DEVELOPING A COMPREHENSIVE RISK ASSESSMENT FRAMEWORK FOR GEOLOGICAL STORAGE OF CO2

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Presentation Outline

1. Benefit to the Program
2. Goals and Objectives
3. Technical Status Project
   (a) Toxicity CO_2
   (b) Risk implications of Lake Nyos incident
   (c) Pipeline transport risk
4. Accomplishments to Date
5. Summary

Benefit to the Program

The research project is developing a comprehensive understanding of the programmatic (business), and technical risks associated with CCS particularly the likelihood of leakage and its potential consequences. This contributes to the Carbon Storage Program's effort of ***ensuring 99 percent CO_2 storage permanence in the injection zone(s) (Goal).***

Project Overview:
Goals and Objectives

- Develop and quantify the nature of programmatic risks;
- Employing Bayesian inference to evaluate sequestration risks;
- Utilize the safety record of the CO_2 based Enhanced Oil Recovery industry (CO_2-EOR) and pilot sequestration projects to identify and evaluate potential risks;
- Utilize diverse, highly qualified expert panels drawn from industry and nongovernmental organizations (NGO) to evaluate changing perceptions of programmatic risks;
- Develop an understanding and quantify the role that a pressure field generated by injected CO_2 (and the dissolution of CO_2 from the plume into the brine phase) may play in risk, and
- Assess the possible consequences to water ecology and energy resources from potential leakage of CO_2 from deep brine reservoirs.

Technical Status

Project started by focusing on surface risks such as pipeline leakage

What is risk?

Risk = Likelihood x Consequences

Risks generally given as the probability of an individual death… such as 10^{-6}

CO_2 Pipelines May be the Highest Risk Aspect of CCS

"If CO2 is transported for significant distances in densely populated regions; **the number of people potentially exposed to risks from CO_2 transportation facilities may be greater than the number exposed to potential risks from CO_2 capture and storage facilities**" Doctor et al, (2005)

"**Transporting CO2 is the least risky aspect of CCS**, both technically and economically, and it is not a barrier to CCS implementation" Snyder et al (2008)

Why does CO_2 pose a risk?

Most fundamental risk is risk of leakage incidents resulting in death.

It is essential to understand the circumstances that could lead to “adverse outcomes”.

What do Sequestration Researchers say about CO_2 Toxicity?

- "**safe, non-toxic, inert gas**" (Benson and others, 2003; Benson, 2004; Benson, 2005)

- "**non-toxic**" Stenhouse and Savage (2004), Heinrich et al (2004), Hepple (2005), BEST (2007), and Bachu (2008)

What do Chemical Engineers Say about CO_2 Toxicity?

- "**low toxicity**" Hoefling et al (1991)
- "**non-toxic**" DeSimonea and Keiper, (2001)
- "**intrinsically safe, non-toxic**" Roosen et al (2007).

What do Federal Agencies say about CO_2 Toxicity?

- "non-toxic" CDC
- "non-toxic" EPA
- "non-toxic" OSHA

So why is CO_2 Dangerous?

- "**asphyxia**" Heinrich et al (2004) Hepple (2005), Bachu (2008)
- "**CO_2 is a simple asphyxiant**" BEST (2007)
- "**simple asphyxiant**" Luttrell and Jederberg (2008)
- "**displacement asphyxia**" Alberts (1994)

So what is Asphyxia?

- Oxford Dictionary defines **asphyxia** as "a condition arising when the body is deprived of oxygen"
- In the medical literature **asphyxia** is regarded as "lack of oxygen due to physical restraint"
- The term "**hypoxia**" refers to effects of oxygen deprivation.
- "**Hypercapnia**"… unusually high concentrations of CO_2 in the blood

What does the Toxicology Literature say about CO2 Toxicity?

- CO_2 has "a chemical action as a respiratory stimulant and narcotic" (Williams,1958)
- **CO_2 is "toxic"** (Ikeda et al, 1989; Ernst and Zibrak, 1998; Gill et al, 2002; Stuhmiller and Stuhmiller, 2002; Langford, 2005)

What do Small Animal Experiments Show?

- Ikeda et al (1989) dogs in a mix of 80% CO_2 and 20% O_2: respiration ceased in one minute, death by CO_2 poisoning.
- Watanabe and Morita (1998) dogs in 80% CO_2 and 20% O_2 (that is, a normal level of oxygen) death occurred within 19–23 minutes.

What do Human Subject Experimental Data Show?

- At 27.9% CO_2 and 15% O_2: three subjects unconscious after 20-52 seconds (Spealman, 1953)
- At 30% CO_2 and 70% O_2: unconsciousness in under 2 minutes (Lambertsen, 1971).
- At 30% CO_2 and 70% O_2: 37 young adults for 50-52 seconds, "the average patient" lost consciousness in 24-28 seconds (Friedlander and Hill, 1954)

Conclusion: CO_2 is Toxic and Kills by Chemical Action not Asphyxia

- Need to monitor CO_2 levels not O_2 levels
- Emergency response workers must have CO_2 proof respirators not just O_2 supplies
- Chemical interactions of gases must be considered

Does Asphyxia Play a Role in Death from CO_2?

- Assume displacement asphyxia, 20% CO2 in a closed space
- At 20% displacement of air by CO_2 levels of O_2 would be 16%, and just as symptoms of asphyxia were beginning death would likely have occurred from CO_2 toxicity
- the **average lethal level of oxygen depletion** for humans exposed for 30 minutes is **8.5%**.

Why do Brewery Workers Die from Asphyxia?

Atmosphere in fermentation tanks depleted in oxygen by fermentation reactions… so asphyxia probably played a role deaths in breweries.

Can we Model Nature of CO_2 Toxicity Impacts on Humans?

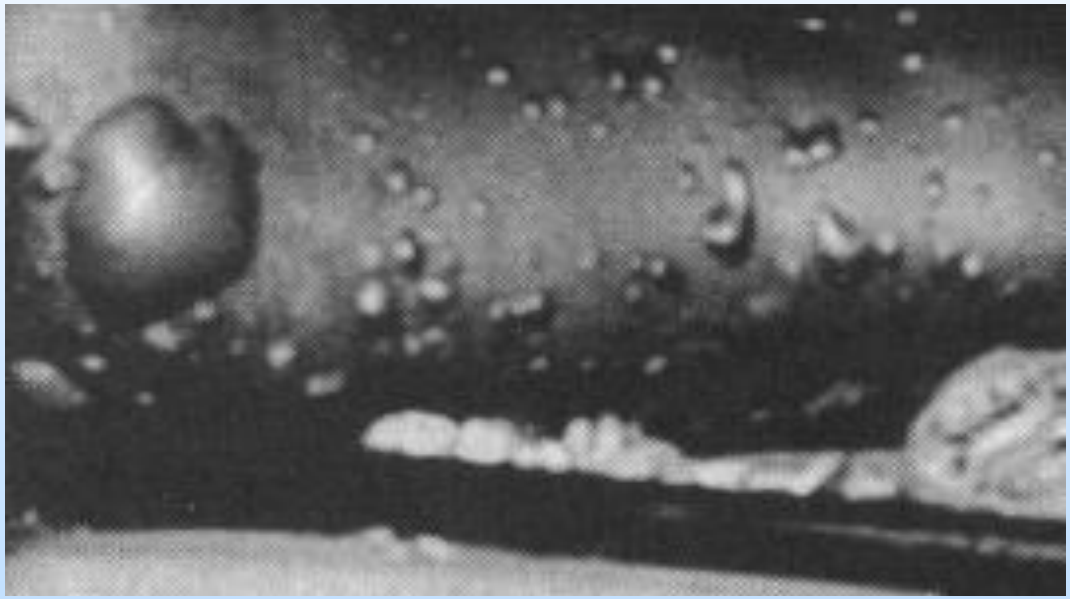
- CO_2 is the only common toxic gas without adequate models for human toxicity
- No large primate experimental data available for CO_2 to create viable models

Case Study: Lake Nyos Incident

- CO_2 release event at lake Nyos is often pointed to as an analogue for potential risks to human populations of leakage from CO_2 pipelines
- 0.25 to 2.0 million tons of CO_2 released in a short period of time from overturning of a stratified lake (several months of flow from a CO_2 pipeline)
- Evidence that CO_2 was not the only toxic component

So What Killed the Lake Nyos Victims?

Many victims had prominent skin bullae (blister like features) Baxter et al (1989).



Bullae are only found in CO poisoning cases and heroin overdoses

A Digression:

In an age when cars have catalytic convertors that oxidize CO to CO_2…why is that suicidal death from CO poisoning from car exhausts continues to occur?

On the order of 1% CO on a time scale of 10 minutes is a lethal level.

Measured Gas Levels in Vehicle Suicide Deaths

Case 1:

Initial exhaust CO level 0.034% within 15 minutes was 0.004% (same as the OSHA 8 hour safety level)

Case 2:

5 minutes CO level was 0.02%, CO_2 0.3%, O_2 20.3%,

60 minutes CO 0.02%, CO_2 1.3% , O_2 19.2%

Measured Gas Levels in Vehicle Suicide Deaths

Case 3:

Initial CO 0.12%, CO_2 0.1%, O2 20.7%

After 32 min. CO very low, CO_2 2.3%, O_2 17.5%

Recall that 1% CO is a lethal level on a time scale of 10 minutes and that the average lethal level of oxygen depletion for humans exposed for 30 minutes is O_2 = 8.5%.

Some Obvious Questions

(1) Why has no one suggested this before?

Several MD's specializing in CO poisoning wrote letters to the British Medical Journal suggesting CO was the cause of the Lake Nyos deaths however their arguments were shouted down by geologists.

Another Obvious Question

(2) Where could the CO have come from?

- It was a cold winter night and many killed were huddled around fires, some were sleeping in mud huts heated by wood fires. Wood fires have a flu concentration of about 0.5% CO.
- Layered anoxic lakes that overturn frequently have CO levels on the order of 0.00001% CO. CO contents have not been measured in the bottom layers of Lake Nyos or similar lakes similar to Nyos.

Conclusions on Cause of Death

Lake Nyos victims were likely killed by mixed gas toxicity, with CO playing a key role.

Implications for CO_2 Pipeline Risk

Results of experiments on small animals suggest the “mixed gas effect” occurs in association with most, if not all, toxic gases.

Normally nonlethal levels of minor gases (such as SO_2, H_2S and CO) will significantly increase the risk of handling and transport of CO_2

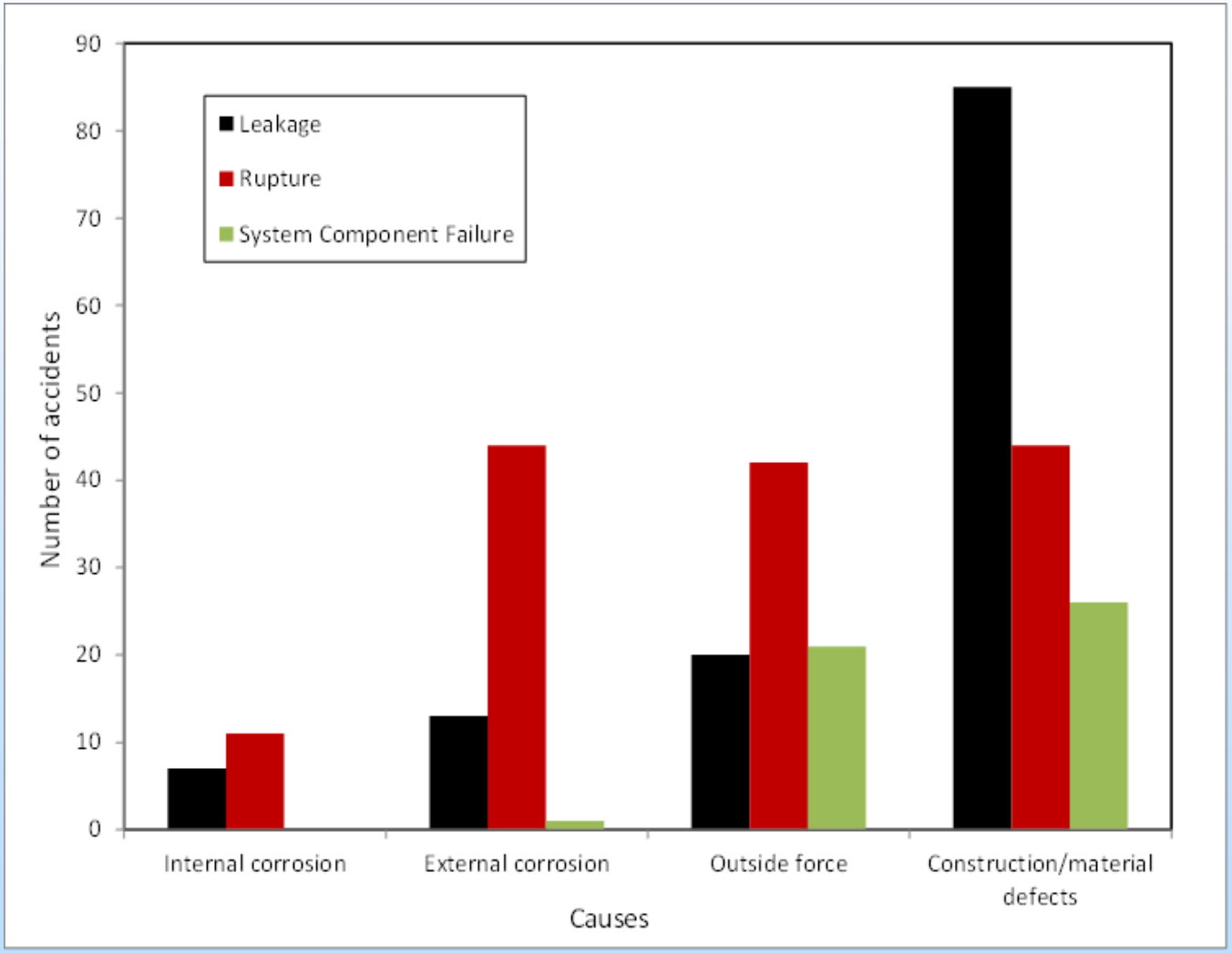
Previous risk assessments of CO_2 pipelines with mixed gases should be reevaluated.

Likelihood of CO_2 Pipeline Accidents?

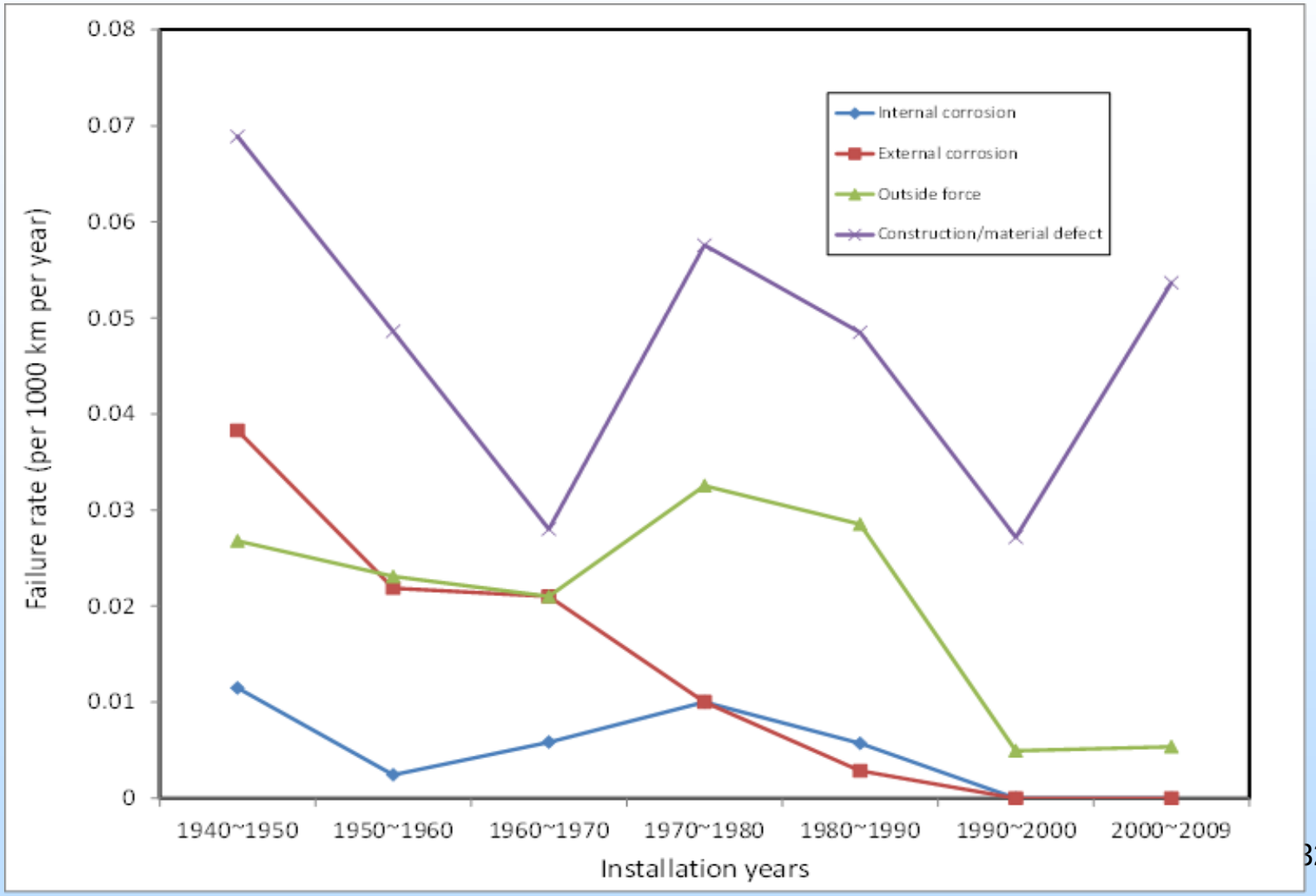
CO_2 pipelines have had very small number of accidents of any significance.

Part of our project has been to understand the factors that control natural gas pipeline accident rates and use them to estimate CO_2 pipeline risks.

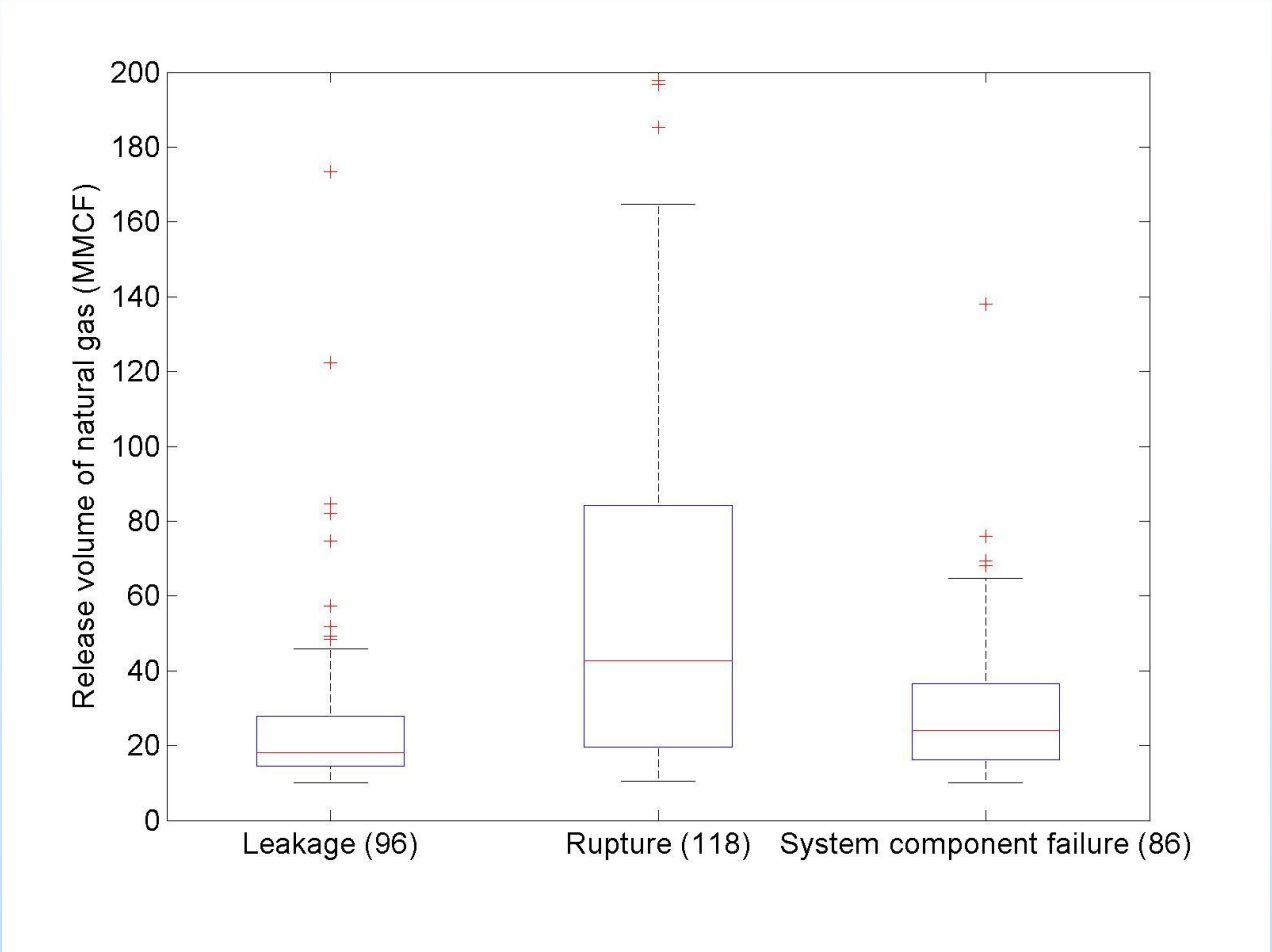
Causes of Pipeline Failure



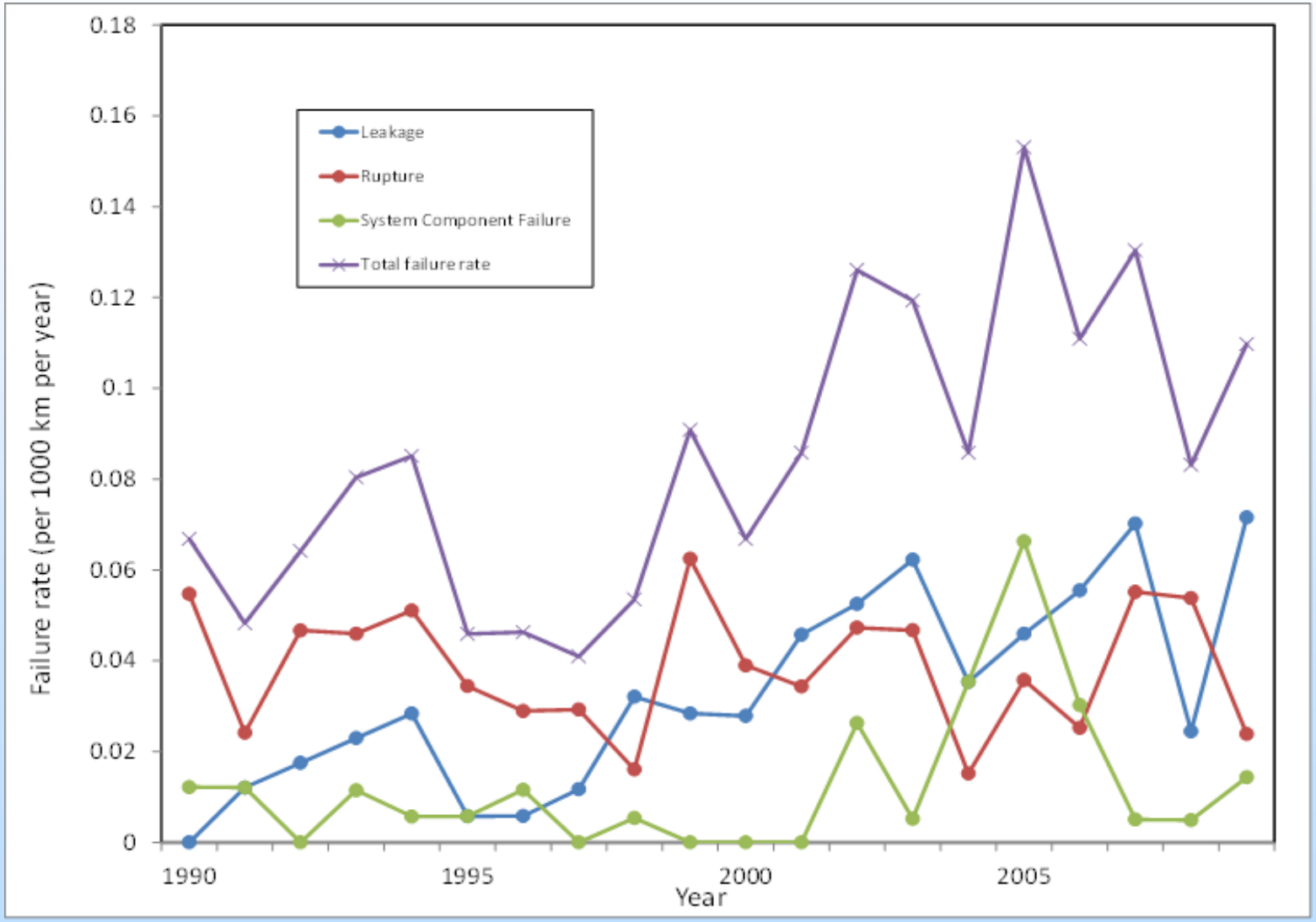
Failure Rate versus Pipeline Age



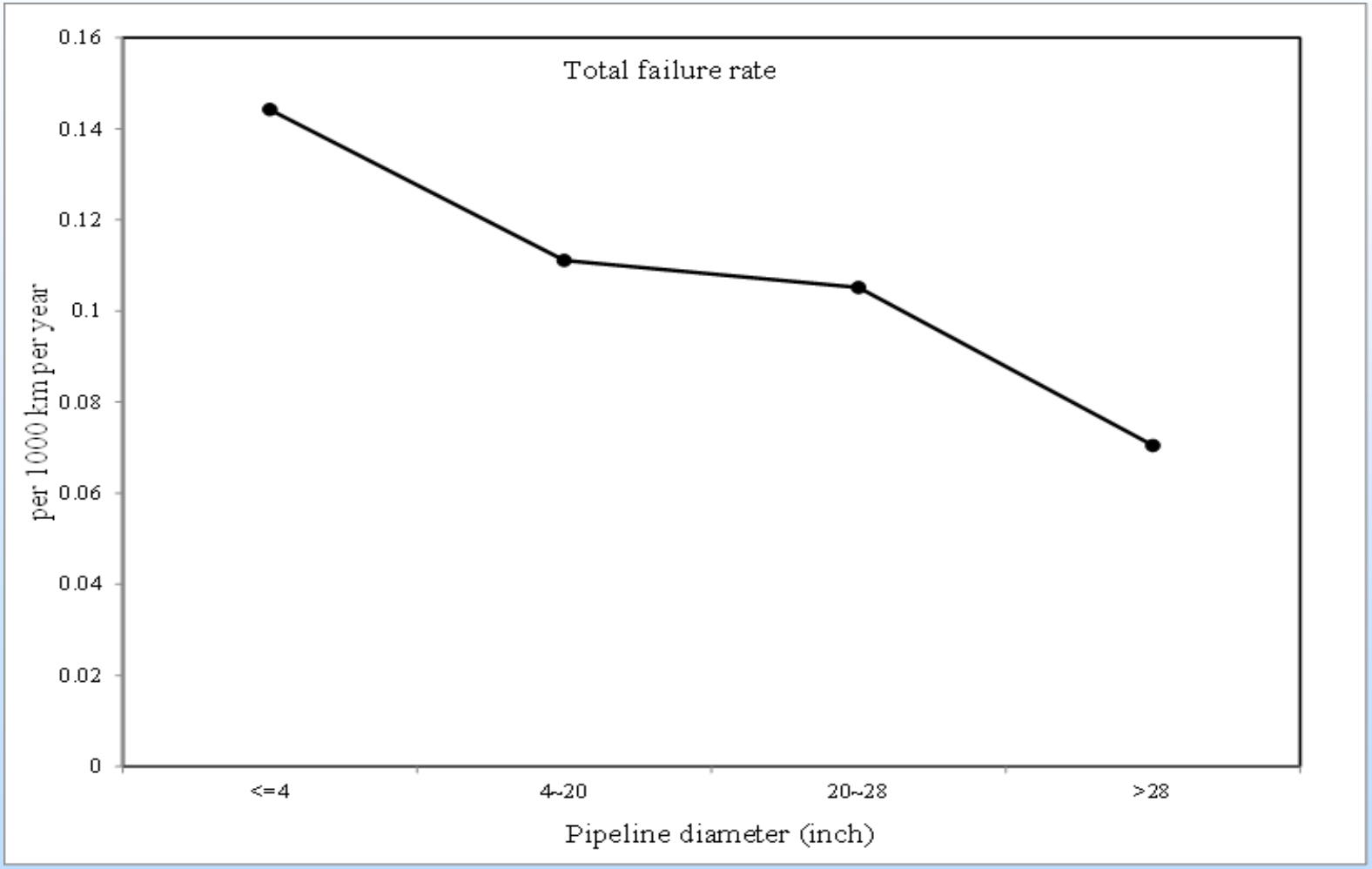
Volume of Gas Released



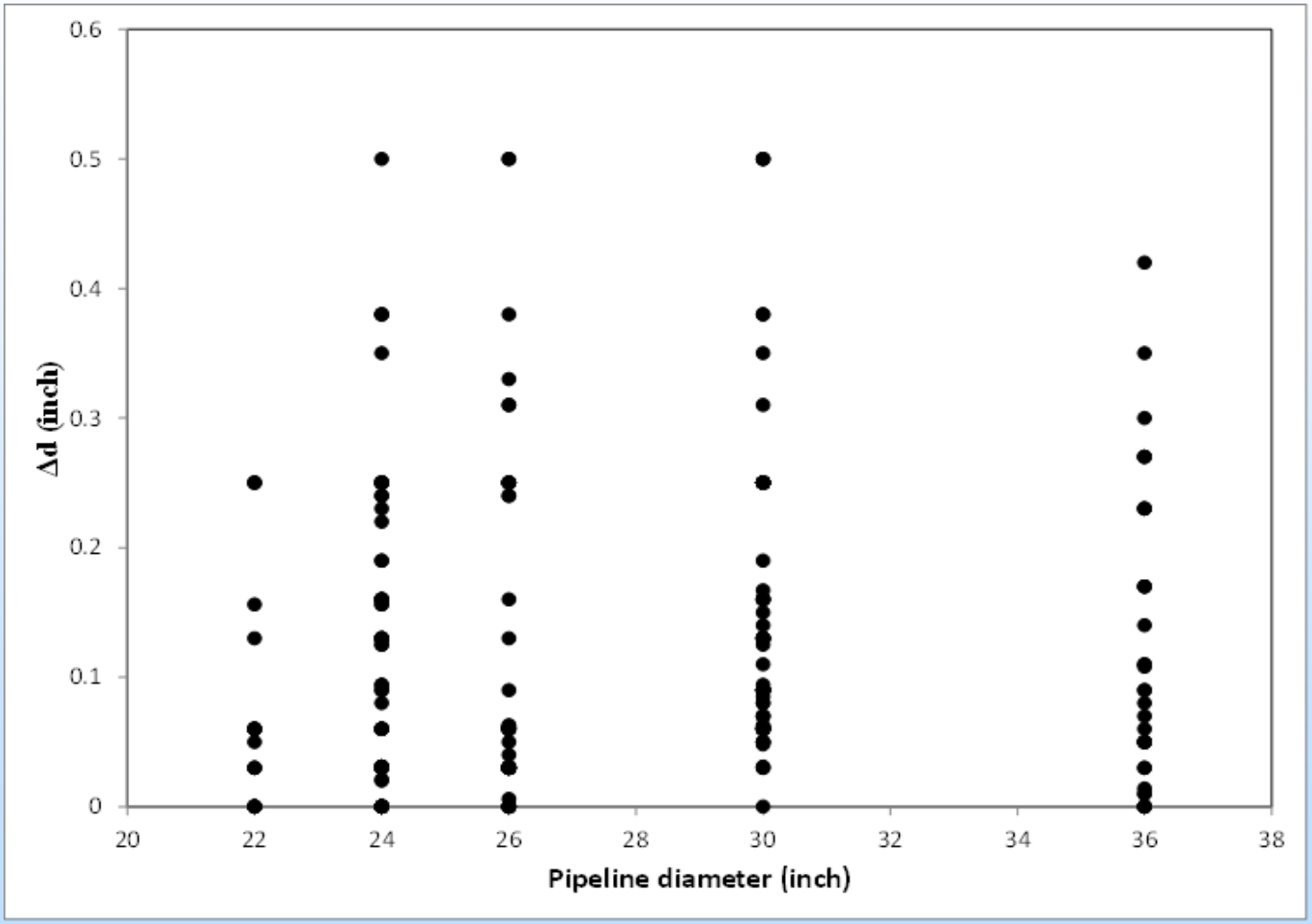
Pipeline Failure Rate 1990 to 2010



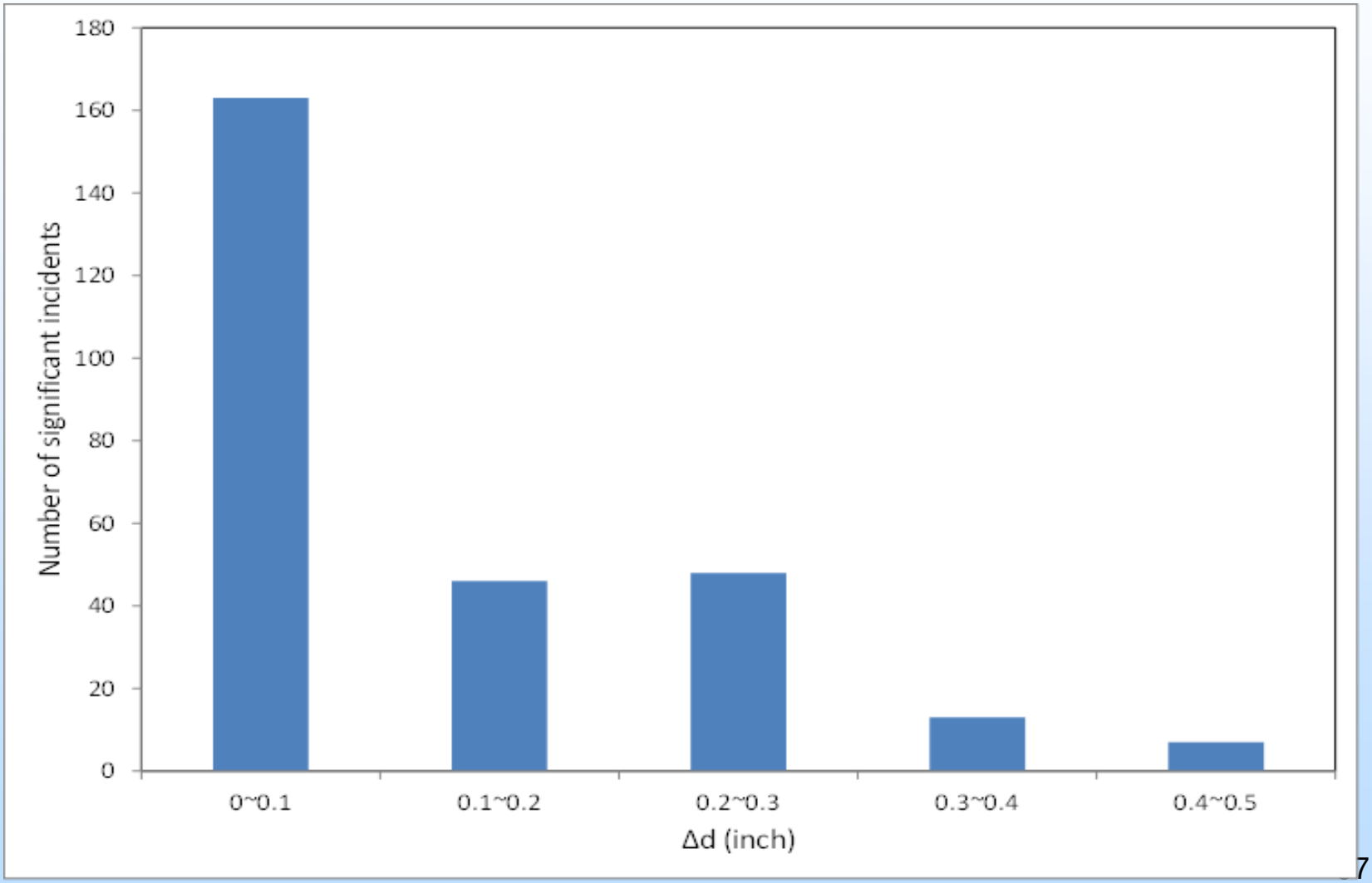
Failure Rate and Pipe Diameter



Failures as function of Pipe Thickness



Failures as function of Pipe Thickness



Conclusions on Likelihood of Pipeline Leakage Events

- Probabilities for leakage events previously used in CCS literature may significantly overestimate risks
- Probability of significant leakage less for larger diameter pipelines, less for thicker wall pipe
- External corrosion is the dominant time dependent risk factor

BUSINESS RISKS of CO_2 SEQUESTRATION

Project Financing Issues

Regulatory Environment

Legal (pore space ownership, liability)

Technology Risks

Operational risks (Including Project Delays)

Leakage Risks (contamination of groundwater, climate risk)

Induced Earthquakes and Earthquake Rupture

Contamination of Natural gas reservoirs

Injectivity Decline

Summary

Risk identification for CCS and CCUS projects must be based on understanding of CO2 and mixed gas toxicity.

Implications of the Lake Nyos incident for CCS risk are the dangers of mixed gas toxicity.

Progress and Future Plans

- Paper on the nature of business/programmatic risks (completed)
- Development of Bayesian inference to evaluate sequestration risks (underway, to be completed by Nov 2012))
- Analysis of the safety record of the CO_2 based Enhanced Oil Recovery industry (CO_2-EOR) to identify and evaluate potential risks. (a) CO2 injection well blowouts (completed); (b) CO2 pipeline leakage risk (completed); (c) CO2 injection rate; (d) CO2 well integrity issues (underway)

Progress and Future Plans

- Using expert panels drawn from industry and nongovernmental organizations (NGO) to evaluate changing perceptions of programmatic risks (underway, major activity for next project year)
- Investigating the role that a pressure field generated by injected CO_2 (and the dissolution of CO_2 from the plume into the brine phase) may play in risk. Role of bubble flow in fractures versus dissolution underway.
- Assessing the possible consequences to water. ecology and energy resources from potential leakage of CO_2 from deep brine reservoirs (one paper in final draft, further research focusing on consequences underway)

THANKS

Appendix

Organization Chart

Ian Duncan (PI)

Collaborators:

Professor Eric Bickel (Risk Modeling Lead)

Professor Greg Rodin (Geomechanical Modeling Lead)

Post Doctoral Fellows:

Dr Jong-Won Choi (Geomechanics)

Dr Xiaodong Zheng (Hydrology, Geochemistry)

Dr Hui Wang (Bayesian Risk Modeling)

Accomplishments to Date

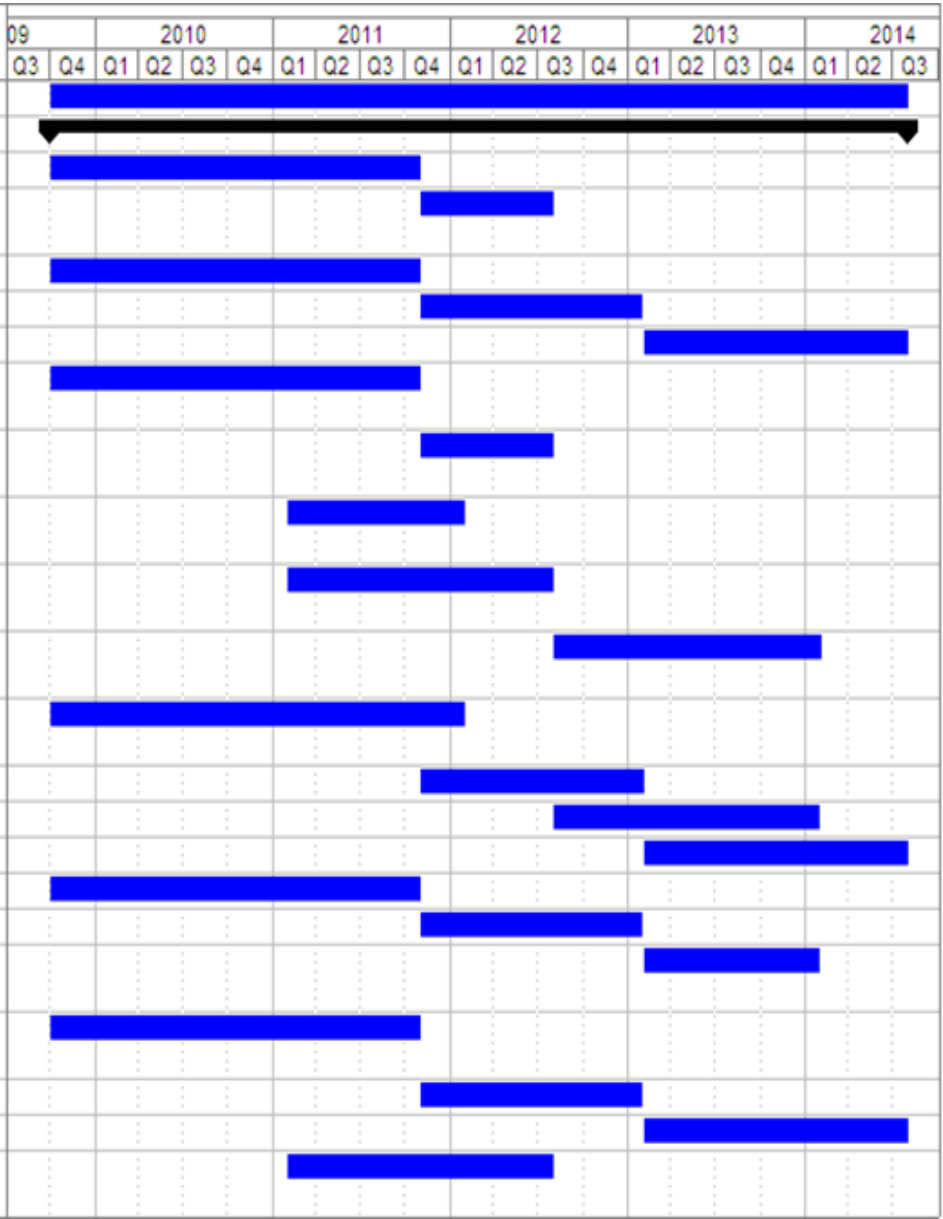
- Developed a comprehensive analysis of the business risks associated with CO_2 sequestration projects
- Developed a comprehensive risk identification for CCS and CCUS projects
- Developed new understanding of the implications of the toxicity of CO_2
- Completed new analysis of the risk implications of the Lake Nyos incident.
- Developed new analysis of CO_2 leakage from wells based on bubble flow in fractures

Accomplishments to Date

- Completed analysis of the nature of accidents associated with natural gas pipelines based on new rich data sets newly available from DOT.
- Completed analysis of CO_2 pipeline incidents including gathering of previously non-public data from industry.
- Completed analysis of factors controlling blowouts of CO_2 injections wells based in part on data supplied by industry.
- Analysis completed of CO_2 injection data from continuous CO_2 injection versus WAG

Gantt Chart

ID	Task Name
1	1 Project Management, Planning, and Reporting
2	**2 Development and Application of Conceptual Framework for Risk Assessments**
3	2.1 Compilation and critical review of existing site-specific risk assessments
4	2.2 Compilation of information on operational risks from CO2-EOR industry and identification of linkages between programmatic and technical risks
5	2.3 Development of prototype risk analysis methodologies
6	2.4 Implementation and testing of proposed risk analysis methodologies
7	2.5 Refinement of risk analysis methodologies
8	2.6 Analysis of programmatic and operational risks for CO2 sequestration projects based on data from CO2-EOR projects
9	2.7 Projection of risks for CO2 sequestration projects (based on data from commercial natural gas storage)
10	2.8 Identification of realistic, fact based, scenarios for leakage from geologic reservoir containment
11	2.9 Evaluation of the risk of leakage from geologic reservoir's containment based on an innovative new analysis using Bayesian inference based on flow simulations
12	2.10 Modeling of the risk of leakage from geologic reservoirs based on multiple flow simulations
13	2.11 Identification of risk associated with injection pressures and development of approaches to model flow under the influence of a pressure front
14	2.12 Modeling risks associated with pressure driven brine flows
15	2.13 Modeling risks associated with seal leakage
16	2.14 Estimating risk associated with seal leakage through fault, and fracture zones
17	2.15 Identification of risk associated with injection pressure inducing earthquakes
18	2.16 Development of site-specific risk protocols for pressure induced earthquakes
19	2.17 Modeling and analysis of risks associated with injection pressure induced earthquakes.
20	2.18 Evaluate risk related to CO2 dissolution into brine and entering regional flow systems
21	2.19 Modeling the changes in leakage risk related to CO2 dissolution into brine
22	2.20 Modeling the leakage risk related to CO2 dissolution in regional flow systems
23	2.21 Compilation of Data Relevant to Evaluating Consequences of Possible Leakage from Deep Brine Reservoirs



Bibliography

We have six peer reviewed type publications in preparation, two submitted (including 2 single authored papers and 6 multi-authored papers).