CO_2-Water-Rock Interactions and the Integrity of Hydrodynamic Seals

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Bill Carey

Los Alamos National Laboratory

Los Alamos, NM

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage

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Benefit to the Program

- Program Goal: Ensure retention of 99% of injected CO_2
- Focus: Wellbore integrity
- Approach: Use field, experimental and computational methods
  - Determine long-term compatibility of wellbore materials with CO_2
  - Determine leakage mechanisms
  - Predict well performance
- Benefit: The research will provide a basis for evaluating the long-term performance of wells, guide remediation strategies, facilitate use of reservoirs with numerous existing wells (i.e., EOR), and reduce risk in CO_2 storage projects

Project Overview: Goals and Objectives

- Project Goals
  - Conduct field studies to determine decade-scale behavior of wellbore systems
  - Conduct experimental studies to determine chemical and mechanical integrity of cement-steel-rock composites representing wellbore systems
  - Conduct computational studies to simulate chemical, mechanical, and hydrologic flow processes in wells
  - Use collaborations to leverage research efforts
- Success Criteria
  - Complete 2-3 field studies of CO_2-exposed and CO_2-free wells
  - Complete experiments studying flow of CO_2 and brine at cement-steel, cement-casing and cement-cement interfaces
  - Complete a numerical model capable of representing two-phase flow along wellbore interfaces and accounting for chemical and mechanical effects
  - Demonstrate consistency among field, experiment and numerical approaches to assessing wellbore integrity

What Does Wellbore Failure Look Like? What are the Impacts?

Crystal Geyser: CO_2 from abandoned well
http://www.4x4now.com/cg.htm

Deep Horizon Blowout
Natural gas and oil
http://whistleblowersblog.org
Credit: US. Coast Guard

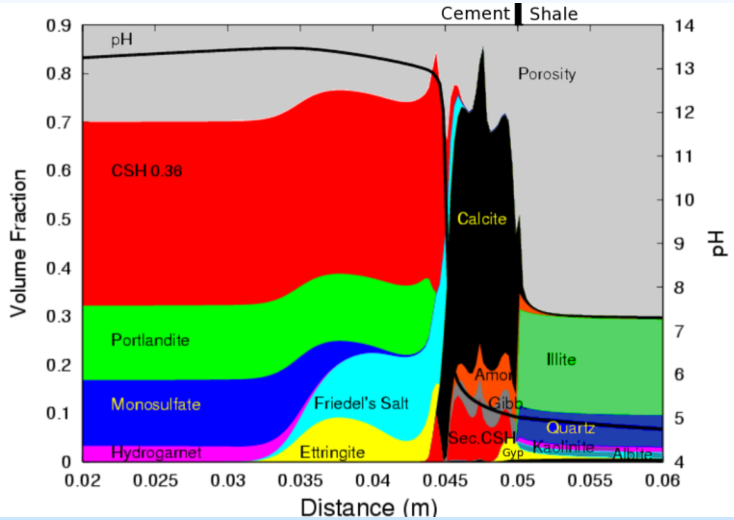
Slow casing leak
Natural gas
Watson and Bachu 2007

Research Methods

Field Studies

Experimental Studies

Computational Studies



Field Studies

- **SACROC, West Texas: CO_2-EOR, 55-year old well, 30 years exposure: First samples ever recovered from CO_2-exposed well (Carey et al. 2007)**
- **Natural CO_2 Producer: 30-year old well, continuous exposure (Crow et al. 2010)**
- **Buracica, Brazil: CO_2-EOR, 10 years old**
- **Wyoming: Non-CO_2, 10 years old (See Dwight Peters presentation)**
- **Weyburn, Non-CO_2 exposure**

Carey et al. (2007) Int. J. Greenhouse Gas Control

Slic

Key Results from Field Studies

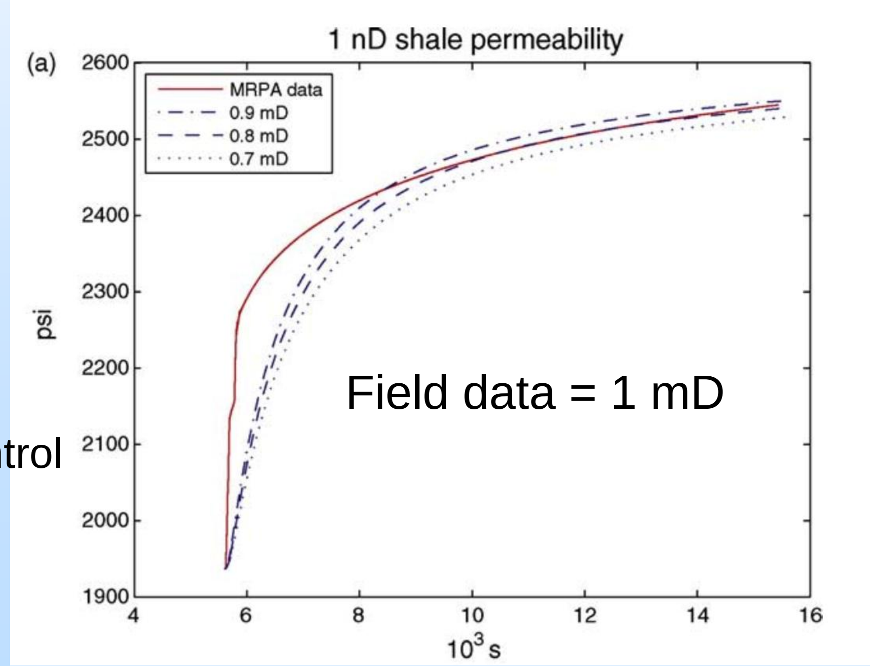
- Cement can provide hydrologic isolation for decades in CO_2 fields
- CO_2 can migrate behind casing
- Quantities/rates not known
- Effective well permeability greater than cement permeability (0.1 versus 1 mD)
- Cement is altered by time, formation fluids and CO_2
- Hydrologic and mechanical significance of alteration not established
- Revealed importance of interfaces as leakage pathways

Carey et al. (2007) Int. J. Greenhouse Gas Control

First measurements of wellbore leakage permeability

Collaboration with Walter Crow and the CO_2 Capture Project

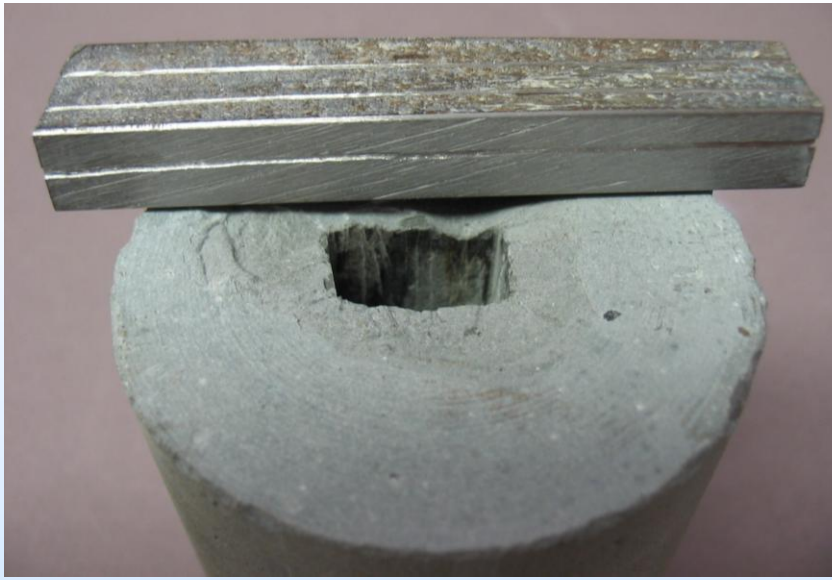
- *In situ* measurement of permeability outside the casing
  - Natural CO_2 producer
- Established concept of finite leakage rates
  - All wells have some permeability

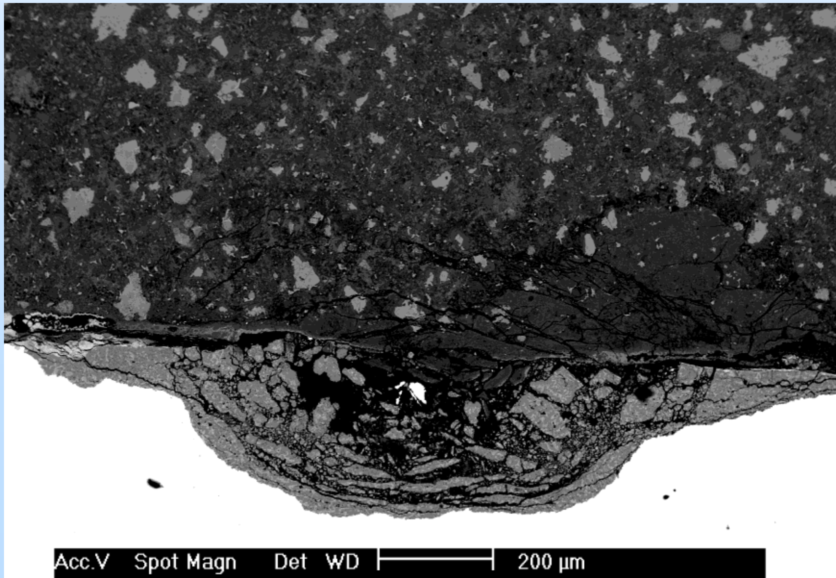


Crow, Carey et al. (2010) Int. J. Greenhouse Gas Control

Experimental Core-Flood Studies of Cement-Casing Interface

- Rates of CO_2 penetration limited
  - Also see Kutchko et al. who also demonstrate fly ash increases CO_2 penetration
  - Hydrologic impact of carbonation may be limited
- Permeability drops with time
- Corrosion potentially more significant than carbonation
  - Fe-carbonate precipitate may protect steel and reduce defects

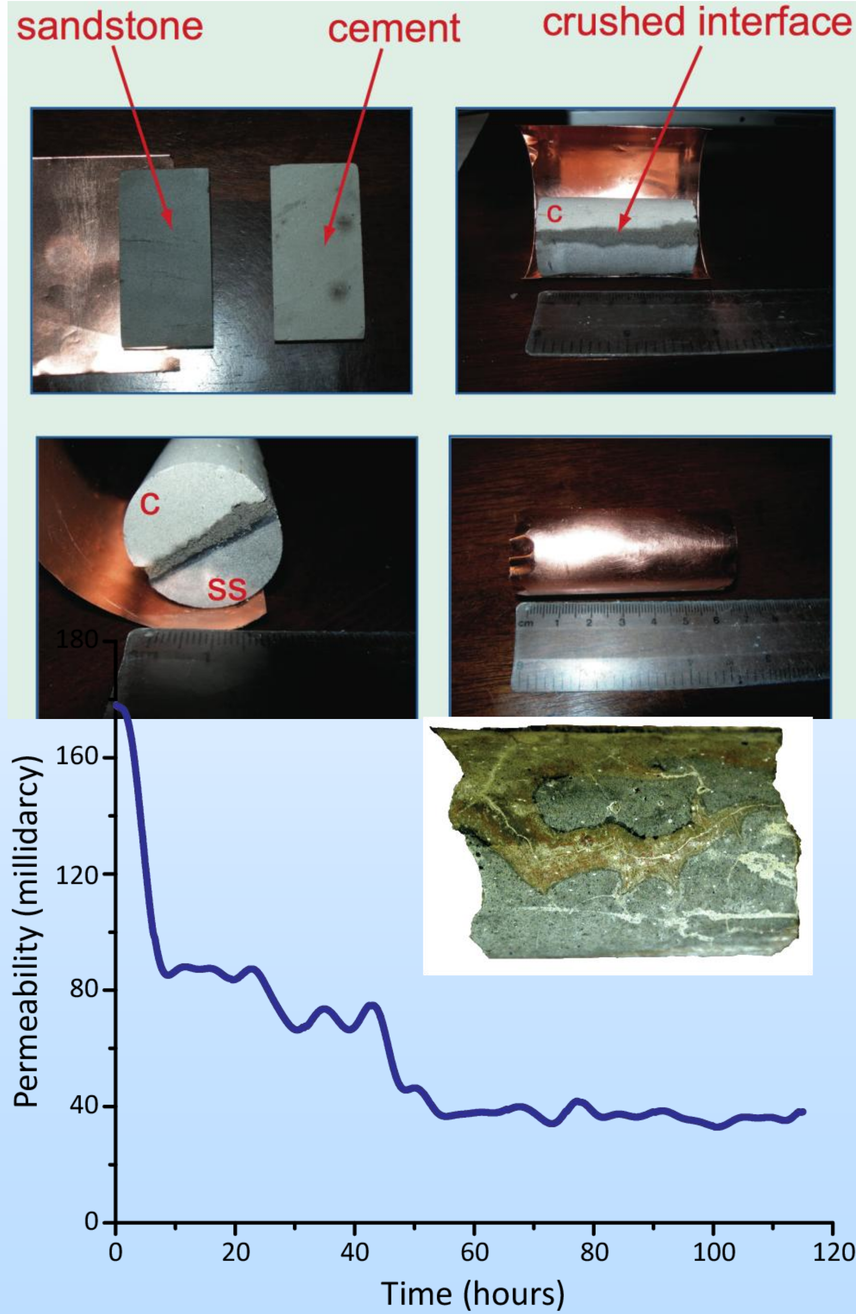




Carey et al. (2010) Int. J. Greenhouse Gas Control

Experimental Coreflood Studies of Casing-Caprock Interfaces

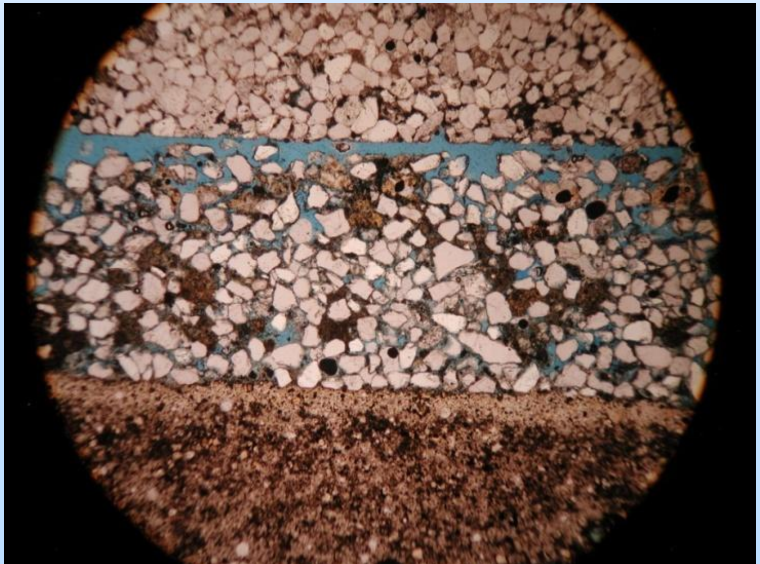
- Flow confined to interface
  - CO_2 penetrates cement only by diffusion
  - Hydrologic impact of carbonation appears limited
- No erosion of cement
- Permeability drops with time
  - Fines migration and re-precipitation of cement phases rather than carbonates



Newell and Carey (2012) ES&T

Self-Healing in Wellbore Systems

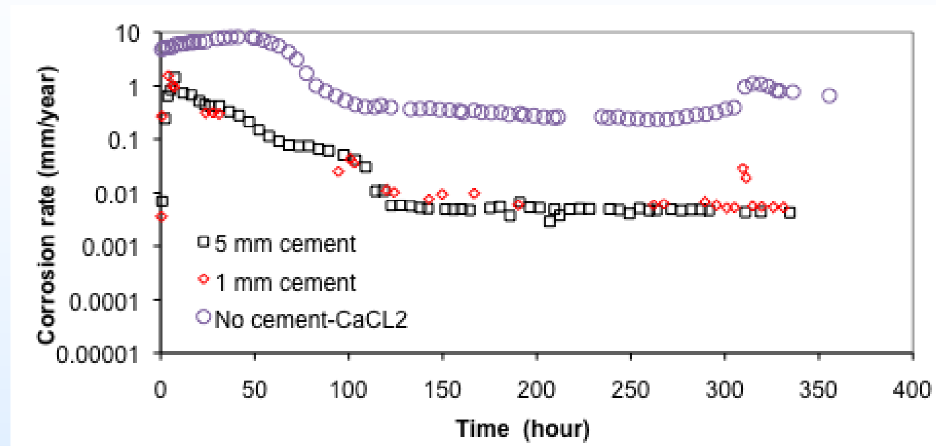
- Precipitation and particle migration observed to heal fractures and reduce permeability
  - Cement-casing
  - Cement-caprock
  - Cement-cement (Huerta et al.)
- More limited evidence in the field
- Key area of ongoing research

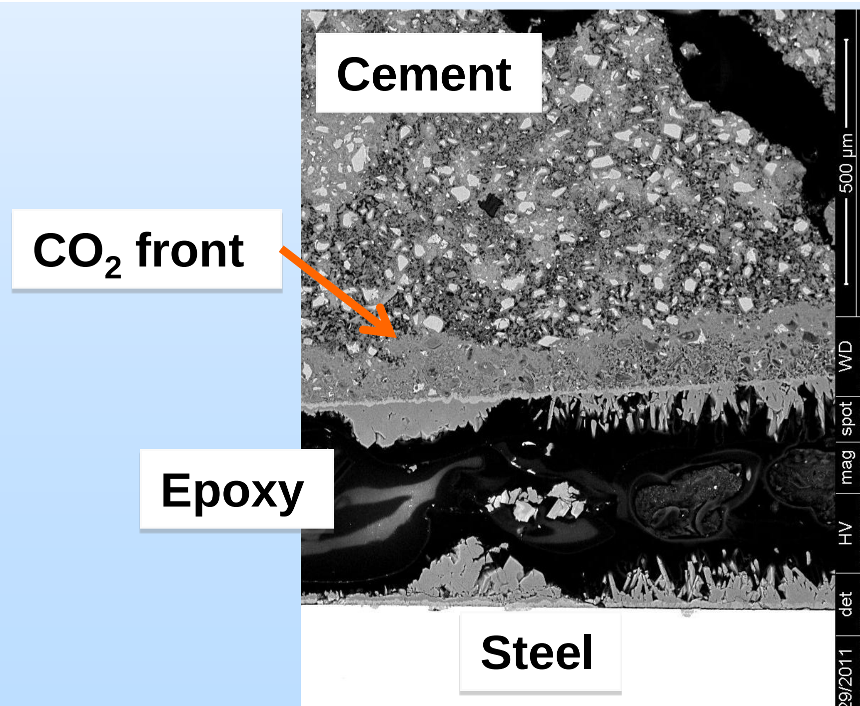


Newell and Carey (2012) Env. Sci. & Technology

Corrosion in wellbore systems

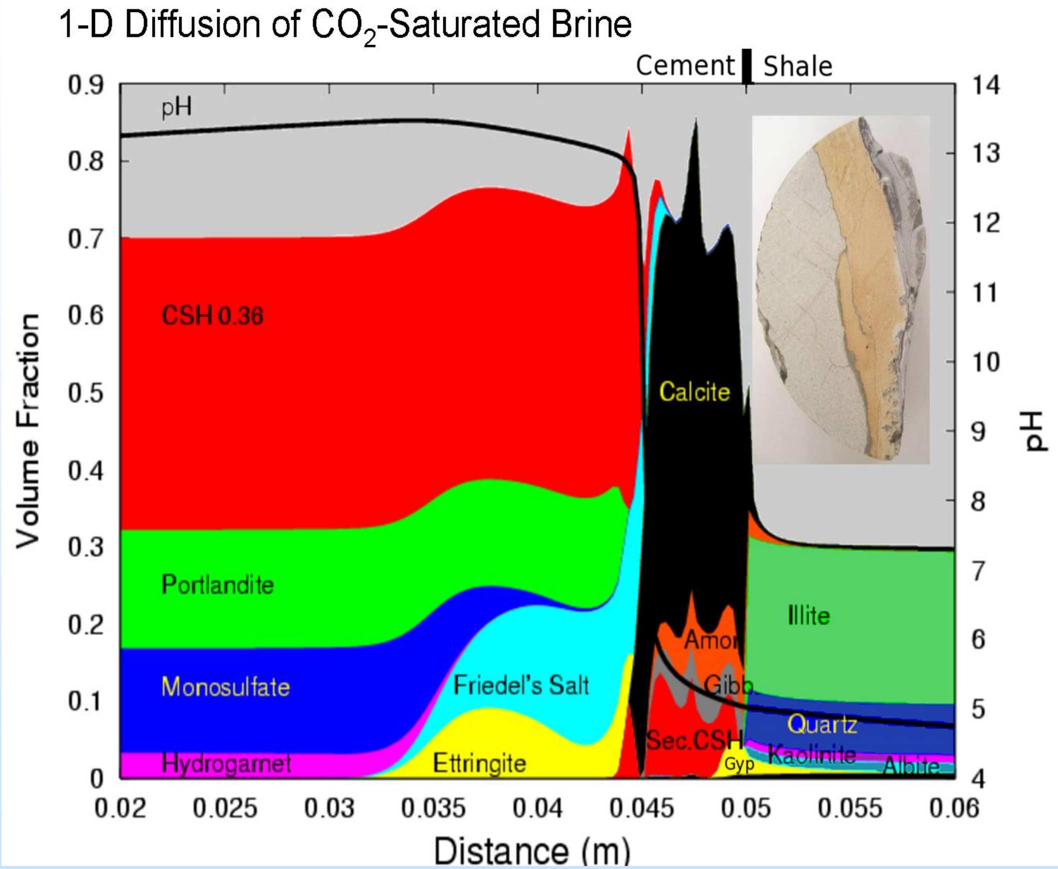
- Measured and modeled rates of corrosion in high-PT, saline systems (Han et al. 2011)
  - First predictive model of corrosion rates of bare steel in sequestration environments
- Experimental studies of corrosion at the cement-interface
  - Impact of gap size on corrosion rates
  - Impact of cement carbonation on corrosion rates





Geochemical Model of Cement-CO_2 Reactions

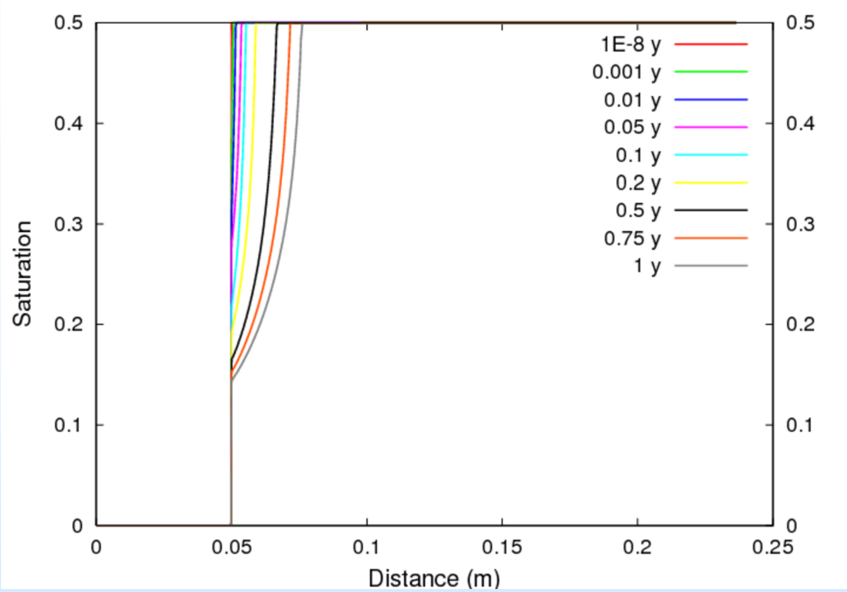
- Accurately represents CO_2-cement reactions
- Explains field and laboratory observations

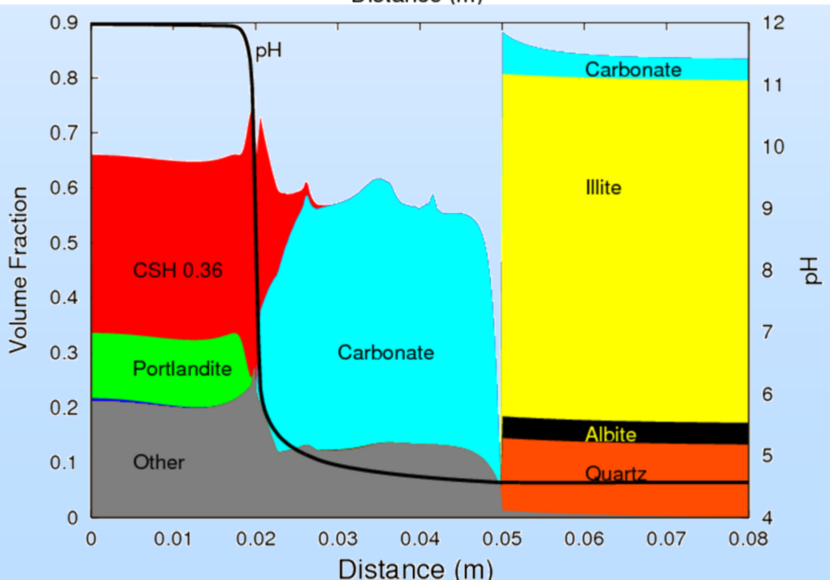


Carey and Lichtner (2007) Transport Properties and Concrete Quality

Multiphase Flow and Reaction in Wellbore Systems

- Demonstrated that CO_2 does not penetrate good-quality cement
  - Capillary forces prevent CO_2 migration in cement
- Interfaces key to leakage

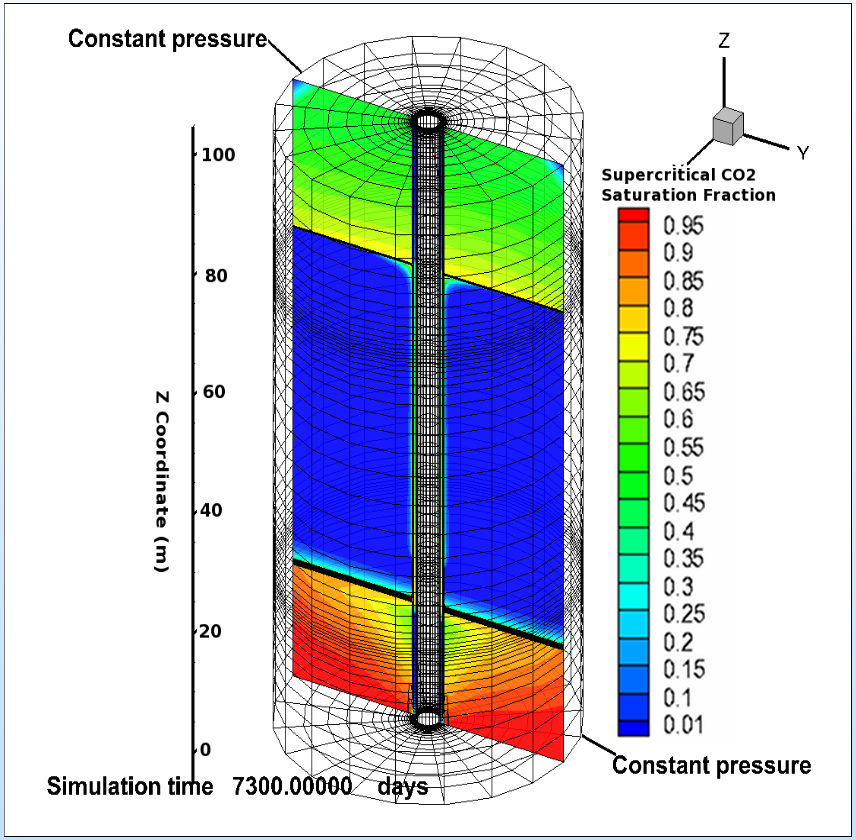




 Carey and Lichtner (2011) SPE Journal

Geomechanical Model of Wellbore Systems

- Fully 3-D model of stress and multiphase flow
  - Shear- and tensile-failure modes
- Impact of thermal and mechanical stress on enhanced permeability and flow



Lewis, Carey et al. (2012) American Rock Mech. Assoc. Proceedings

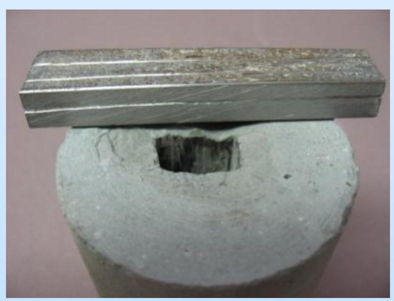
Bridge to NRAP: Wells in Risk Assessment

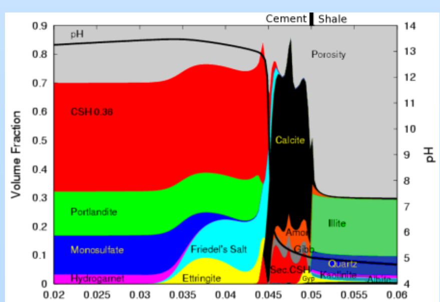
Storage System
- Capacity
- Injectivity

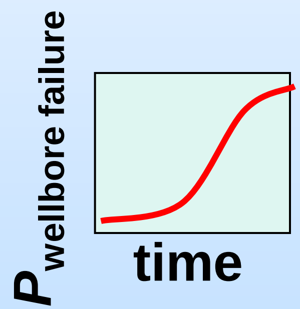
Containment
- Caprock
- Fault
- Wellbore

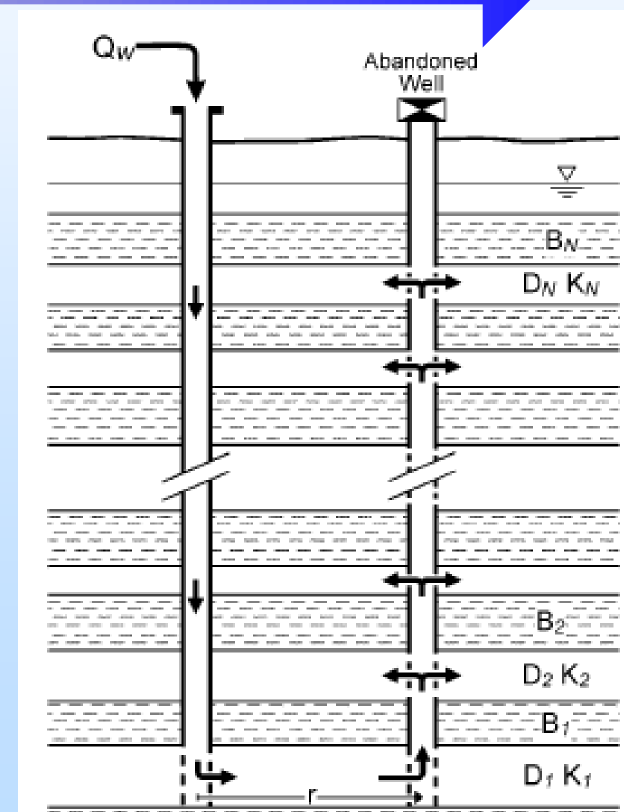
Potential Receptors

Potential Consequences









Norbotten, Celia, et al.

Development of a probabilistic system model (Stauffer, Pawar, et al.)

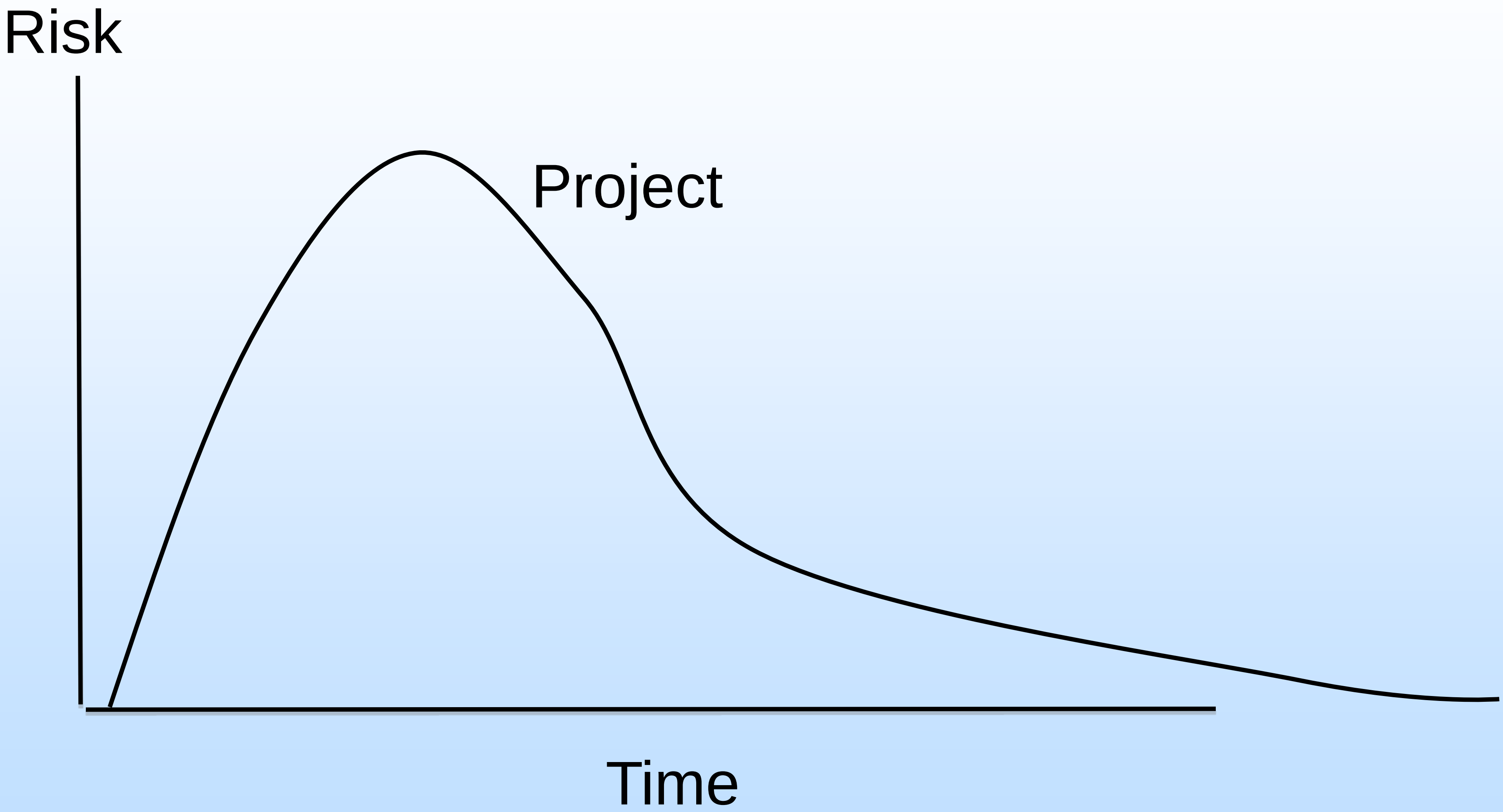
Accomplishments to Date

- Portland cement can last at least for decades despite exposure to CO_2 and continues to provide substantial zonal isolation (Carey et al. 2007; Crow et al. 2010).
- Interfaces are the key points of weakness in wellbore systems (Carey et al. 2007).
- CO_2 cannot flow through good-quality cement due to capillary pressure barriers (Carey and Lichtner 2011).
- Experimental coreflood experiments show that Portland cement can survive relatively high flow-through rates of CO_2-brine mixtures and steel corrosion can be more significant than cement carbonation (Carey et al. 2010; Newell and Carey 2012).
- Self-healing of wellbore defects occurs, at least under some conditions, by precipitation of calcium and iron carbonates and migration of fines (Carey et al. 2007; Carey et al. 2010; Newell and Carey 2012).
- While bare-steel corrosion rates are high, Portland cement offers substantial protection for steel (Han et al. 2011).

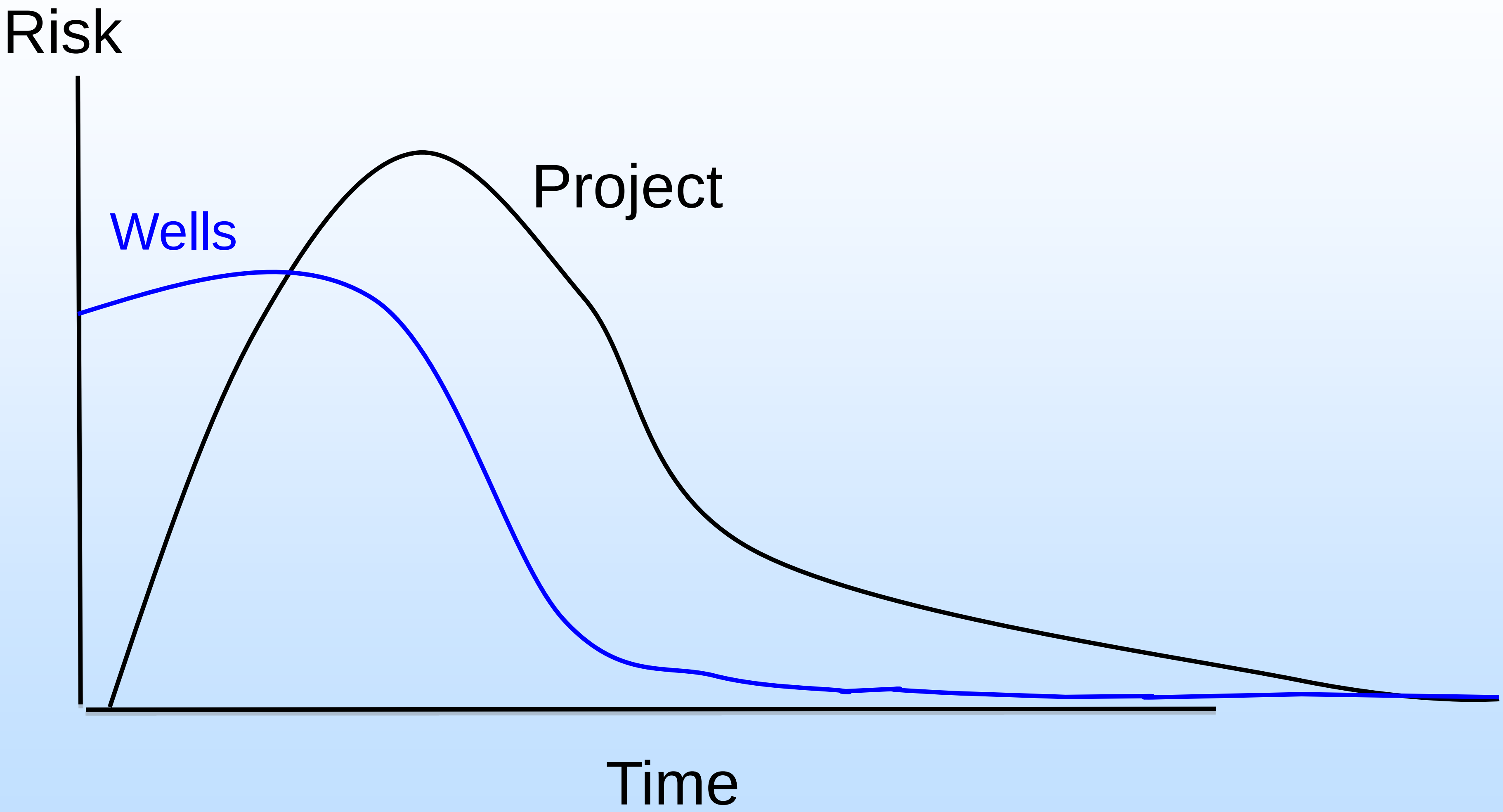
Future Plans

- Development of integrated model of geomechanical and chemical response of wellbore systems
  - Experimental investigation of combined impacts of confining stress and precipitation on *self-healing* mechanisms in wellbore systems
  - Numerical representation of CO_2-brine leakage as a function of time in response to geomechanical forces and geochemical processes
- Comparative analysis of corrosion and cement carbonation
  - Experimental, numerical and theoretical consideration of relative importance of corrosion and cement degradation in CO_2-brine systems
- Geomechanical behavior of caprock
  - Experimental investigations to determine CO_2-brine flow rates in shale, anhydrite and carbonate caprock experiencing dynamic deformation

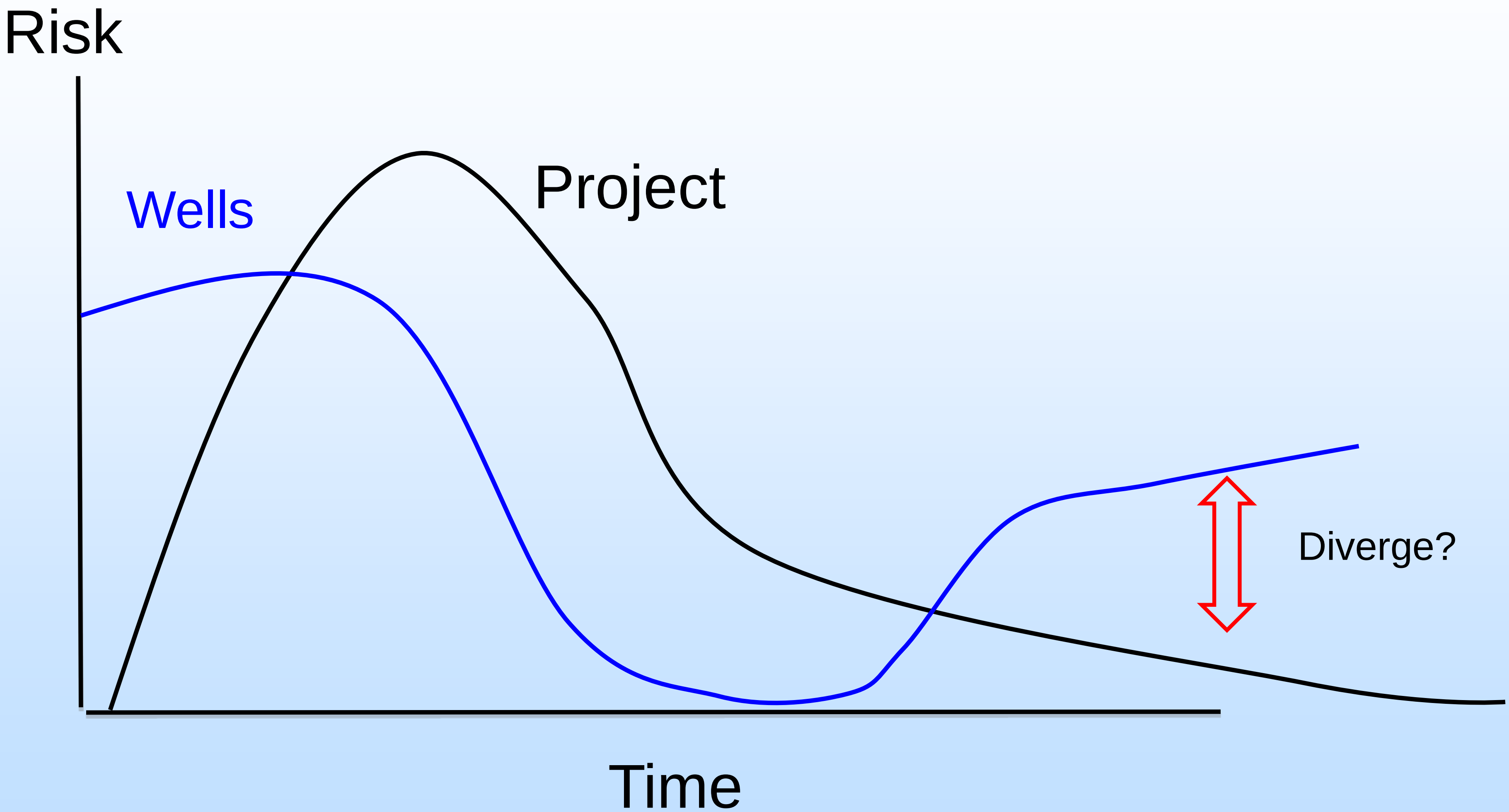
Long-term Risk and Wellbore Integrity



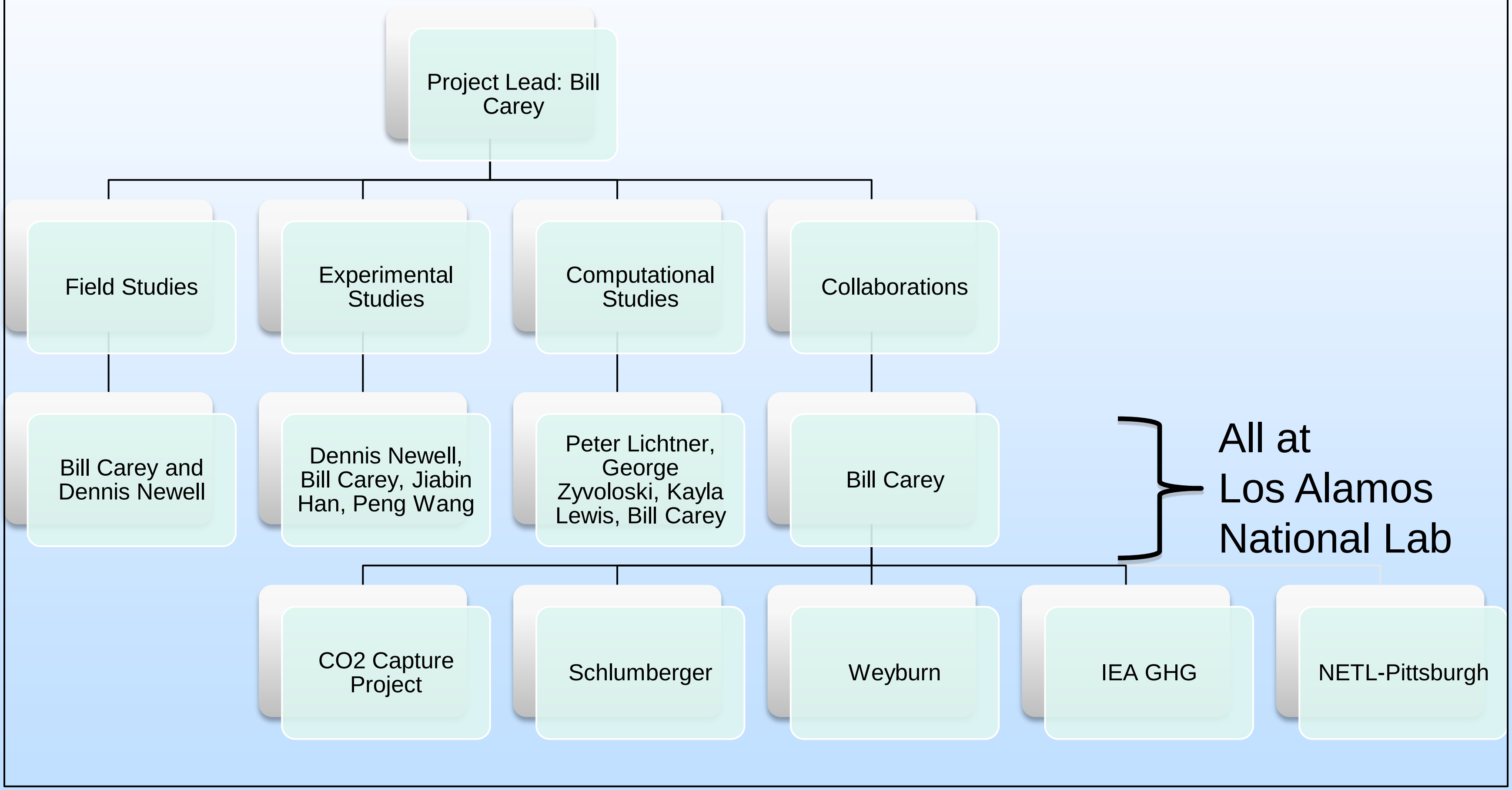
Long-term Risk and Wellbore Integrity



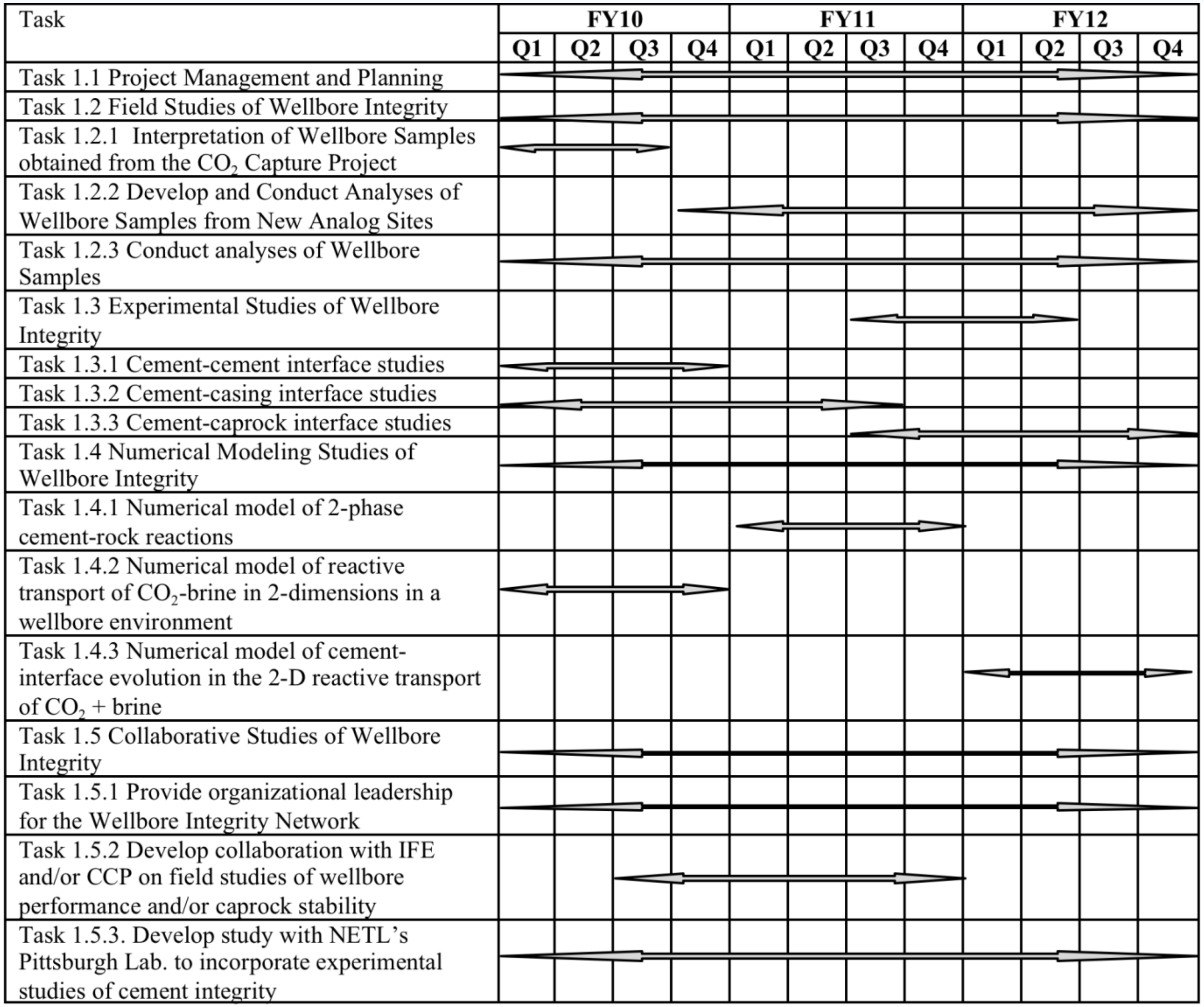
Long-term Risk and Wellbore Integrity



Organization Chart



Gantt Chart


Task
FY10
FY11
FY12
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Task 1.1 Project Management and Planning
Task 1.2 Field Studies of Wellbore Integrity
Task 1.2.1 Interpretation of Wellbore Samples obtained from the CO_2 Capture Project
Task 1.2.2 Develop and Conduct Analyses of Wellbore Samples from New Analog Sites
Task 1.2.3 Conduct analyses of Wellbore Samples
Task 1.3 Experimental Studies of Wellbore Integrity
Task 1.3.1 Cement-cement interface studies
Task 1.3.2 Cement-casing interface studies
Task 1.3.3 Cement-caprock interface studies
Task 1.4 Numerical Modeling Studies of Wellbore Integrity
Task 1.4.1 Numerical model of 2-phase cement-rock reactions
Task 1.4.2 Numerical model of reactive transport of CO_2-brine in 2-dimensions in a wellbore environment
Task 1.4.3 Numerical model of cement-interface evolution in the 2-D reactive transport of CO_2 + brine
Task 1.5 Collaborative Studies of Wellbore Integrity
Task 1.5.1 Provide organizational leadership for the Wellbore Integrity Network
Task 1.5.2 Develop collaboration with IFE and/or CCP on field studies of wellbore performance and/or caprock stability
Task 1.5.3. Develop study with NETL's Pittsburgh Lab. to incorporate experimental studies of cement integrity

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