.

• The broad categories of failure scenarios and potential consequences are known, e.g., corrosion, external impact, inhalation hazard, dense-gas filling topographic lows.

• The pipeline and well design features applicable to the failure scenarios are known, e.g., diameter, materials, pressure, buried or above-ground, location.
New framework convolves population location, likelihood, and consequences

1) Pipeline runs from City A to GCS site B over distance s.

2) There is population along the pipeline \( \text{Pop}(x,y) \)

3) There are multiple failure scenario classes that threaten safety along the pipe (e.g., impact to pipe by vehicle, corrosion, seismic, etc.) or at the wellhead.

4) For each failure scenario \( i \), there is a range of release characteristics, e.g., total amount released, release rate, style of release, etc. which control consequences.

5) For each potential failure resulting in release \( R_i(s) \) along the pipe or at the wellhead, we can estimate the concentration as a function of space and time \( C_{R_i}(x,y) \).

6) Setting a concentration of concern \( CC \), e.g., 100,000 ppmv for \( CO_2 \), we can find the locations around the release point where people could potentially be impacted if they are present, i.e., where \( C_{R_i}(x,y) > CC(x,y) \). These locations fall within a region called \( \text{DSR}(x,y) \).

7) The convolution of the \( \text{DSR}(x,y) \) and \( \text{Pop}(x,y) \) is the number of people impacted which represents the consequences (\( C_{sq_{R_i}}(x,y) \)).

8) The likelihood \( (L_i) \) of \( C_{sq_{R_i}} \) is estimated from fault-tree analysis, data, or time-to-event statistics applied to the failure scenario \( i \).

9) The risk is the product of the likelihood and consequences, i.e., \( L_i \times C_{sq_{R_i}}(x,y) \).
\( R_i \) = release associated with failure scenario \( i \)
\( C_{Ri} \) = Concentration distribution arising from release \( i \)
\( CC \) = conc. of concern (e.g., 100,000 ppmv \( CO_2 \))
\( \text{Pop} \) = population along the pipe
\( \text{DSR} \) = downstream safety radius
\( \text{Csq} \) = consequences (\( \text{Pop} \) convolved with \( \text{DSR} \))
\( L_i \) = likelihood of scenario with release \( R_i \)
**CO₂ pipeline and well failure risk assessment framework workflow**

1. Characterize the pipeline or well

2. Characterize populations at risk and other risk endpoints

3. Identify the applicable failure scenarios from within the known broad categories

4. Analyze and estimate the likelihood of each failure scenario within the broad categories

5. Characterize quantitatively the release(s) associated with each failure scenario

6. Characterize quantitatively the temporal and spatial CO₂ concentrations resulting from each failure scenario

7. Calculate the risks to the vulnerable populations and to other risk endpoints

8. Estimate and analyze uncertainties in the calculated risk numbers

9. Perform sensitivity analyses to determine origins and dependencies of likelihood and consequence

10. Identify and analyze risk mitigation strategies
Conclusions

• We developed a risk assessment framework for CO₂ pipelines and wells.
• The framework is based on the FEP-scenario approach and uses fault-tree methods where appropriate.
• The framework recognizes the spatial variability of vulnerable populations and resources along a pipe or in the vicinity of a wellhead.
• Estimates of safety distances for releases associated with various failure scenarios are convolved with population footprints to estimate consequences.
• The likelihood per year of the failure scenario and its release type are multiplied by the consequences to calculate risk per year.
• Uncertainty and variability in the consequences need to be considered.
• Sensitivity of results to various properties of the pipeline or well system can be used to focus risk mitigation efforts.
Acknowledgments

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Fault Tree Example

**Exact Solution:**
\[ P_{\text{TOP}} = P_S + (P_P P_K) - (P_P P_K P_S) + (P_B P_P) - (P_B P_P P_S) - (P_B P_K P_P) + (P_B P_K P_P P_S) \]

**Rare Event Approximation:**
\[ P_{\text{TOP}} = P_S + (P_P P_K) + (P_P P_B) \]
The severity (e.g., release amount, or release character) is considered uncertain and can be described by a probability density function.

The framework propagates this uncertainty through to the risk calculation.

\[ R_i = \text{release associated with failure scenario } i \]
\[ C_{Ri} = \text{Concentration distribution arising from release } i \]
\[ CC = \text{conc. of concern (e.g., 100,000 ppmv CO}_2\text{)} \]
\[ \text{Pop} = \text{population along the pipe} \]
\[ \text{DSR} = \text{downstream safety radius} \]
\[ C_{sq} = \text{consequences (Pop convolved with DSR)} \]
\[ L_i = \text{likelihood of scenario with release } R_i \]