Project Title: DEVELOPING A COMPREHENSIVE RISK ASSESMENT FRAMEWORK FOR GEOLOGICAL STORAGE OF CO2

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U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS
August 20-22, 2013

Presentation Outline

1. Benefit to the Program
2. Goals and Objectives
3. Technical Status Project
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 GOALS and OBJECTIVES

- **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**
- **Identify and quantify the nature of programmatic 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**
- **Assess the possible consequences to water ecology and energy resources from potential leakage of CO_2 from deep brine reservoirs.**

Comprehensive Risk Study of CCUS:

Quantifying above ground Risks Associated with CO_2

Risk = Likelihood x Consequences

BUSINESS RISKS of CO2 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

ASSESSING OPERATIONAL RISKS CO2 SEQUESTRATION

- Pipeline Accidents
- Well Blowouts
- Induced Earthquakes
- Seal Leakage
- Earthquake Rupture of Reservoir
- Groundwater Contamination

What are Stakeholders Saying about Risk of CO2 Sequestration?

“Because of the **unknown risk** — this could perhaps be **catastrophic** — you’d have to have some sort of overlying federal layer of protection... otherwise [carbon capture and storage (CCS) operators] wouldn’t do it ... they wouldn’t go forward and capture carbon and put it deep underground unless they had some assurance that liability issues would not come back to bite them.”

Tim Peckinpaugh, lawyer

"[Failure to deal with risk and liability] could delay the construction of billions of dollars of carbon capture and storage infrastructure."

Kip Codington, lawyer Alston & Bird

“Liability [and risk?] concerns are overstated”

David Hawkins The Natural Resources Defense Council

WHAT ARE STAKEHOLDERS READING ABOUT THE RISK OF CO2 SEQUESTRATION?

Work on Risk Assessment for CCS

Stevens and van der Zwaap (2005)

"the most frightening scenario [related to risks associated with geologic CO2 sequestration] would be a large, sudden, catastrophic leak".

Saripalli et al (2004):

“acute hazards” related to geologic CO2 sequestration are

“wellhead failure [blowouts], seismic hazard during injection, accumulation and explosion in lakes, and massive efflux in soils”.

Wilson et al (2003)

"Catastrophic events [associated with CCS] maybe caused by slow leaks if the CO2 is temporarily confined in the near-surface environment and then suddenly released".

"while the specific mechanism active at Lake Nyos can occur only in tropical lakes (because they do not turn over annually), mechanisms may exist that could confine slowly leaking CO2 in the subsurface, enabling sudden releases".

"it is conceivable … that CO2 leaking from deep underground could infiltrate karst caverns at shallow depths and that such CO2 could then be rapidly vented …".

Health Risks of CO_2

Consensus amongst CCS Researchers

- CO_2 “generally regarded as a safe, non-toxic, inert gas” (Benson, 2005)

- CO_2 is a nontoxic substance (Stenhouse and Savage, 2004; Heinrich et al. 2004; BEST, 2007; and Bachu, 2008)

If it is nontoxic how does CO2 Kill People?

- "CO_2 acts as an **asphyxiant** at concentrations in the 7–10% range [of CO_2] and can be fatal" (Bachu, 2008; Hepple, 2005)
- 10% by volume of CO_2 will cause **asphyxiation** (Heinrich et al.,2004; BEST, 2007; OSHA, 1996; Luttrell and Jederberg, 2008).
- "CO2 levels, above 20–30%, will cause death by **suffocation** to humans" (Damen et al. 2006)

ESTIMATED LETHAL LEVEL OF CO_2

"Death occurs within minutes at 30% CO_2" Benson et al. (2002)

CO_2 levels of 25 to 30% "may cause convulsions". NIOSH (1981)

"Concentrations of 10% [CO_2] can produce unconsciousness or death" OSHA (1996)

LETHAL LEVEL OF CO_2 USED IN RISK ANALYSES

“10%, minutes” Tetra Tech (2007)

“11.5%, 5 minutes” Harper (2012)

“25% 1 minute” Mazzoldi et al. (2012)

What was the Lake Nyos Disaster?

August 21st, 1986 in a large village located by Lake Nyos. between 1.2 and 1.6 million metric tons of CO2 were released, **killing 1,746 people**.

It has been suggested that the **“Lake Nyos incident offers a vivid image of the catastrophic effects of CO2”**.

Lake Nyos Photo

Lake Nyos, usually with blue waters shown here shortly after the carbon dioxide outgassing event. Photo by Jack Lockwood, 1986 (U.S. Geological Survey).

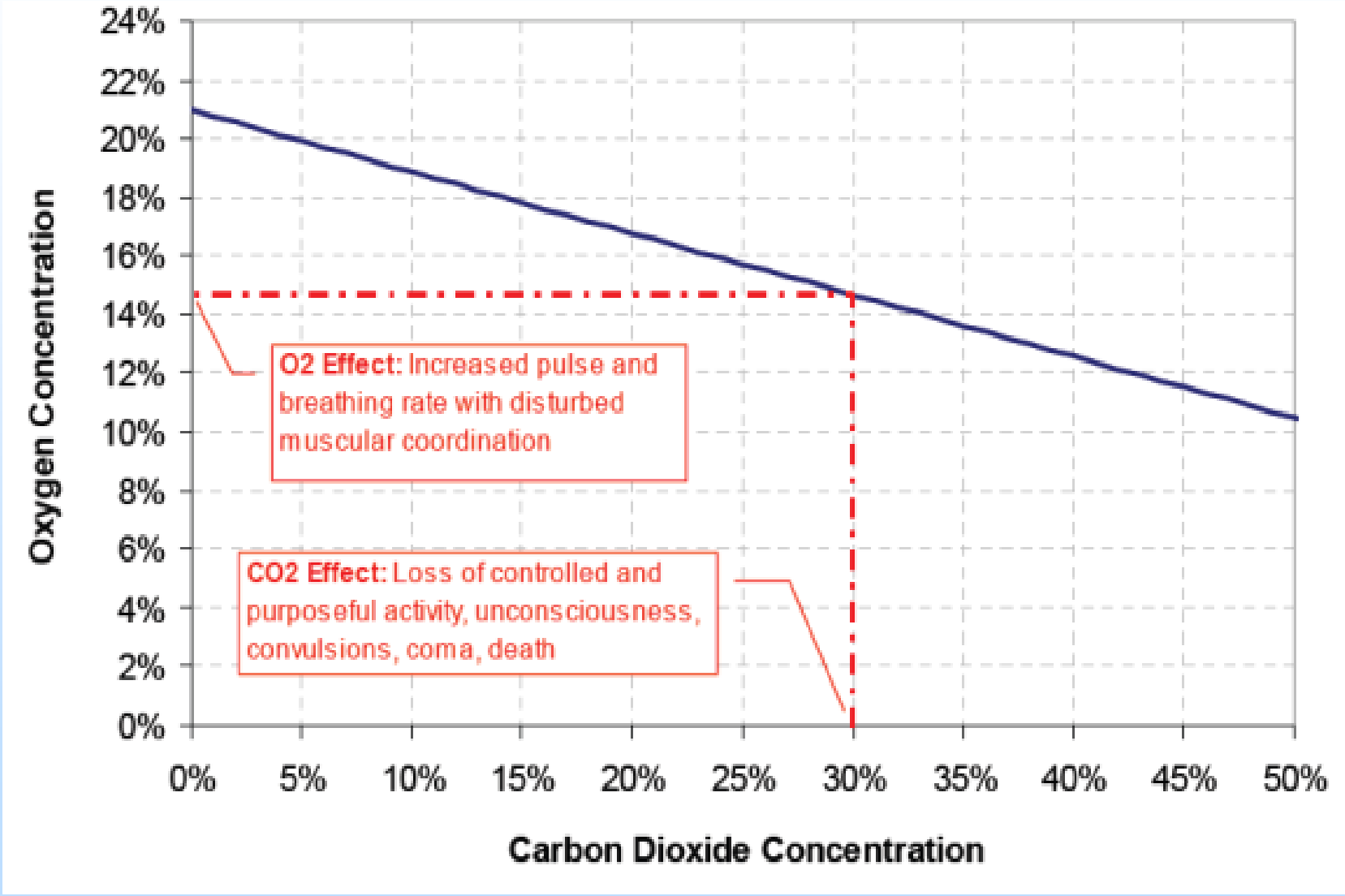
“The frequently-cited example of Lake Nyos in Cameroon illustrates the potential dangers of a large scale, undetected CO2 pipeline failure”

Monast J, 2008, Carbon Capture to Storage: Designing an Effective Regulatory Structure for CO2 Pipelines http://www.nicholas.duke.edu/ccpp/ccpp_pdfs/co2_pipeline.pdf

Research Issues

- CCS literature presents a very inconsistent array of estimates for lethal level of CO_2
- Strong evidence that CO2 does not kill by asphyxia
- Experimental evidence that CO2 kills even at normal oxygen levels

Does CO2 Cause Death by Asphyxia?



Death by CO_2 Inhalation: DOGS

Dogs in 80% CO_2 with 20% O_2 died in 2 minutes (Ikeda et al.,1989)

Concluded that cause of death was not asphyxia but rather **CO_2 toxicity**

Death by CO2 Inhalation: RATS

(1) mice exposed to **40% CO_2** and 21% O_2 none of ten rats exposed for 24 hours died (Prior et al., 1969)

(2) **50% CO_2**, 21% O_2, for 4 hours, two of ten rats died (Prior et al., 1969)

(3) **60 to 67% CO_2** and 6% O_2, death occurred within 30 minutes (Watanabe and Morita, 1998)

Death by CO2 Inhalation: RATS

(1) mice exposed to 40% CO_2 and **21% O_2** none of ten rats exposed for 24 hours died (Prior et al., 1969)

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(3) 60 to 67% CO_2 and **6% O_2**, death occurred within 30 minutes (Watanabe and Morita, 1998)

Death by CO2 Inhalation: MONKEYS

(1) Rhesus monkeys at a rate of increase of 30% CO_2 per hour, (21% O_2) died at **60% CO_2** (Stinson and Mattsson, 1970)

(2) Three chimpanzees survived in air with up to **51% CO_2** (Stinson, and Mattsson,1971)

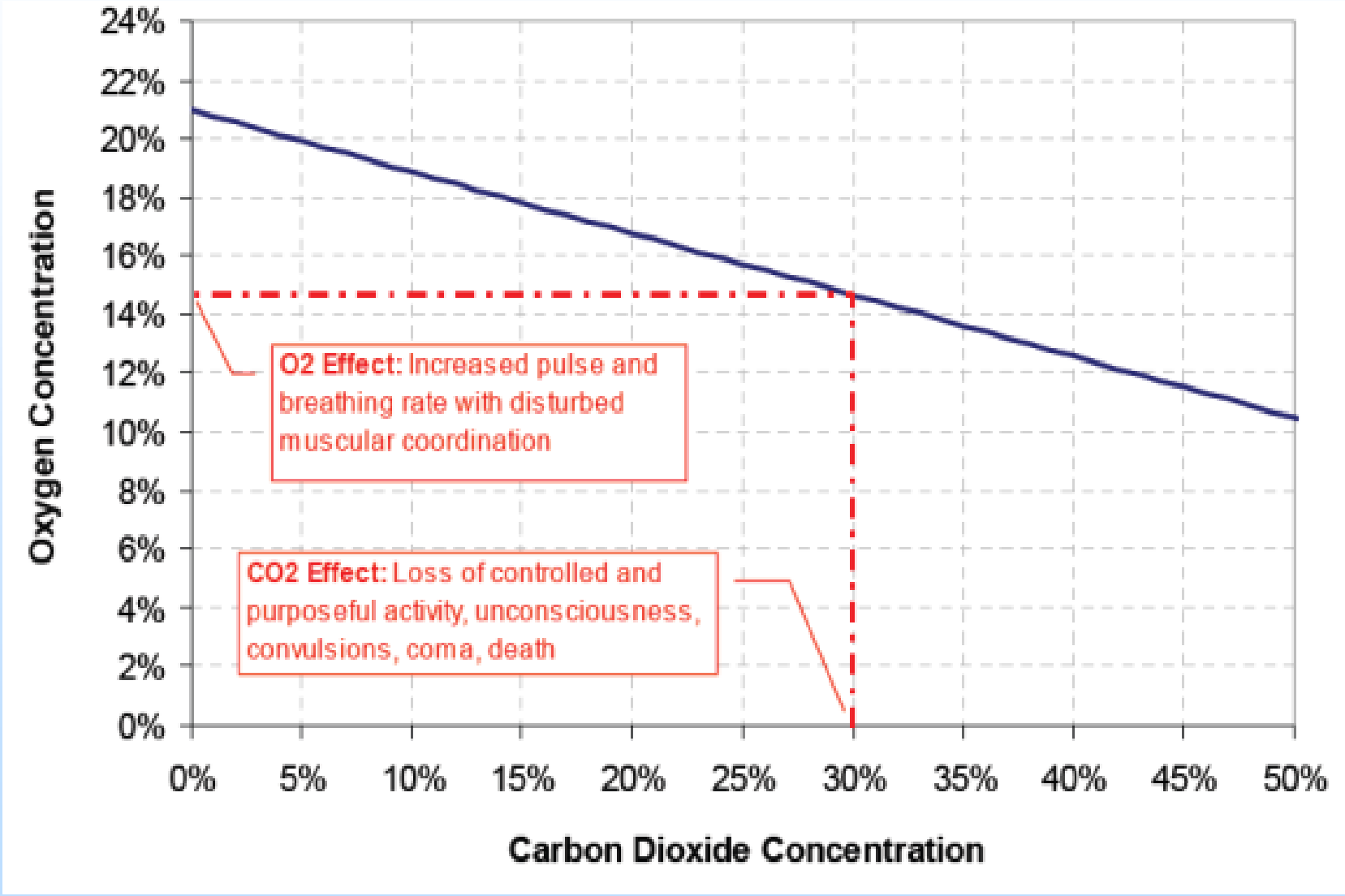
Death by CO2 Inhalation

(1) 35 year old worker died in a closed fermentation tank with **49% CO_2** and 6% O_2 (NIOSH, 1994)

(2) CO_2 fire suppression system in 1998 at Idaho National Lab, **50% CO_2**, 3 for ten minutes, and 3 for 20 minutes. One victim died, and 5 survived

(3) 59-year-old man dead shortly after entering walk-in freezer containing dry ice with13% O_2 and **40% CO_2**.

Does CO2 Cause Death by Asphyxia?



What levels of CO2 are Lethal?

50 to 60% at normal oxygen concentrations

45 to 55% at oxygen concentrations caused by gas displacement.

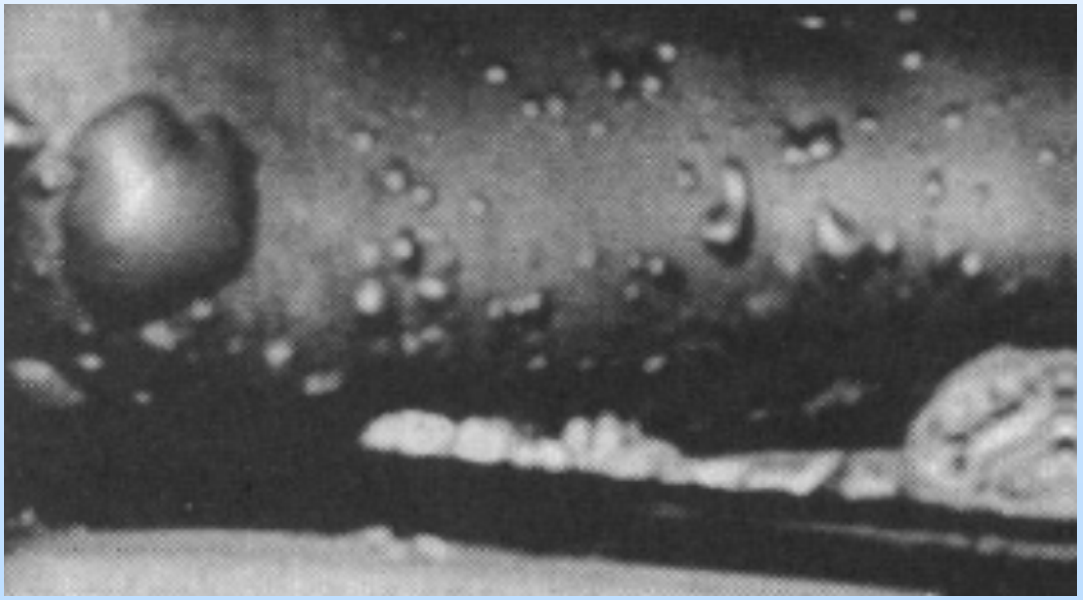
So What Killed the Lake Nyos Victims?

CO_2 levels at Lake Nyos during the incident have been estimated to be 10 to 15 %

These are not lethal levels.....

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



Is Lake Nyos a useful analogue for CCS Risks?

The Volume of CO2 is not analogous to Sequestration

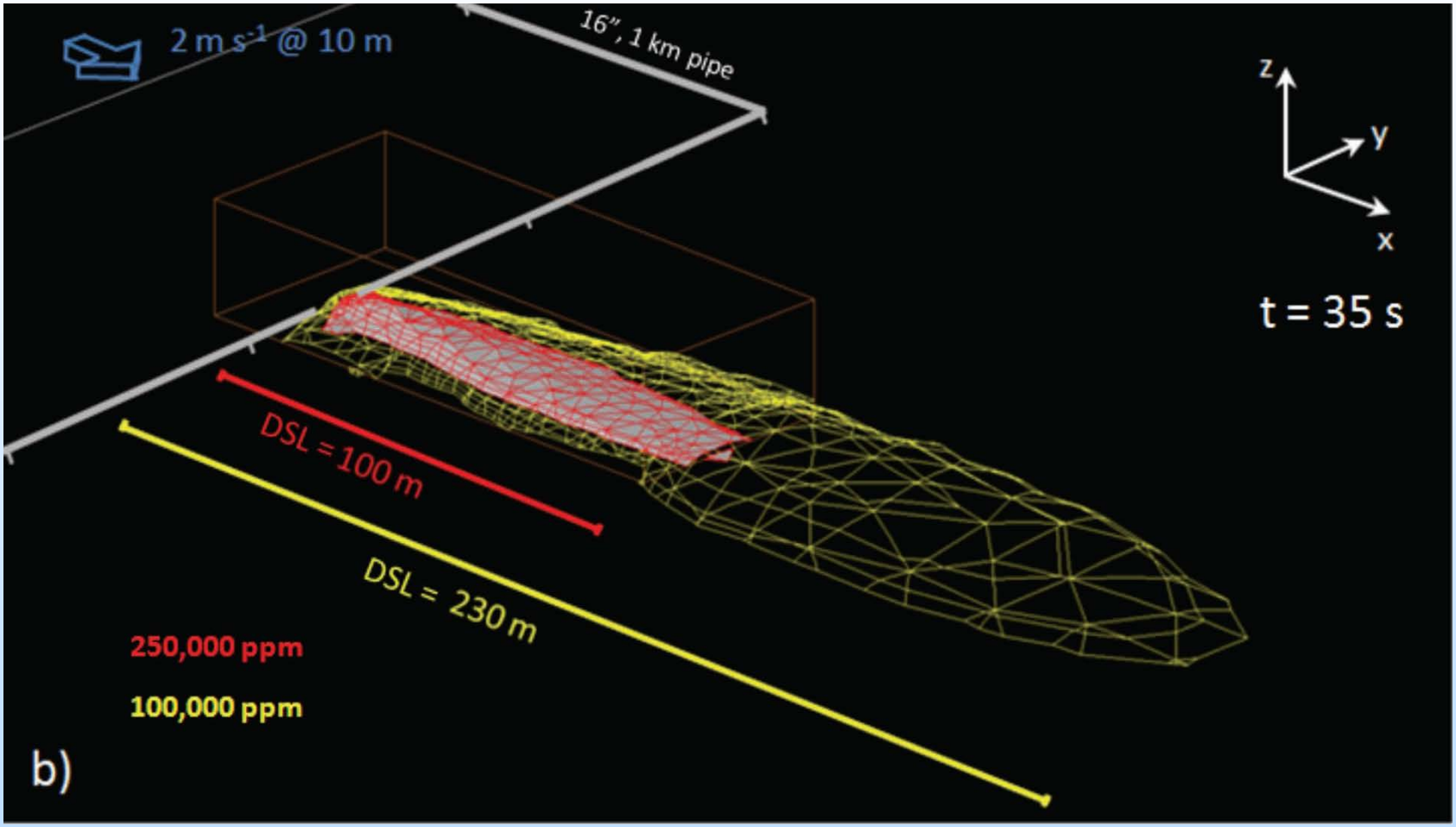
An exceptionally large quantity of CO2 that was abruptly released in the incident, between 1.0 and 1.6 million metric tons of CO2.

This corresponds with approximately four months emissions from a 275 MW FutureGen type IGCC.

This volume of CO2 is also equivalent to weeks or months of gas that would be transported in the largest pipelines contemplated for a future sequestration project.

How does this Data Impact Risk Modeling?

Mazzoldi et al. (2012) CFD Modeling Results



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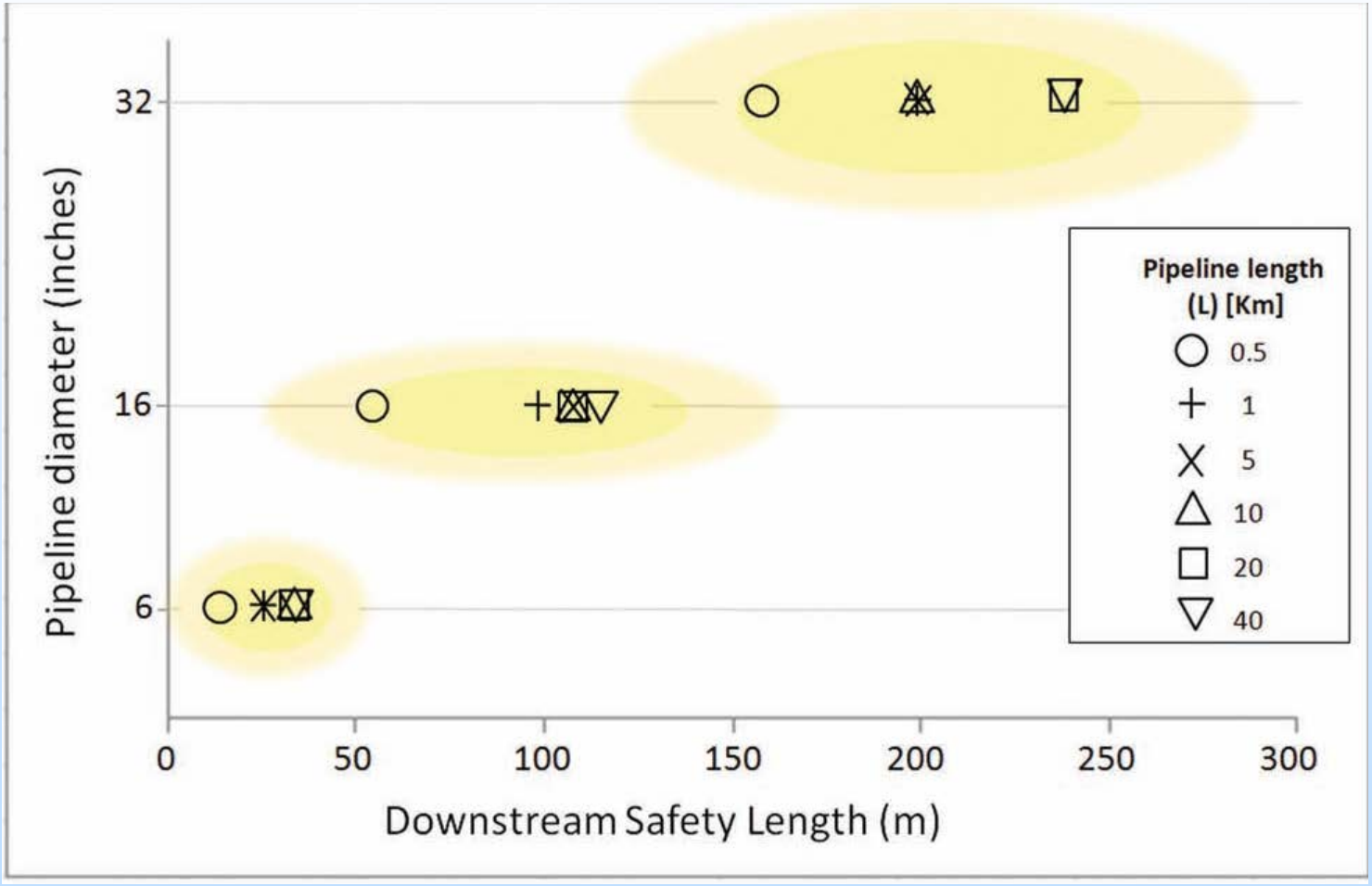


A Lake Nyos type Event is Inconceivable in a Sequestration Context

Deep, stratified lakes similar to Lake Nyos both exceptionally rare and readily identifiable.

Most lakes overturn on an annual basis.

Conclusions on Health Impact of CO_2

- CO_2 is lethal at much higher levels (40 to 60%) than previously thought by the CCUS community (10 to 30%)

- The deadly agent at Lake Nyos was CO not CO_2

- Risk modeling of CO2 activities have overestimated health risks

Why Study Risks Associated with CO_2 Pipelines?

IPCC (2005):

"If CO2 is transported for significant distances in densely populated regions; the number of people potentially exposed to risks from CO2 transportation facilities may be greater than the number exposed to potential risks from CO2 capture and storage facilities"

"Public concerns about CO2 transportation may form a significant barrier to large-scale use of CCS".

CONCLUSIONS: CO_2 Pipeline Risk

- **Likelihood of CO2 pipeline failure significant enough to cause deaths at least 3 orders of magnitude less than assumed in previous risk studies.**

- **Individual risk of CO_2 pipelines is likely in the range of 10^{-6} to 10^{-7} or lower**

- **Fatality risk of a well designed, appropriately mitigated CO2 pipeline in an urban area is even lower**

Summing Up

- The most risky aspects of CCUS and CO2 EOR have fatality risk on the order of 10^{-7} to 10^{-8}.... Less than the risk of dying from a lightening strike....

- Exaggerated risks can increase insurance rates and increase the cost of capital...

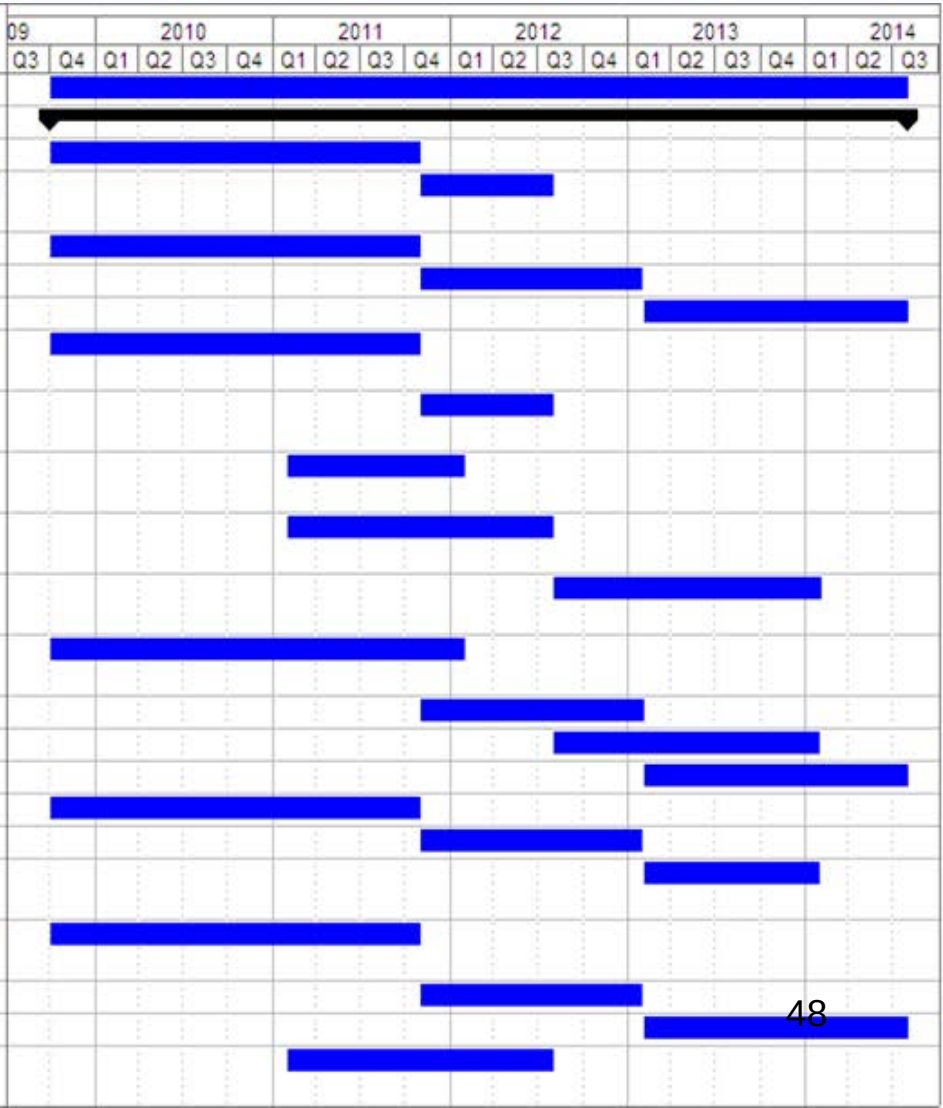
Appendix

Organization Chart

Project Director Ian Duncan Phone: 512-471-5117 Cell: 512-923-8016 ian.duncan@beg.utexas.edu		
Task 1 Management	**Task 2** Development and application of Conceptual Framework for Risk Assessments for CO2 Sequestration Projects in Deep Brine Reservoirs	**Task 3** Development of protocols for risk assessment for geologic sequestration in brines
Task Leader: Ian Duncan	**Task Leader:** Eric Bickel 512 232 8316 ebickel@mail.utexas.edu	**Task Leader:** Ian Duncan

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



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