Overview of the IEA Greenhouse Gas R&D Programme's Wellbore Integrity Network

Bill Carey (Los Alamos)
Charles Christopher (BP)
John Gale (IEA GHG)

EPA Technical Workshop on Geosequestration:
Well Construction and Mechanical Integrity Testing
March 14, 2007
Albuquerque, NM

LA-UR-07-1894

Origins and Charter

- Founded by Charles Christopher and developed in collaboration with John Gale
- Funded by IEA Greenhouse Gas R&D
- Annual meetings gather experts in industry, academia, government laboratories, as well as policy makers
- Purpose is to assess and communicate the state of knowledge, nature of research programs, and the research needs to understand the long-term integrity of wellbore systems in CO_2-rich environments

Steering Committee Members

- Toby Aiken, IEA GHG
- Idar Akervoll, SINTEF
- Bill Carey, LANL
- Mike Celia, Princeton University
- Charles Christopher, BP (Chair)
- Rich Chalaturnyk, University of Alberta
- John Gale, IEA GHG
- Daryl Kellingray, BP

Workshop Format

- Invited presentations in key areas
- Informal format with extended discussion
- Breakout groups develop approaches and philosophies surrounding a key issue
- A summary report of the presentations, discussion, and breakouts is written by IEA Greenhouse Gas R&D Programme

Meetings

(Organized and supported by the IEA Greenhouse Gas R&D Programme, BP, EPRI and the host institutions)

- 1st: Houston, Texas, April 2005
- 2nd: Princeton, New Jersey, March 2006
- 3rd: Santa Fe, New Mexico, March 2007

Wellbore Integrity Focus Areas

1. Field experience of CO_2 and wellbore materials including EOR and CO_2 fields
2. Research and development of field monitoring and evaluation methods
3. Remediation approaches
4. Experimental research on cement-CO_2 interactions including new cement formulations
5. Numerical modeling of CO_2 in the wellbore and in multiple-well fields
6. Policies and regulations

Topics in Field Experience (1.)

- Practice and art of cement placement in the wellbore environment
- Case histories from EOR fields and CO_2 reservoirs
- Coring, sampling, and logging studies of wells with significant CO_2 exposure
- Case histories from sequestration sites
- Wellbore statistics from petroleum provinces

Topics in Field Monitoring Evaluation (2.)

- Review of logging methods
- Research into enhanced acoustic logging methods
- Results of wellbore logging

Topics in Wellbore Remediation (3.)

- Experience with remediation
- Methods of remediation

Topics in Laboratory Experiments (4.)

- Cement samples studied in CO_2-rich environments at room conditions, at various temperatures, and at elevated pressures to simulate wellbore environments
- Results from both closed-system and flow-through experiments
- New CO_2-resistant cement formulations evaluated

Topics in Numerical modeling of CO_2 and the Wellbore Environment (5.)

- CO_2 distribution and fate in the reservoir
- Effects of CO_2 on water saturation and possible desiccation of pore system
- Reactive transport modeling of CO_2-cement
- Simulation of CO_2 leakage through wellbore annulus or open hole
- Simulation of wellbore leakage in a field of many wells
- Incorporation of wellbore integrity into system-level modeling of CO_2 sequestration

Policies and Regulations (6.)

- American Petroleum Institute recommended practices
- Mineral Management Service (MMS) regulations (particularly with respect to sustained casing pressure)
- Alberta, Canada regulatory framework
- European approaches

Topics in Breakout Groups

- Do wellbores represent a significant leakage risk?
- Do we know how to reduce the potential for CO2-induced cement degradation?
- Are there standard industry methods to minimize leakage?
- How are leaky wells remediated?
- Historical wellbore integrity record
- Wellbore materials and mechanisms of reaction
- Design of a wellbore integrity experiment
- Research Directions

Summary of Key Issues (1)

- Wellbore integrity problems do exist in oil and gas operations (e.g., SCP) and are often due to cementing practices. We need to develop a basis for evaluating leakage potential from legacy wells
- New approaches to wellbore remediation are needed as well as means to evaluate the potential costs of remediation for sequestration projects
- Laboratory experiments on reactivity of CO_2 and cement need to reconcile effects of key variables: confining pressure, fluid flow, matrix vs. interface flow, and effect of reservoir rock
- New CO_2-resistant cements are in development and methods for evaluating their performance and determining their suitability are needed
- Casing and tubular corrosion can be more rapid than cement degradation
- More sensitive and diagnostic logging and field monitoring tools are needed

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Key Issues cont. (2)

- Numerical models of wellbore geochemistry and geomechanics are needed for providing long-term predictions
- Numerical models incorporating realistic permeability distributions for wells are needed to evaluate the leakage potential of fields with multiple wells
- Integrated field evaluations in fields with long CO2 exposure are needed to develop logging/monitoring methods, understand mechanisms of CO2-induced degradation, and assess effective permeability of the wellbore
- Data mining of the rich resources available in private companies and regulatory bodies should be a priority for developing a statistical basis for evaluation of wellbore performance

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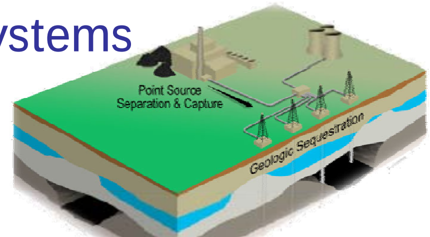
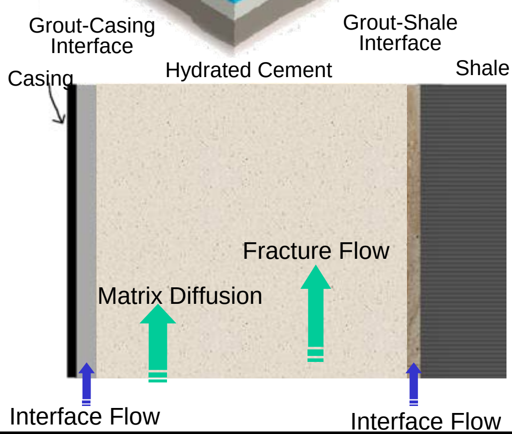
Mechanism of CO2 Interaction with Wellbore Systems

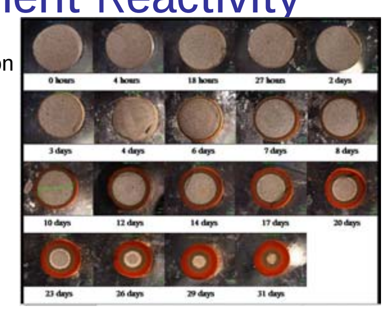
- Determine mode of CO_2 interaction with cement
- Develop model of changes in effective cement permeability as function of CO_2 reaction
- Couple with geomechanics



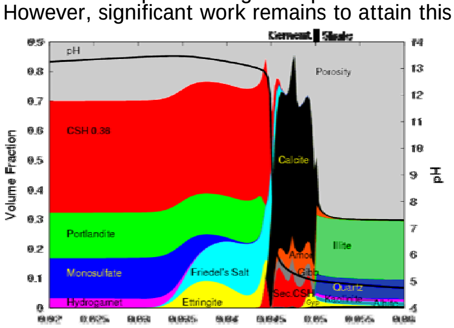


Example Focus: Reconciling Field, Lab, and Modeling in CO_2-Cement Reactivity

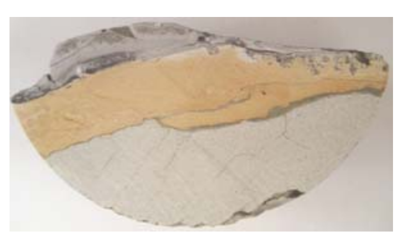
- Lab results vary from extensive reactivity (Duguid et al.) to limited reactivity (Kutchko et al.) and depend on imposed conditions (T,P, fluid, etc.).
- Field observations (Carey et al., SACROC) show CO_2-induced alteration similar in character to some lab experiments but without significant apparent CO_2 leakage.
- Modeling studies have the potential to reconcile laboratory and field observations and provide a mechanism to predict long-term performance. However, significant work remains to attain this goal.



Duguid et al. (2005) experiments at 1 atm



Carey et al. (2007a) Reactive transport calculations



Carey et al. (2007b) field study at SACROC

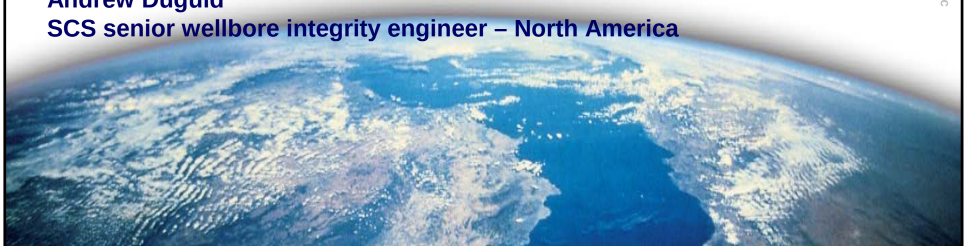
Conclusions

- Meeting summaries and details are available at http://www.co2captureandstorage.info/networks/wellbore.htm
- Discussion point: will wells in a potential CO_2 storage field that have been plugged and abandoned by UIC-approved methods be considered "sequestration-ready"?

CO_2-cement interactions: from the lab to the well

EPA CO_2 Geosequestration Workshop
2007 Mar 14

Matteo Loizzo
SCS engineering program manager
Andrew Duguid
SCS senior wellbore integrity engineer – North America



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Outline of the presentation

- Portland cement and CO2
- Length and time scales
- CO2 reaction effects on well integrity
- From lab to well: acceleration of CO2 degradation
- Cement sheath defects and effect on scales
- Assuring cement integrity over the well life
- Risk mitigation: CO2 Resistant Cement
- Conclusions

We wish to thank Veronique Barlet-Gouedard and her team at Schlumberger Well Services, without whose data and insight this presentation would not have been possible

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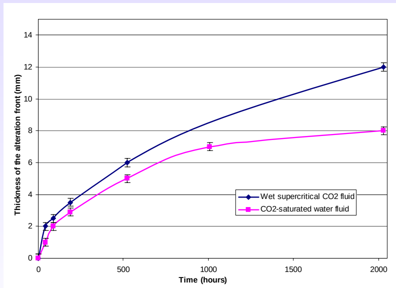
Portland cement and CO_2: a 3-step process

- Carbonic acid diffusion
- Dissolution/Carbonation
  - Portlandite ($Ca(OH)_2$) and CSH gel
  - Precipitation of $CaCO_3$
- Leaching



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Portland cement and CO_2: reactions

- CO_2 dissociation
  - $CO_2 + H_2O \leftrightarrow H_2CO_3^* \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$
- Cement dissolution and calcium carbonate precipitation
  - $Ca(OH)_2(s) + 2H^+ + CO_3^{2-} \rightarrow CaCO_3(s) + 2H_2O$
  - $C_{3.4}\text{-}S_2\text{-}H_8(s) + 2H^+ + CO_3^{2-} \rightarrow CaCO_3(s) + SiO_xOH_x(s)$
  - $Ca(OH)_2(s) + H^+ + HCO_3^- \rightarrow CaCO_3(s) + 2H_2O$
  - $C_{3.4}\text{-}S_2\text{-}H_8(s) + H^+ + HCO_3^- \rightarrow CaCO_3(s) + SiO_xOH_x(s)$
- Calcium carbonate dissolution (“leaching”)
  - $CO_2 + H_2O + CaCO_3(s) \leftrightarrow Ca^{2+} + 2HCO_3^-$
  - $2H^+ + CaCO_3(s) \leftrightarrow CO_2 + Ca^{2+} + H_2O$

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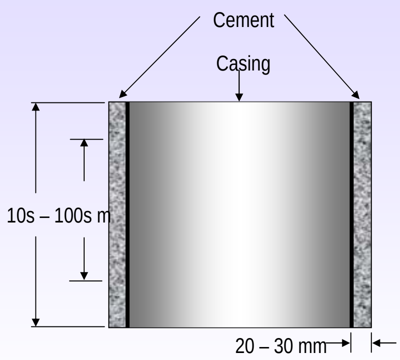
Length and time scales: long and slender wells

- Length: isolation across a gas-tight boundary (cap rock)
  - ~100 ft scale (10s to 100s of meters)
- Length: isolation through the cement sheath
  - ¾" (20 to 30 mm) scale
    - Casing eccentering may reduce to 0
  - Design of casing and production tubing/packer
    - Joint effect of chlorides, H_2S, temperature
    - Safe-life design of carbon steel vs. premium grades
- Time: 40 years of injection life, or 1000 years of storage



Experimental results

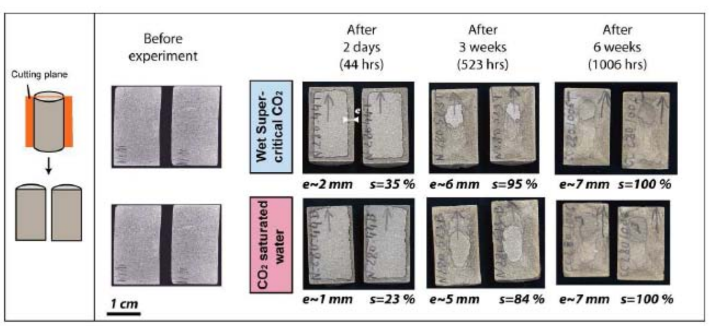
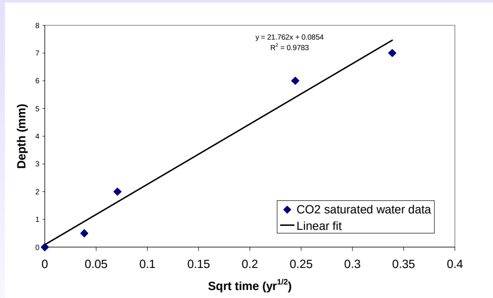


Figure 16. Cuttings of the Portland cement cores before attack and at different selected durations of experiment at T=90°C and P=280 bars, according to the fluid-type in which the samples are placed in the reactor. e: thickness of the alteration front; s: ratio between the alteration front surface and the whole cutting surface.

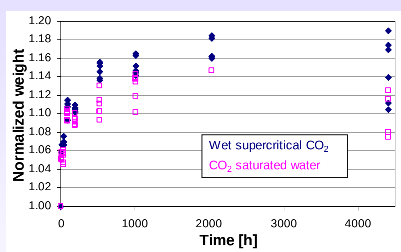
Diffusion-controlled reaction

- CO_2-saturated water
  - Time to react to 25 mm – 1.3 years
  - Time to react to 1000 mm - 2100 years
- Wet supercritical CO_2
  - Time to react to 25 mm – 1.4 years
  - Time to react to 1000 mm - 2200 years



CO_2 reaction effects on well integrity

- Carbonation
  - Matrix reacts: Portlandite/CSH → Calcite
    - Water release
  - At an early stage, may affect marginally matrix permeability ($10^{-4} \rightarrow 10^{-3}$ mD)
  - May lead to mechanical instability (Calcite molar volume increase) •
  - ¾" in 7-10 months, 1 m in 2000 years
    - CO_2 diffusion in water: ¾" in 3 days, 1 m in 20 years
- Leaching
  - Strong dependency on local Ca^{2+} concentration gradient
  - Cement effectively dissolves •



From lab to well: acceleration of CO_2 degradation

- CO_2-cement reactions are diffusion-driven processes through the cement matrix
  - Surface-to-volume ratio
  - Fluid volumes
  - Effective transport
- At the well length scale, matrix permeability seems to guarantee isolation
- Cement sheath defects will cause acceleration

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Cement sheath defects – liquid cement

- Placement defects – fluid dynamics
  - Channels
    - Pockets or strings of bypassed drilling mud
    - Increase of fluid volumes and SVR, direct communication to the casing, may increase transport by establishing a communication path
  - Mud films
    - Increase of fluid volumes, further reduction of cement thickness
- Gas migration during cement hydration may cause channels
  - Driven by a drop in cement pore pressure during hydration
  - Placement design and system selection

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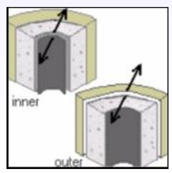
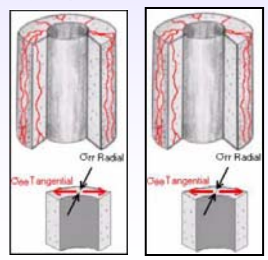
Cement sheath defects – solid cement

- Solid mechanics
  - Cracks and microannuli
    - Cracks caused by cement failure in compression/traction, microannuli caused by debonding at the interfaces with casing and/or rock
    - Increase of SVR, may increase transport by establishing a communication path
- Worst case: channels, microannuli and cracks leaving a path for fluids to flow
  - Wet CO_2 much more likely to flow, even in ~20 μm gap





Cement sheath defects – effects on scale

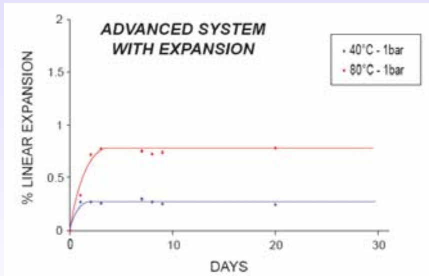
- Fluid flow vs. matrix diffusion
  - Preferential path of fluid flow bridges the scales
  - Issue not limited to CO_2: 15%-20% of wells may show hydraulic communication to surface
- Carbonation healing/plugging may be effective only at small scales
  - Karst
- Positive feedback effect from enhanced leaching on defect walls

Assuring cement integrity over the well life

- Risk factors and scales
  - Casing corrosion
  - Leakage to shallower formations or to surface
- Multiple layers of risk mitigation
  - Especially when repair is difficult
- Cement system selection and optimization
  - Minimize or eliminate cement sheath defects
  - Minimize or eliminate cement degradation
    - Not necessarily cement reaction!

Risk mitigation: CO_2 Resistant Cement

- Novel formulation based on "CRETE" technology and reduced-Portland binder
  - Particle size distribution optimized to minimize porosity and permeability and maximize mechanical properties
  - (Reduced) Portland cement content increases compatibility with CO_2
- Quick reaction, no degradation
  - Reduced Portland content and porosity → good residual CS, no mechanical instability
  - Limited calcite → limited leaching
- Excellent engineered expansion behavior
  - To match casing contraction during CO_2 injection



Conclusions

- Interaction between cement and CO_2 follows a 3-step process
- A relatively quick dissolution carbonation is followed by a (possibly) slower leaching of calcium carbonate
- Carbonation and $CaCO_3$ precipitation may cause mechanical instability of the cement sheath
- Leaching may become a concern when effective transport (fluid flow) is present. Fluid flow is in turn caused by cement sheath defects. Experiments are needed to substantiate this positive feedback hypothesis
- Sound cement design is required, both for the placement and post-placement phases
- Use of cement that minimizes leaching potential adds a risk mitigation layer to better ensure medium-term well integrity

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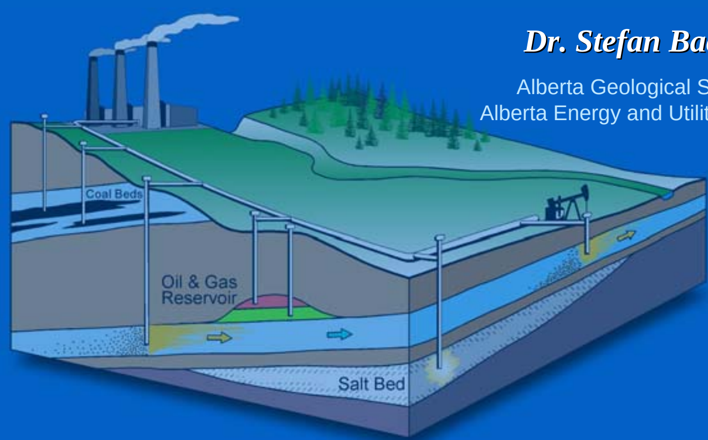
Well Integrity Experience in Alberta, Canada



Dr. Stefan Bachu

Alberta Geological Survey
Alberta Energy and Utilities Board

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Canada's Constitutional Division of Jurisdictions

- Provinces have sole jurisdiction over natural resources, including the subsurface
- The federal government has jurisdiction over territories, territorial waters, ocean and fisheries, trans-boundary issues and international matters (Kyoto Protocol, London Convention of the Seas)
- Both provincial and federal governments have jurisdiction over environmental issues: federal on air, lake sediments, provincial on water quality (groundwater and rivers), both on emissions

➢ Deep injection falls entirely under provincial jurisdiction

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Alberta's Regulatory Agencies

- Alberta Department of Environment is in charge of groundwater protection (establishes the depth of protected groundwater: TDS<4000 ppm; licenses water wells)

- Alberta Energy and Utilities Board (EUB) has jurisdiction over oil and gas production, and deep well injection and disposal (licenses all deep wells), including well construction and abandonment

Directive 65 for Application for Disposal Operations, and
Directive 51 for Well Construction
http://www.eub.ca/docs/documents/directives/Directive051.pdf
http://www.eub.ca/docs/documents/directives/Directive065.pdf

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Main Regulatory Objective in Deep Well Injection

Ensure that there is no migration and/or leakage out of the injection target that would:
- Contaminate energy and mineral resources
- Contaminate potable groundwater resources
- Endanger life and property

Regulatory attention focuses on:
- Wellbore integrity
- Formation suitability to ensure confinement
- Suitability of the injected stream in regard to the nature of the fluid and well and formation integrity
- Reporting
- Early detection and mitigation of potential problems

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Injection Well Classification in Alberta

Class Ia – oilfield, industrial waste
Class Ib – produced water/specified wastes
Class II – produced water/brine equivalent
Class III – hydrocarbon/inert/sour gases
Class IV – steam/potable water

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Class III Injection Wells in Alberta

Injection of hydrocarbons, or inert or other gases, for the purpose of storage or enhanced hydrocarbon recovery

- Solvent or other HC products for enhanced recovery
- Sweet natural gas for storage
- CO_2, N_2, O_2, air, other gases for storage or enhanced recovery
- Sour or acid gases for disposal, storage or cycling operations

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Requirements for Class III Injection Wells in Alberta

- Hydraulic isolation of the host zone
- Cementing across protected groundwater
- Logging for cement top, hydraulic isolation and casing inspection
- Initial annulus pressure test
- Annual packer isolation test
- Wellhead pressure limitation at <90% of rock fracturing threshold
- Area of review based on reservoir modelling
- Hydraulic isolation of offset wells that penetrate the same zone within the area of review

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EUB's Current Position in Regard to CO_2 Injection

CO_2 – enhanced hydrocarbon recovery falls under Oil & Gas Conservation Regulations

CO_2 injection into deep saline aquifers and depleted oil and gas reservoirs is covered under Disposal Regulations

In both cases Class III wells have to be used

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Drivers of Acid Gas and CO_2 Injection Activities in Canada

The stick! Regulatory control on H_2S emissions

The carrot!

- Additional oil production
- Government incentives for CO_2-EOR
- Economics of H_2S incineration or sulfur recovery

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Location of Acid-Gas Injection Sites in Canada

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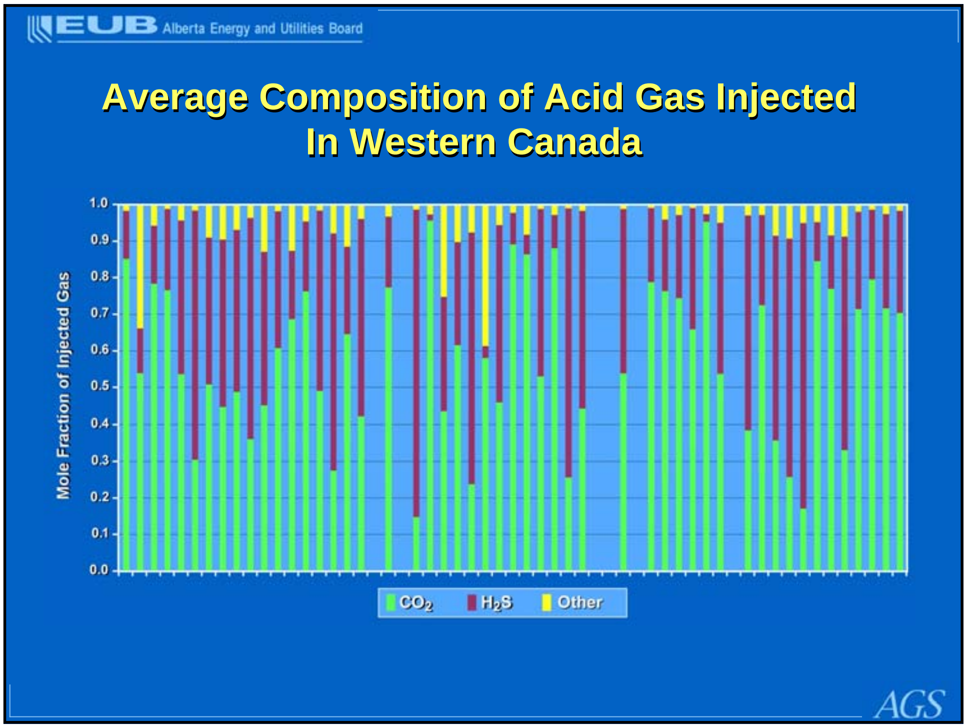
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Average Composition of Acid Gas Injected
In Western Canada
Mole Fraction of Injected Gas
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
CO_2
H_2S
Other
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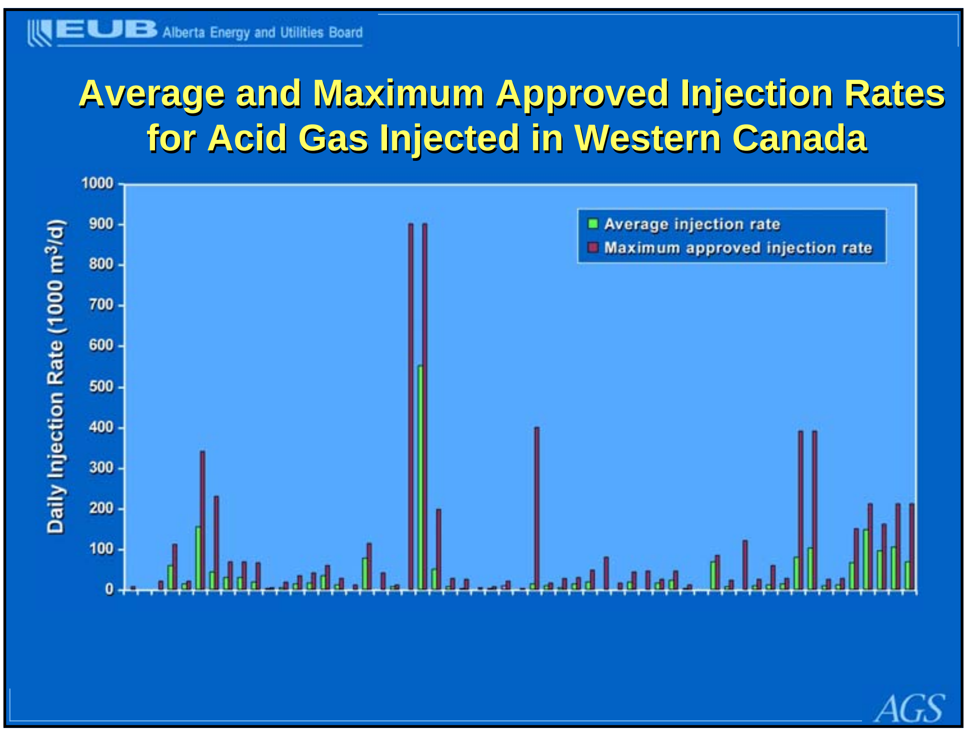
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Average and Maximum Approved Injection Rates
for Acid Gas Injected in Western Canada
Daily Injection Rate (1000 m^3/d)
1000
900
800
700
600
500
400
300
200
100
0
Average injection rate
Maximum approved injection rate
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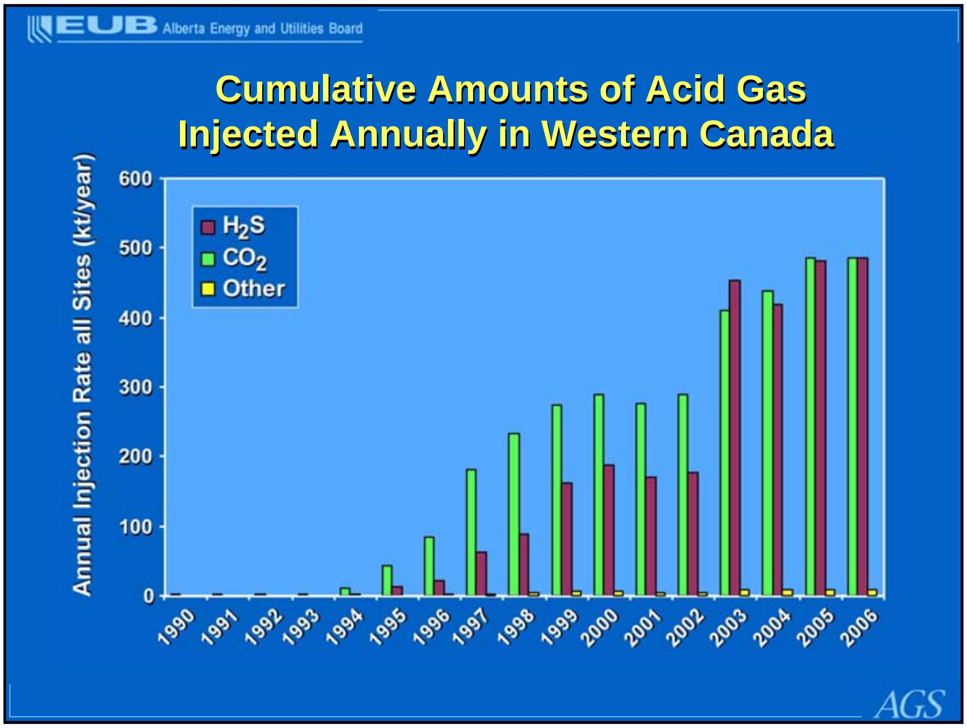
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Cumulative Amounts of Acid Gas
Injected Annually in Western Canada
Annual Injection Rate all Sites (kt/year)
600
500
400
300
200
100
0
H2S
CO2
Other
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
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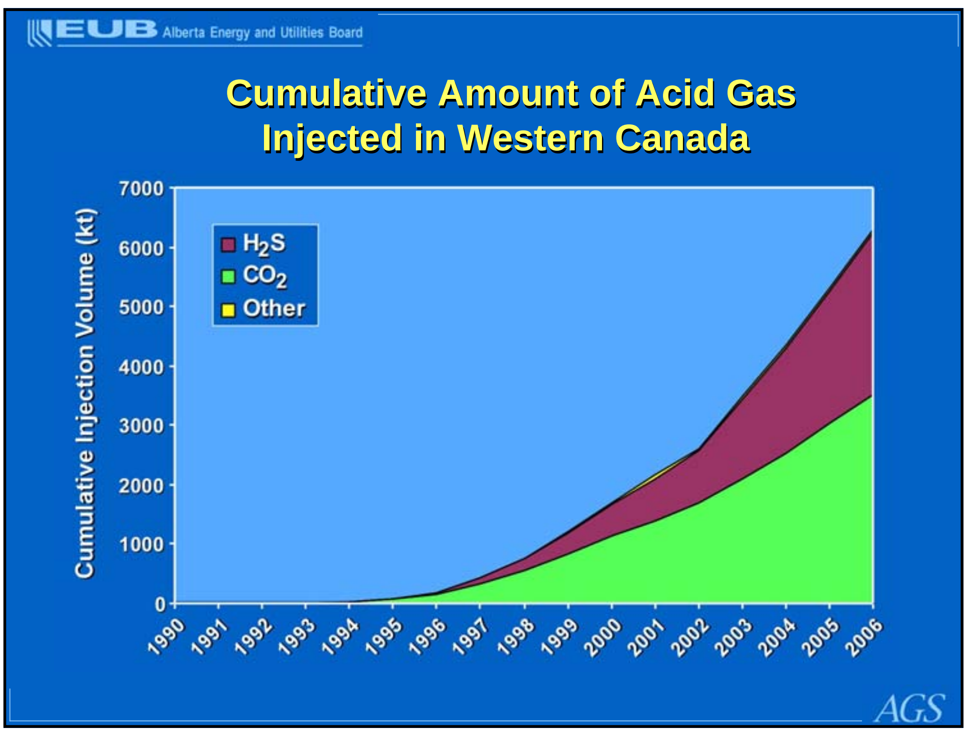
EUB Alberta Energy and Utilities Board
Cumulative Amount of Acid Gas
Injected in Western Canada
Cumulative Injection Volume (kt)
7000
6000
5000
4000
3000
2000
1000
0
H2S
CO2
Other
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
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Operating Ranges of Acid-Gas Injection Schemes in Western Canada

Characteristic	Minimum	Maximum
Licensed H_2S (mol fraction)	0.05	0.97
Actual injected H_2S (mol fraction)	0.02	0.83
Actual injected CO_2 (mol fraction)	0.14	0.95
In-situ acid gas density (kg/m^3)	204.8	728.3
In-situ acid gas viscosity (mPa·s)	0.02	0.09
Maximum well head pressure (kPa)	3,750	19,000
Maximum injection rate (10^3 m^3/day)	4.2	900
Actual average injection rate (10^3 m^3/day)	1.0	500
Maximum injection volume (10^6 m^3)	6	1,876

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Performance of Acid Gas Injection Wells

One acid gas injection well in British Columbia failed in 2004 (tubing and production casing) not because of corrosion or H_2S imbrittlement, but because of ice formation in the annular fluid!

Injection of very cold acid gas (-10°C to -20°C) at 20-30 MMSCF/D for two years led to a substantial cooling of the upper well section and adjacent rock. Water in the 178 mm x 273 mm annulus froze and created sufficient mechanical force to damage the 178 mm casing and 114 mm tubing. The ice plug prevented acid gas leakage (85% H_2S).

- Well repaired and production casing cemented to surface
- Acid gas run through a line heater prior to injection

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Performance of Acid Gas Injection Operations

- No other problems with injection wells
- Two operations injecting acid gas into depleted oil reservoirs in pinnacle reefs have experienced over-pressuring and have been rescinded by EUB
- Three operations injecting acid gas into depleted gas reservoirs have experienced acid gas breakthrough at producing offset wells
- One operation injecting acid gas into a depleted oil reservoir has experienced acid gas breakthrough across a fault (assumed closed) in producing wells from another reservoir and has been rescinded

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Location of Current CO_2 EOR Operations in Canada

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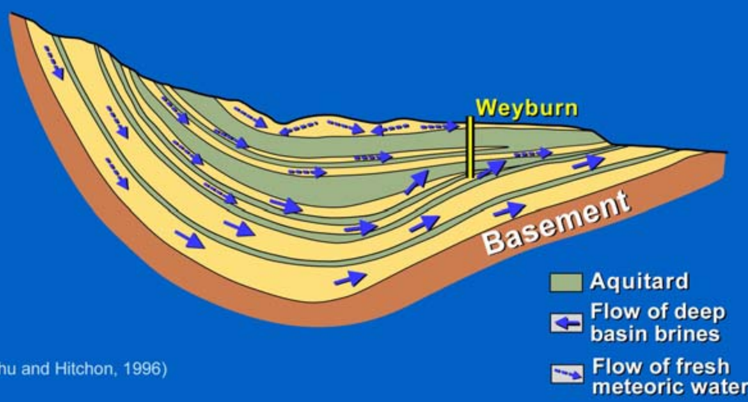
Flow Systems in the Williston Basin



(Bachu and Hitchon, 1996)

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Weyburn Oil Field History

- Discovered in 1954, containing ~1.4 Bbl oil
- Primary recovery to 1964
- Secondary recovery (water flooding) to 2000
- Horizontal wells since 1991
- Tertiary recovery (CO_2 flooding) since 2000

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Capture, Transportation and Injection

- Capture at Dakota Coal Gasification Plant in Beulah
- Transportation by pipeline 320 km to Weyburn
- Gas purity: 95% CO_2, with H_2S
- Injection rate: 5000 t/d (~95 mmccfd) at ~1500 m depth
- Injected in 18 inverted 9-spot patterns
- Expected duration: 25 years for 75 patterns

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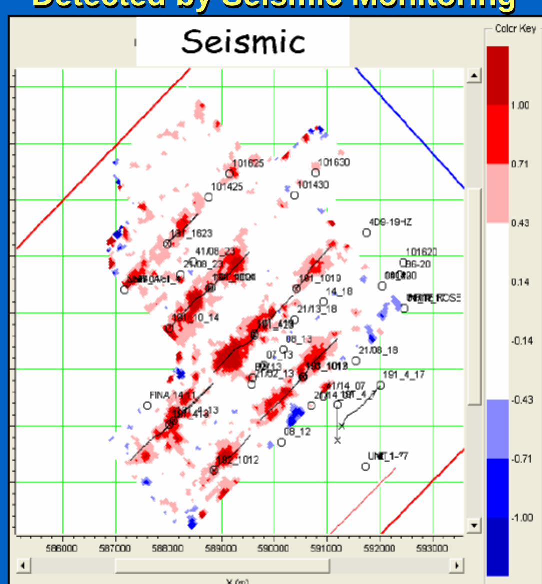
Spread of Injected CO_2 at Weyburn Detected by Seismic Monitoring



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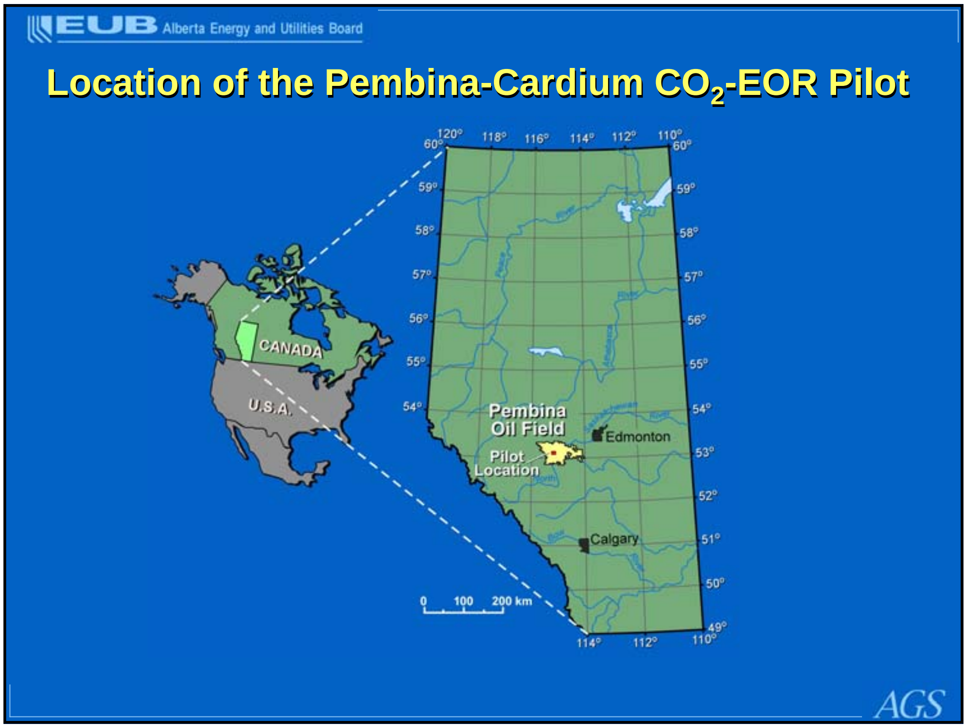
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Location of the Pembina-Cardium CO_2-EOR Pilot
CANADA
U.S.A.
Pembina Oil Field
Pilot Location
Edmonton
Calgary
0 100 200 km
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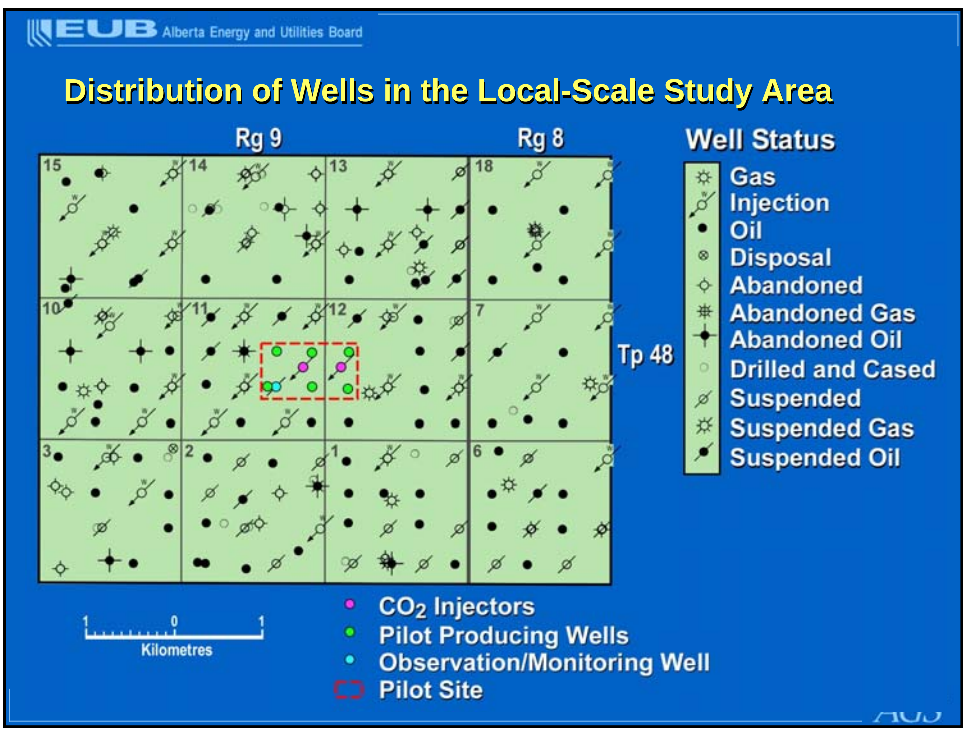
EUB Alberta Energy and Utilities Board
Distribution of Wells in the Local-Scale Study Area
Rg 9
Rg 8
Tp 48
Well Status
Gas
Injection
Oil
Disposal
Abandoned
Abandoned Gas
Abandoned Oil
Drilled and Cased
Suspended
Suspended Gas
Suspended Oil
CO_2 Injectors
Pilot Producing Wells
Observation/Monitoring Well
Pilot Site
Kilometres

EUB Alberta Energy and Utilities Board

Leakage Risk Rating of Wells in the Pembina Cardium Local-Scale Study Area

Well Type	Risk Rating		
	High	Medium	Low
Active		94	26
Suspended		38	1
Abandoned	3	2	3
Drilled and Abandoned			1
Miscellaneous			1
Total	***3***	***134***	***32***

AGS

EUB Alberta Energy and Utilities Board

Lessons Regarding Injection Wells

• Horizontal wells will likely be used for high injection rates in relatively thin injection units (aquifers, reservoirs)

•Regulatory requirements and control seem to be adequate

• Periodic checking of injection-well integrity is critical!

• Monitoring of injection and offset producing wells is essential!

• Proper selection and characterization of the disposal zone is fundamental!

• We don’t know about the long term effects of the injected acid gas on cements and casing in old existing wells

AGS

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However!

It is not the CO_2 injection wells that may/will pose a risk, they will be properly constructed and monitored, and, relatively speaking won't be too many.

It is the existing wells that will pose the greater risk!

Bachu and Watson – Possible Indicators for CO_2 Leakage along Wells, GHGT-8, 2006
Watson and Bachu - Factors Affecting or Indicating Potential Wellbore Leakage; SPE Paper 106817, 2007

AGS

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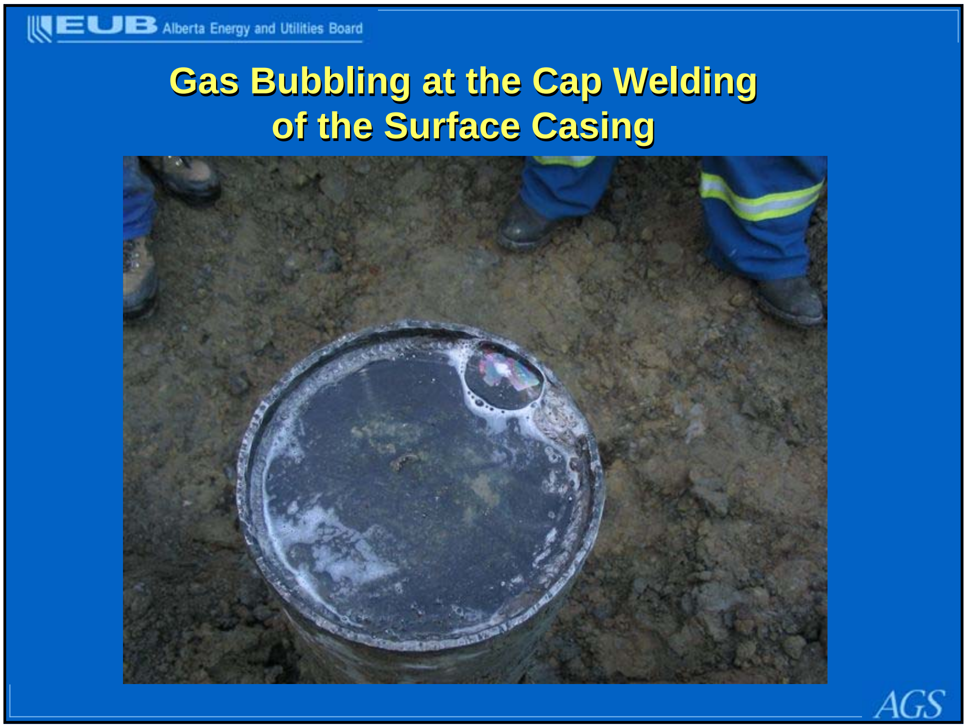
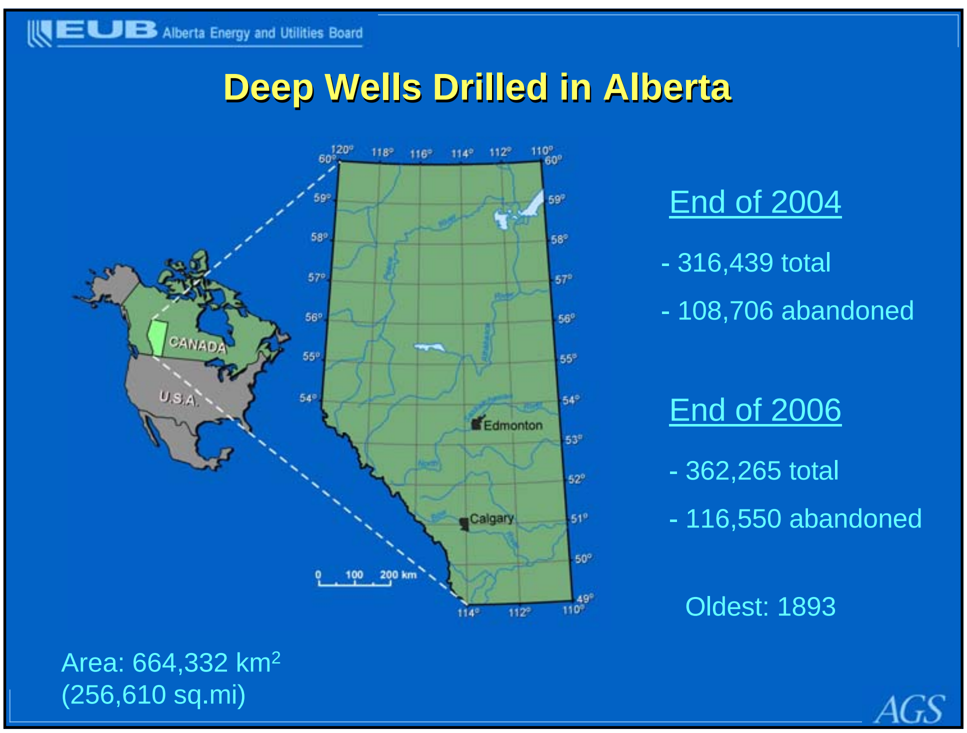
Abandoned Well Leaking Brine and Gas near Peace River, Alberta

AGS


EUB Alberta Energy and Utilities Board
Gas Bubbling at the Cap Welding
of the Surface Casing
AGS


EUB Alberta Energy and Utilities Board
Deep Wells Drilled in Alberta
CANADA
U.S.A.
Edmonton
Calgary
0 100 200 km
End of 2004
- 316,439 total
- 108,706 abandoned
End of 2006
- 362,265 total
- 116,550 abandoned
Oldest: 1893
Area: 664,332 km2
(256,610 sq.mi)
AGS

EUB Alberta Energy and Utilities Board

One Last Word

CO_2 Capture and Geological Sequestration (CCGS) is more than just Underground Injection Control (UIC) and it requires involvement and cooperation of state and federal regulators, on both sides: protection (Environment) and development (Resources)

AGS

CO_2 Capture Project

Wellbore Integrity Study

Charles Christopher
Walter Crow
BP Houston

CO_2 Capture Project

Questions

- What is the magnitude of the problem?
- How are problems detected?
- Remediation methods

CO$_2$ Capture Project

A Comprehensive Wellbore Integrity Program

- Analysis of current well stock
- Compilation of historical statistics on effects of CO2
- Autopsies of wells in contact with CO2
  - Logging analysis as well as sample recovery
- Laboratory analysis of recovered cement and tubulars
- Laboratory understanding of kinetics and mechanisms of attack
- Reactive transport simulation of CO2 attack
- Statistical evaluation of large numbers of wells

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CO$_2$ Capture Project

CO_2 Well Integrity Survey

Objective
- Project the effect of CO2 on the well barrier system and determine mitigation options

Methodology
- Use existing wells to sample and evaluate barrier conditions
- Analyze the samples
- Create simulation to project the future alteration

Status
- First field survey data/samples under evaluation
- Modeling has been progressing independent of well data. Model program details will follow sample analysis results

European Union | Norges forskningsråd | US Department of Energy

CO_2 Capture Project

CO_2 Well Integrity Survey

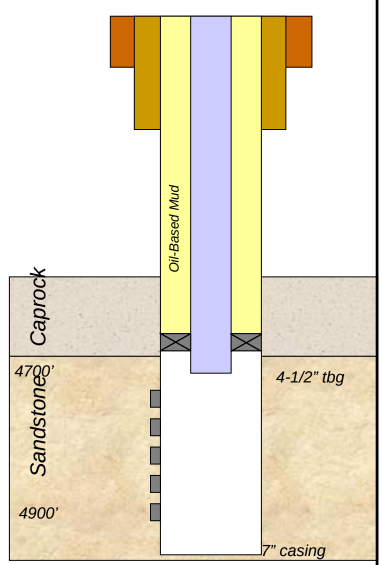
Obligation

- Results will be carefully evaluated
- Nothing will be hidden
- No conclusions/results will be released until they have been thoroughly evaluated

CO_2 Capture Project

Original Well

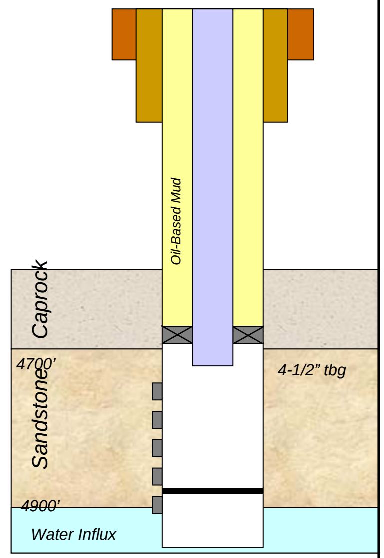
- Drilled & completed 1976 (deviated well)
- Sandstone formation
- Original test: 10 MMSCF/D (CO_2)
- Tubing change out in 1984 to increase dia. (prior to production)
- No significant corrosion
- Normally pressured reservoir ~0.4 psi/ft
- Water saturation ~20%



CO_2 Capture Project

Production

- Initial production 1984
- 1 BBL/MMSCF water production
- Water cut increase in 1997 from lowest zone
- Attempted water shut off - unsuccessful
- Continued production ~1 MMSCF/D CO_2
- Reservoir pressure less than 0.1 psi/ft



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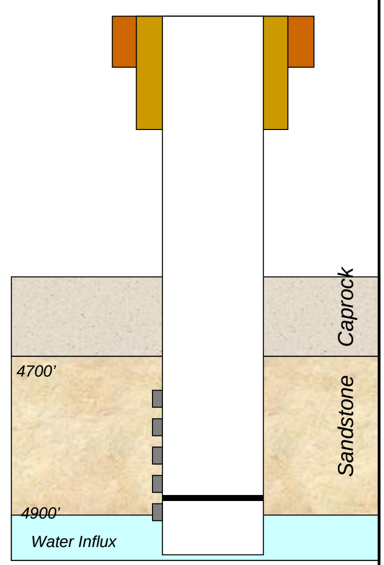
CO_2 Capture Project

Well Integrity Survey

- October 2006
- Rig removed tubing and packer
- Acoustic cement evaluation tools
- Casing caliper log
- Pulsed neutron log
- Fluid samples attempted
- Pressure drawdown tests in cement sheath
- Sidewall cores



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CO_2 Capture Project

Tubing in Good Shape After 22 Years

CO_2 Capture Project

Foundry Stencil Still Visible

CO_2 Capture Project

Logging Run

CO_2 Capture Project

Legend

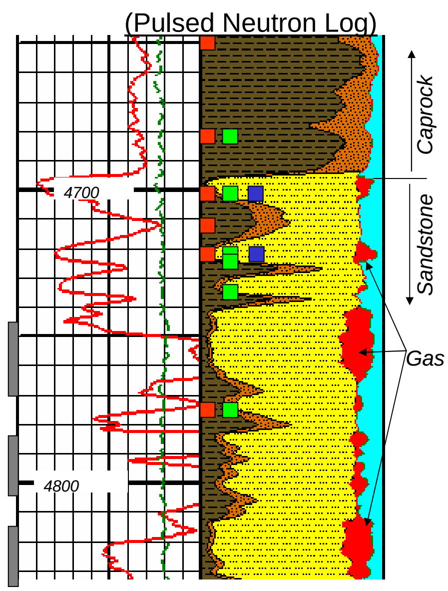
Cement core recovery (red)

Pressure test cement sheath (green)

Fluid / gas sample (blue)

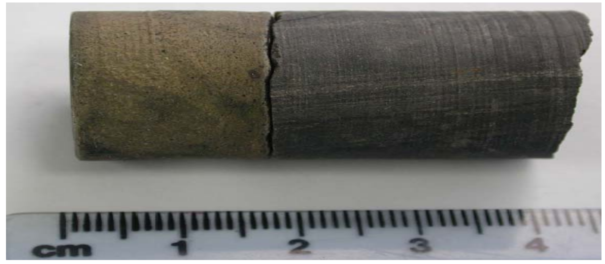
Recovery Summary

- *6 Cement cores*
- *6 Cement pressure tests*
- *2 Fluid samples*



CO_2 Capture Project

Cement / Caprock Shale



Recovered sidewall cores

Cement

CO_2 Capture Project

Data and Sample Analysis

- Solids Analysis / Cement Cores (Los Alamos)
  - Xray diffraction
  - Scanning Electron Microscope
- Fluid/gas analysis (SLB - Oilphase)
  - Gas-Water ratio
  - pH
  - Total dissolved solids
  - Elemental analysis
- Log Analysis (SLB)
  - Permeability measurement from drawdown tests
  - Cement evaluation (bonding / gas or fluid cut)
  - Casing corrosion

CO_2 Capture Project

Modeling / Simulation

- Reaction kinetics (lab and field may be different)
- Depiction of well condition
- History match of well condition
- Well forward simulation
- Engineering solutions for remediation, monitoring & surveillance

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CO_2 Capture Project

A Comprehensive Wellbore Integrity Program - Status

- **Analysis of current well stock – In Design**
- **Compilation of historical statistics on effects of CO2 – In Design**
- **Autopsies of wells in contact with CO2 – In Progress**
  - **Logging analysis as well as sample recovery**
- **Laboratory analysis of recovered cement and tubulars – In Progress**
- **Laboratory understanding of kinetics and mechanisms of attack - Continuing**
- **Reactive transport simulation of CO2 attack – In Design**
- **Statistical evaluation of large numbers of wells – In Progress**

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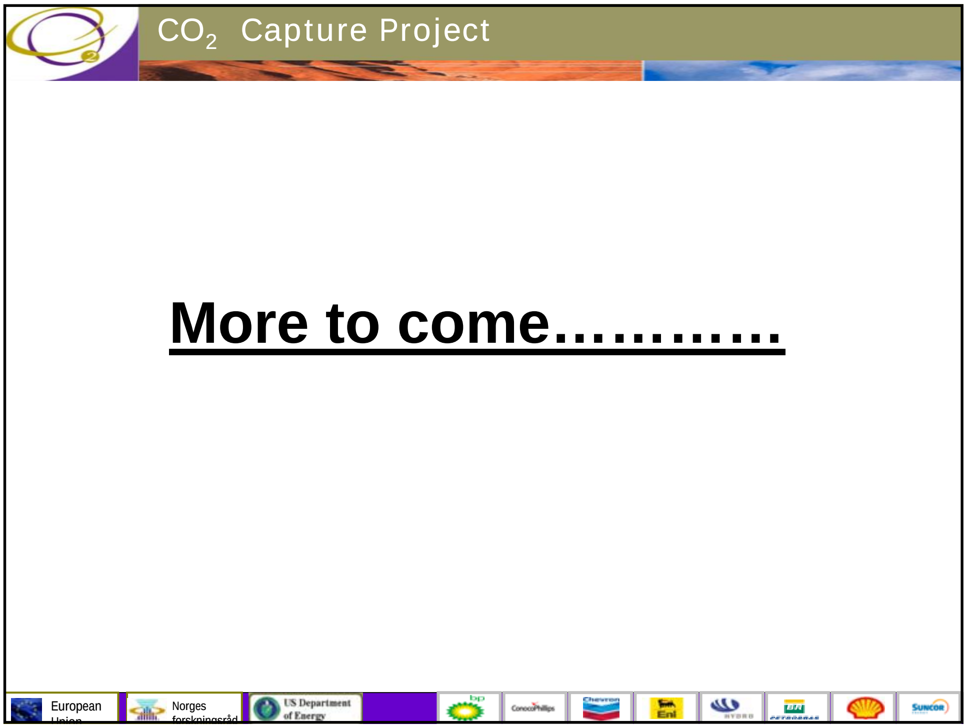

CO2 Capture Project
More to come………..
European Union
Norges forskningsråd
US Department of Energy

Geological Storage of Carbon Dioxide: Models and Parameters

Michael A. Celia (*Princeton University*)
Jan Nordbotten (*U. Bergen and Princeton U.*)
Sarah Gasda (*Princeton U.*)
Dmitri Kavetski (*Princeton U.*)
Stefan Bachu (*Alberta EUB*)

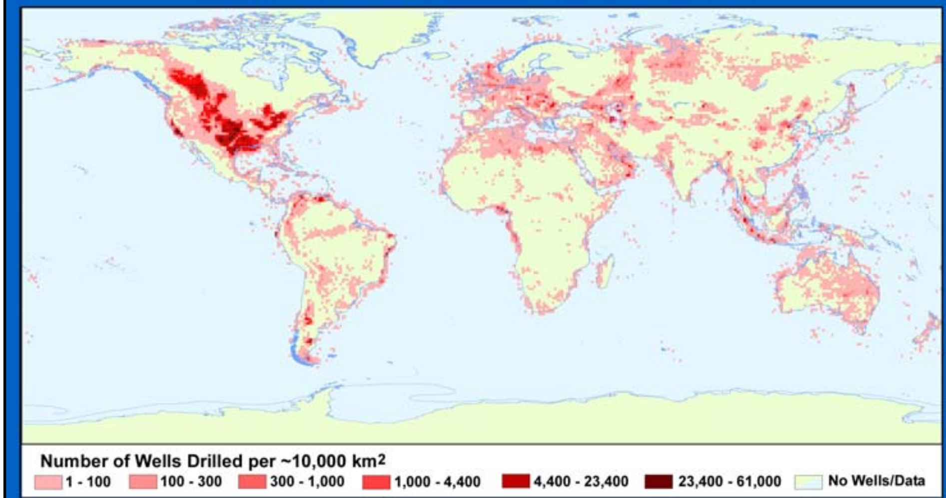
Princeton University

EUB

Three Questions

- How can (should) we model the system?
- What are the critical parameters?
- Can we identify these parameters?

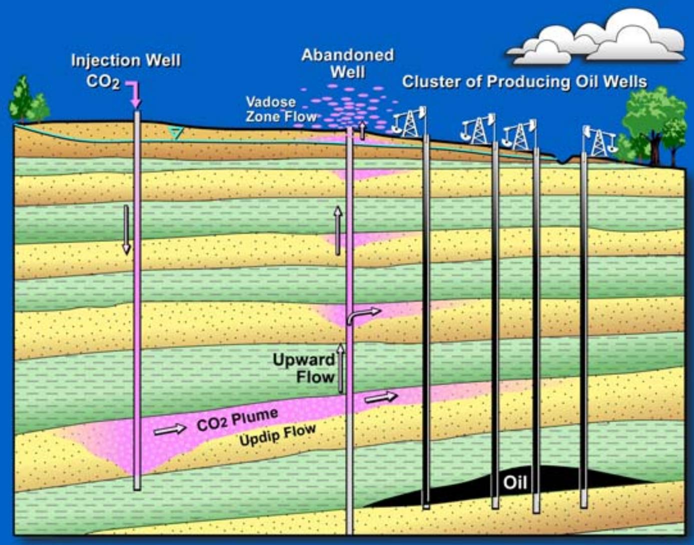
Worldwide Density of Oil and Gas Wells



End of 2004

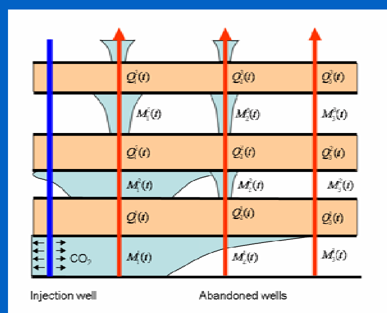
From IPCC SRCCS, 2005

Potential CO_2 Migration and Leakage Paths



Modeling Options

- Full 3-D numerical solutions
- Vertically-averaged equations in aquifers, coupled by leakage in the vertical direction (along wells and through the caprock).
- Semi-analytical solutions

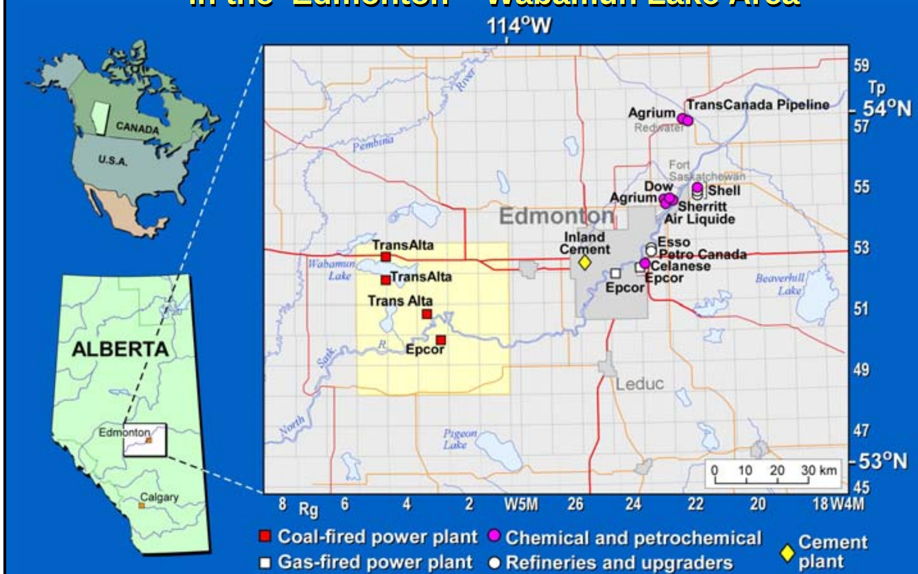


Two Important Properties:

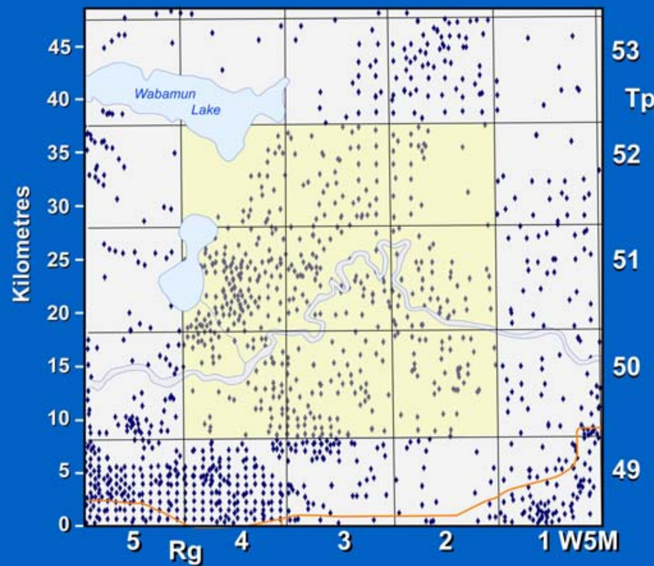
Density ratios: 0.25 to 0.75

Viscosity ratios: 5 to 40.

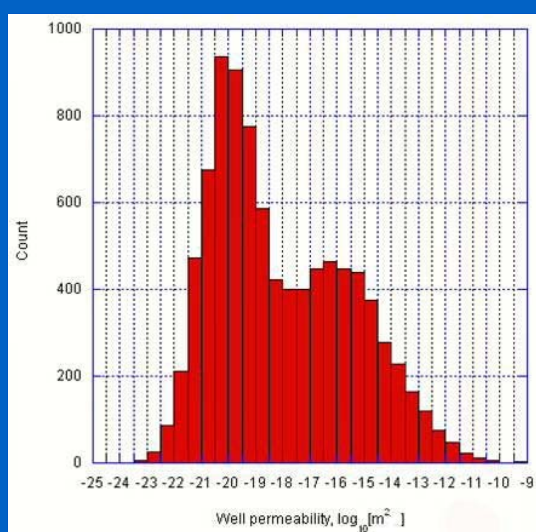
Location of Major CO_2 Sources in the Edmonton – Wabamun Lake Area

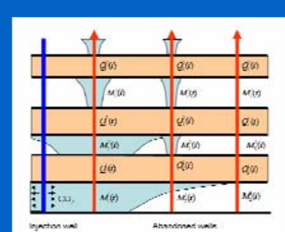


Distribution of Existing Wells in the Wabamun Lake Area



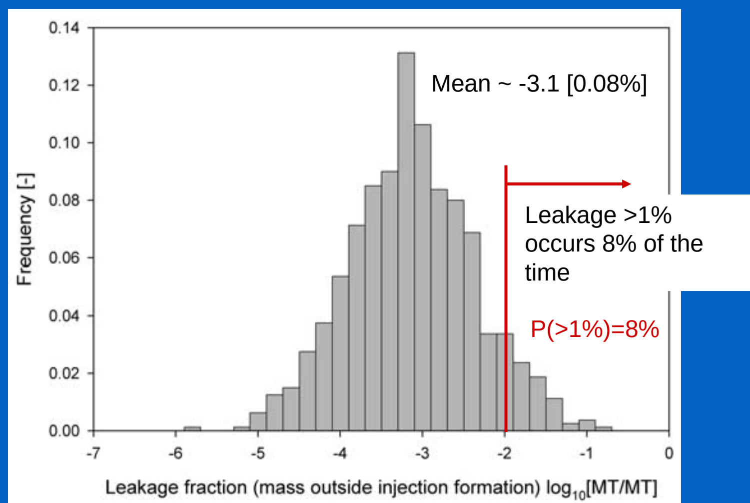
Probability Distribution for Well Permeabilities



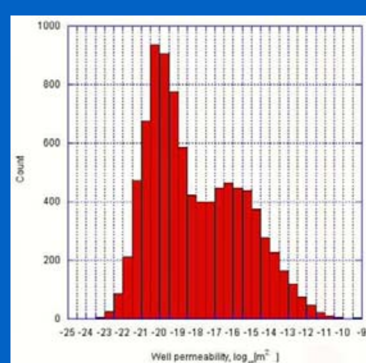


Leakage statistics after 50 years

4:1 Gaussian mixture (10^{-20} m^2: 10^{-16} m^2)



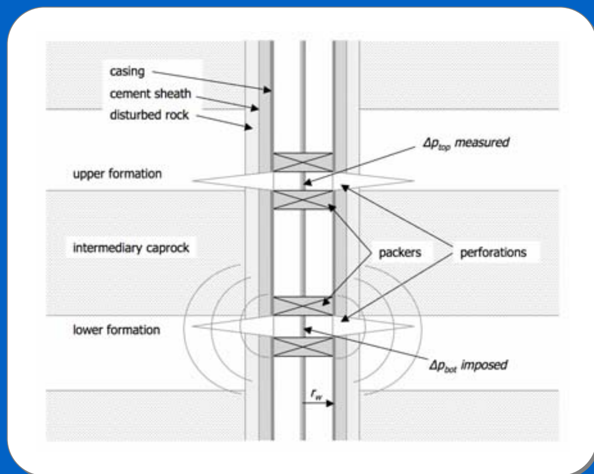
How can we identify this distribution?



We need a targeted field campaign:

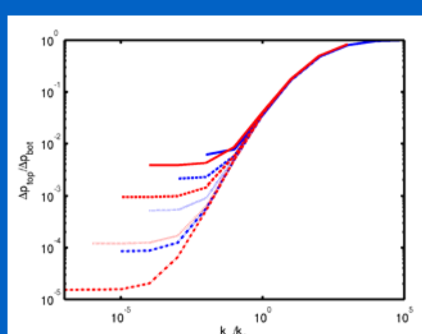
- Re-enter existing (abandoned) wells.
- Use statistical mix of wells (location, depth, age, …).
- Simple pressure tests to identify K_{eff} in well segments.

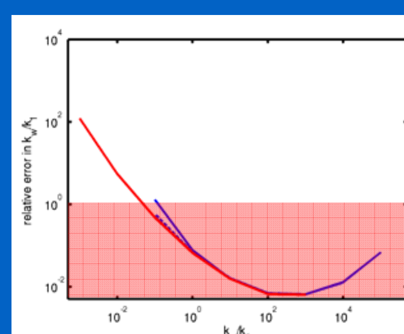
Pressure Test to Determine K_{well}



- Pressurize lower formation and measure pressure signal above.
- Assume we can estimate the permeability in the formation and the caprock.
- Relate k_{well} to the pressure response.

Can we detect k_{well} from a pressure signal?



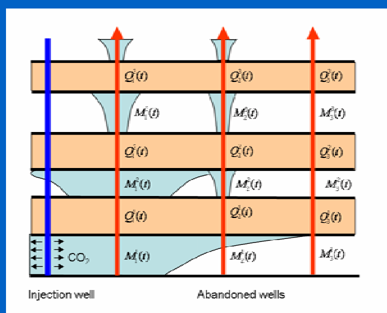


- Simulated response curves have characteristic shape
- Error in instrument accuracy leads to error in estimating k_{well}
- Fracture pressures limit strength of the pressure signal

Critically leaky wells are detectable

Broader Numerical Framework

- Vertically-averaged equations in aquifers, coupled by leakage in the vertical direction (along wells and through the caprock).
- Numerical solution for injection and migration through aquifers.
- Embedded analytical solutions for flow through wells.



Non-uniform geology:

Sloping formations

Structural features

Recent Publications

Nordbotten, J.M. and M.A. Celia, "Similarity Solutions for Fluid Injection into Confined Aquifers", *Journal of Fluid Mechanics*, *561*, 307-327, 2006.

Nordbotten, J.M. and M.A. Celia, "Interface Upconing around an Abandoned Well", *Water Resources Research*, *42*, (doi:10.1029/2005WR004738), 2006.

Bachu. S. and M.A. Celia, "Assessing the Potential for CO2 Leakage, Particularly through Wells, from CO2 Storage Sites", to appear, *The Science and Technology of Carbon Sequestration*, AGU Monograph, 2007.

Celia, M.A., S. Bachu, J.M. Nordbotten, D. Kavetski, and S. Gasda, "A Risk Assessment Modeling Tool to Quantify Leakage Potential through Wells in Mature Sedimentary Basins", *Proc. 8th Int. Conf. on Greenhouse Gas Control Technologies*, Trondheim, Norway, 2006.

Li, L., C.A. Peters, and M.A. Celia, "Upscaling Geochemical Reaction Rates using Pore-scale Network Models", *Advances in Water Resources*, *29*(9), 1351-1370, 2006.

Nordbotten, J., M.A. Celia, S. Bachu, and H.K. Dahle, "Analytical Solution for CO2 Leakage between Two Aquifers through an Abandoned Well", *Environmental Science and Technology*, *39*(2), 602-611, 2005.

Nordbotten, J., M.A. Celia, and S. Bachu, "Injection and Storage of CO2 in Deep Saline Aquifers: Analytical Solution for CO2 Plume Evolution during Injection", *Transport in Porous Media*, *58*(3), 339-360, 2005.

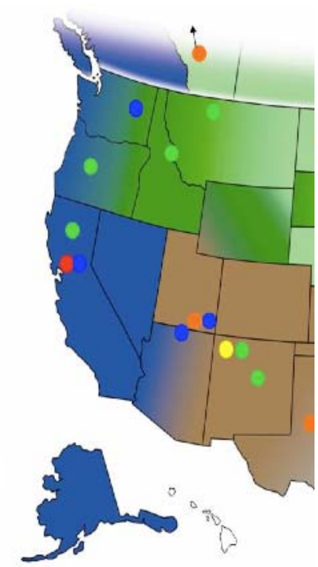
Gasda, S.E. and M.A. Celia, "Upscaling Relative Permeabilities in a Structured Porous Medium", *Advances in Water Resources*, *28*(5), 493-506, 2005.

Scherer, G.W., M.A. Celia, J.H. Prevost, S. Bachu, R. Bruant, A. Duguid, R. Fuller, S.E. Gasda, M. Radonjic, and W. Vichit-Vadakan, "Leakage of CO2 through Abandoned Wells: Role of Corrosion of Cement", in *The CO2 Capture and Storage Project (CCP), Volume II*, D.C. Thomas and S.M. Benson (Eds.), 823-844, 2005.

Nordbotten, J.M., M.A. Celia, and S. Bachu, "Analytical Solutions for Leakage Rates through Abandoned Wells", *Water Resources Research*, Vol. 40, W04204, doi:10.1029/2003WR002997, 2004.

Gasda, S.E., S. Bachu, and M.A. Celia, "Spatial Characterization of the Location of Potentially Leaky Wells Penetrating aMature Sedimentary Basins", *Environmental Geology*, *46* (6-7), 707-720, 2004.


Thank You!



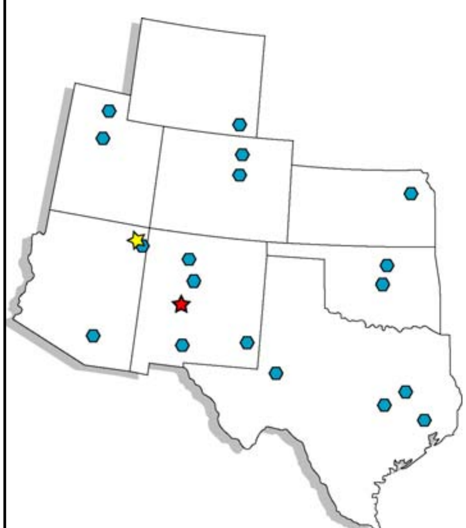
Selecting Sites for Geological Sequestration: Wellbore Integrity and Other Criteria

EPA CO_2 Geosequestration Workshop on Well Construction and Mechanical Integrity Testing

March 14, 2007

Jason Heath and Brian McPherson
Southwest Regional Partnership on Carbon Sequestration

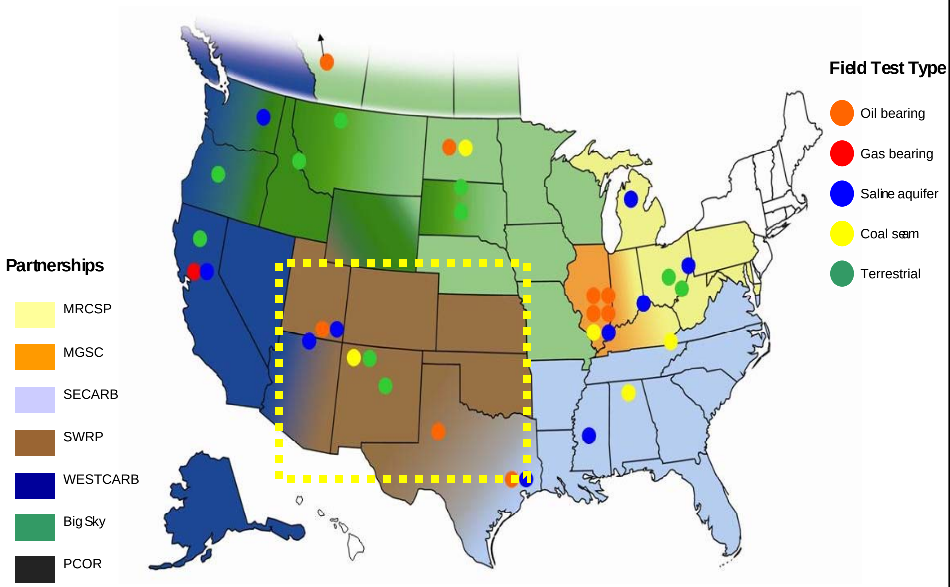
The Southwest Carbon Sequestration Partnership



In all partner states:
- major universities
- geologic survey
- other state agencies

as well as
- Western Governors Association
- five major utilities
- seven energy companies
- three federal agencies
- the Navajo Nation
- many other critical partners

Southwest Portfolio



Southwest CO_2 Sources

- electrical power plants
- cement & other plants
- urban centers
- non-point sources

Total regional point source emissions ~10^8 t/yr.

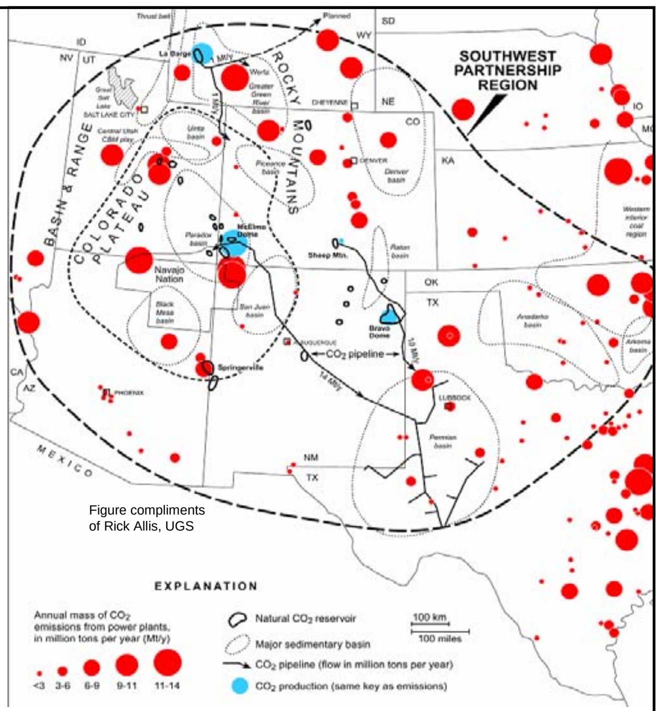
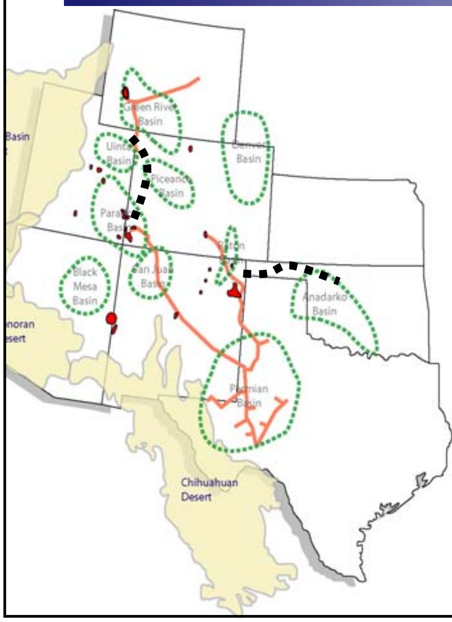


Figure compliments of Rick Allis, UGS

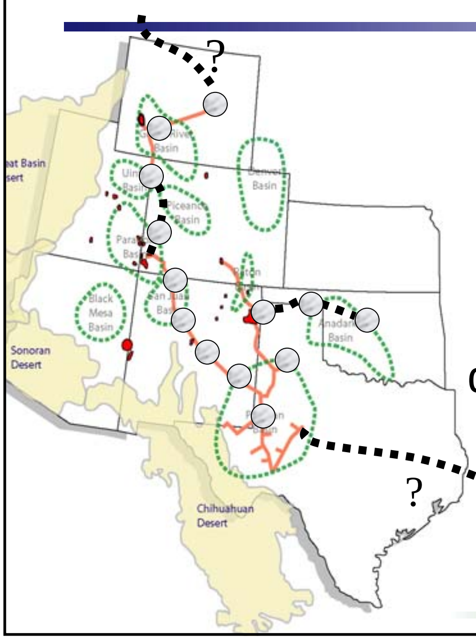
Key Aspect for Site Selection: Identify Best Sink for the Source



For example, in the Southwest project, our first tasks were:

- Characterized region's sources and sinks
- Identified best options by tying sources to sinks
- Outcome: In Southwest, "first opportunities" lie along existing CO_2 pipelines

Regional Characterization → Pilot Demos → Full-Scale Deployment



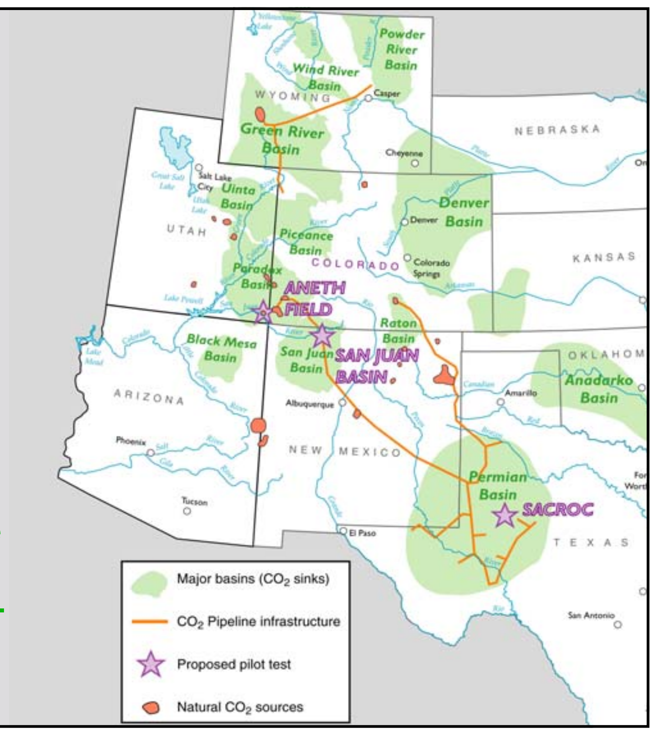
Site Selection Concept:
"String of Pearls"

Ongoing pilot demonstrations will test short-term strategy: ***sequester along pipelines***

What is a good approach for selecting a site for commercial-scale geologic sequestration?

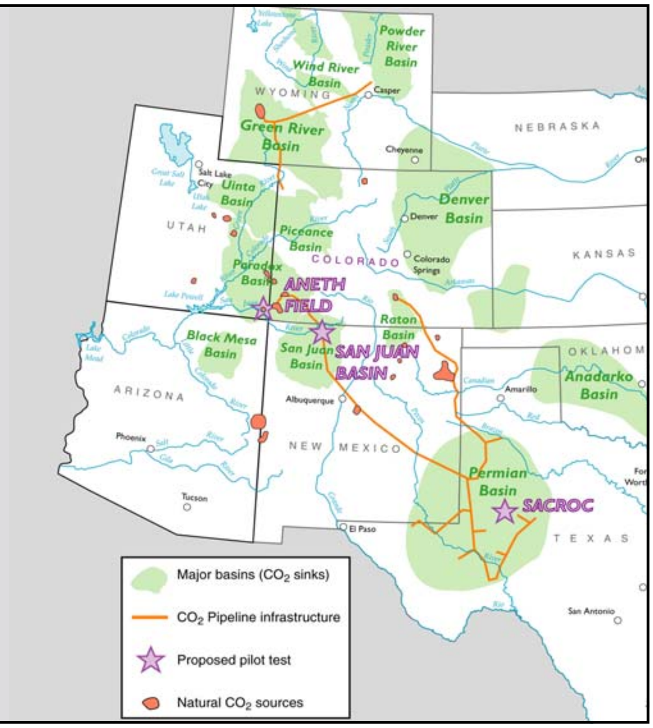
Sequestration Site Selection Depends on some important practical issues:

- site ownership
- details of liability for site
- details of regulatory requirements associated with site
- capability for long-term monitoring at the site



Sequestration Site Selection Depends on some critical technical issues:

- proximity to high-capacity storage reservoirs
- proximity to existing pipelines
- proximity to transmission lines or railroads (e.g., for right-of-way)
- low-risk geology, e.g., deep, thick seals, no faults, etc.



Another criterion:

- **Well Integrity**

Example: Well integrity analysis at the SWP Phase II test site, the Aneth Unit in southern Utah

Greater Aneth Oil Field: History

Shapefiles from Utah AGRC and the Utah Geologic Survey

Greater Aneth Oil Field

- Long history of oil field operations since 1956
- Secondary recovery by injection of produced water and "make-up" water from the alluvial aquifer
- Kimball (1992) hypothesized that oil field operations have caused high salinity in the Navajo Aquifer
- High salinity in the aquifer is a major concern
- However, high salinity was documented in some wells prior to oil company operations in the field (Spangler et al., 1996)

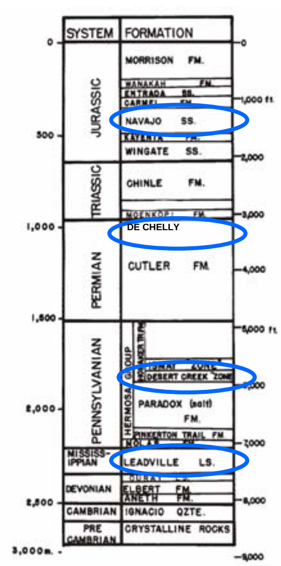
Aneth Unit Oil Field: The New Pilot

Shapefiles from Utah AGRC and the Utah Geologic Survey

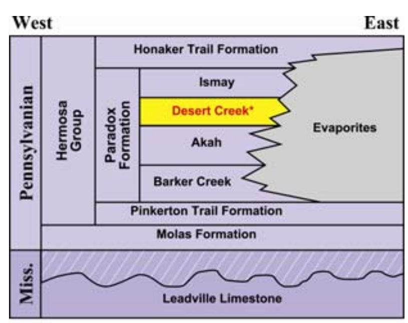
Aneth Unit will be flooded with CO_2 this June

- Concern: will CO_2 leak from the target reservoir (e.g., to adjacent reservoirs) and how may this be monitored effectively?
- Easiest way to address this question: measure salinity, which may be a tracer for leaky wells in the system
- Impacts of leakage: monitor groundwater chemistry

Stratigraphy



The USGS (Spangler et al., 1996) found a correlation between the Cutler Formation water and the high salinity in the Navajo Sandstone



*Reservoir Unit at Greater Aneth field

(Peterson, 1992; Chidsey and Wakefield, 2006)

Well Construction: Potential Effects on Pilot Test

EPA's (Jim Walker) work on well integrity
USEPA Region IX Ground Water Office

Quotes are from a recent memorandum from EPA (Walker)

Well construction details from:

- Texaco Exploration & Production, Inc.
- EPA Region IX Navajo injection well database
- Bureau of Land Management well files
- Utah Oil and Gas Information Center website
- USGS Report 96-4155 (Spangler et al., 1996)

Well Construction: Potential Effects on Pilot Test

Definition of construction deficiencies:

Some wells possess "insufficient casing and cementing to isolate the Navajo aquifer from the Upper Paleozoic saline aquifer, such as the De Chelly sandstone in the Cutler formation…"

Completion information:

"Many of the early wells drilled in the Aneth Field were completed with insufficient surface or intermediate casing to entirely cover the Navajo aquifer, which includes the Entrada, Navajo, and Wingate Sandstone."

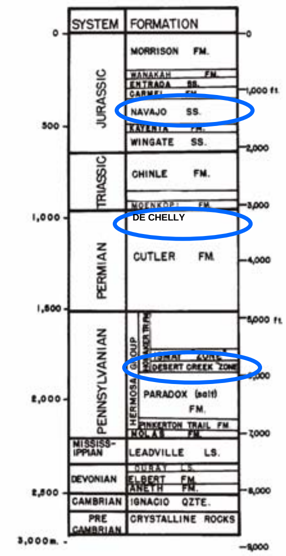
"…the long string casing/wellbore annulus was usually filled only with sufficient cement to cover the Paradox formation… No cement was placed in the annulus of those wells at the Upper Paleozoic and Navajo aquifer intervals."

Well Construction: Potential Effects on Pilot Test

Potential impact of construction deficiencies:

Construction deficiencies could "provide a potential pathway for fluid migration between aquifers where there exists a differential in hydraulic head between aquifers."

"Because the De Chelly aquifer hydraulic head exceeds the Navajo aquifer head in much of the Aneth Field area, saline water from the De Chelly Aquifer could potentially migrate upward into the Navajo aquifer through the partially cemented wellbores."



Well Construction: Potential Effects on Pilot Test

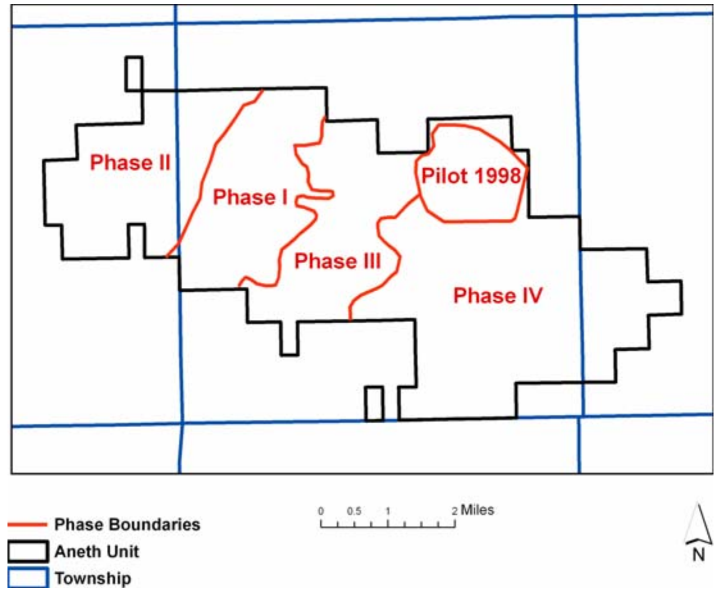
Analysis of well construction deficiencies used the following:

- Calculation of the top of the cement
- Temperature logs or cement bond logs
- Information on the depth of surface or intermediate casing

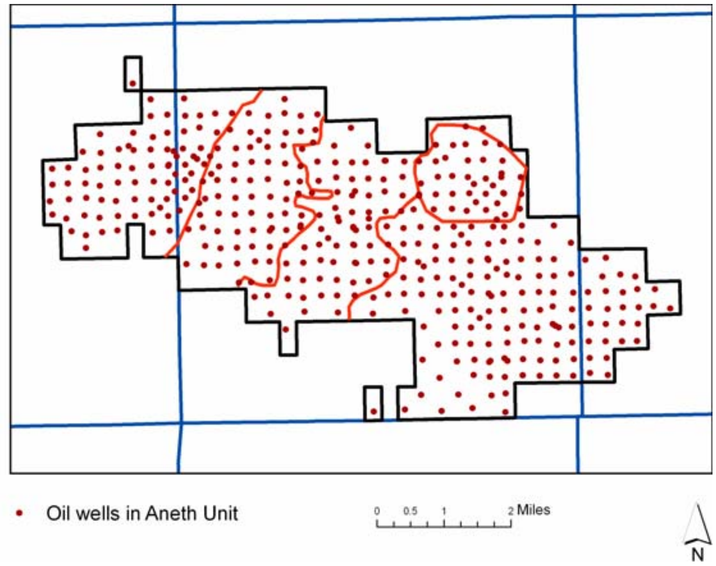
These were used to look for potential communication from the Upper Paleozoic to the Navajo Sandstone.

Now let's visually inspect the data. Note that the information provided is for injection wells. EPA (Walker) is currently compiling well construction information for production wells and abandoned wells.

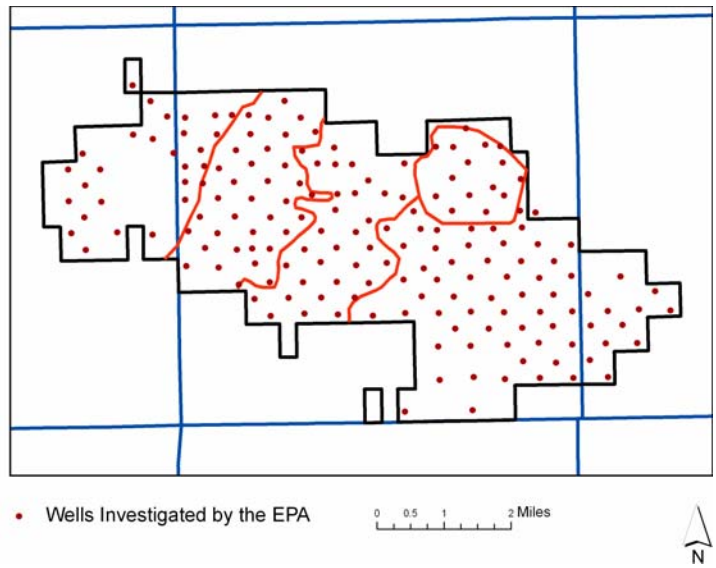
Well Construction: Potential Effects on Pilot Test



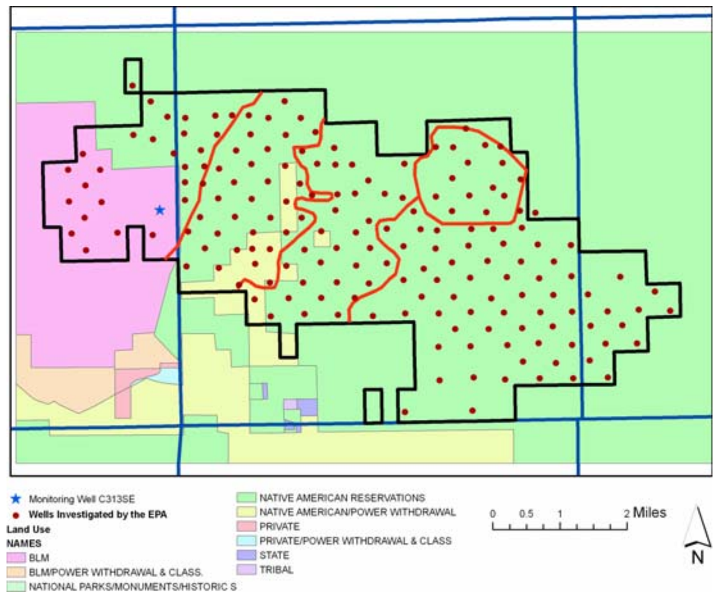
Well Construction: Potential Effects on Pilot Test



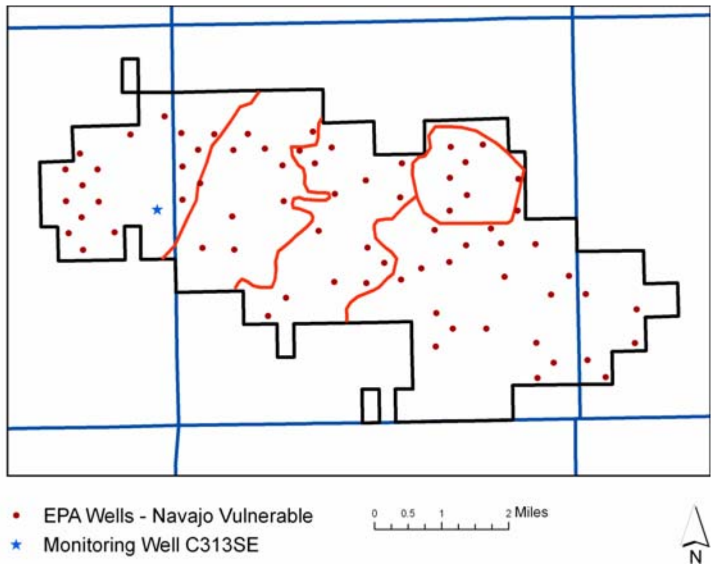
Well Construction: Potential Effects on Pilot Test



Well Construction: Potential Effects on Pilot Test



Well Construction: Potential Effects on Pilot Test



Well Construction: Potential Effects on Pilot Test

How "risky" for CO_2 migration are the wells that are vulnerable to communication between the Upper Paleozoic Aquifer and the Navajo Aquifer?

We think that the integrity and reactivity of the cement at/above/below the target reservoir (e.g., at the Paradox Formation in this case) is very important.

If CO_2 can leak through these "vulnerable" cement zones (e.g., the Paradox Formation here), then superjacent groundwater reservoirs may be impacted. ***Well cements must be sampled and characterized, and the conditions recorded and implemented in associated reservoir models for quantifying potential risk.***

General Summary

Sequestration site selection depends on both practical and technical issues:

- site ownership
- details of liability for site
- regulatory requirements associated with site
- capability for long-term monitoring at the site
- proximity to high-capacity storage reservoirs
- proximity to existing pipelines
- proximity to transmission lines or railroads (e.g., for right-of-way)
- low-risk geology, e.g., deep, thick seals, no faults, etc.
- well integrity screening:
  - How "risky" is a system that is vulnerable to interformational migration of fluids above an oil reservoir that is cased and cemented?

Mechanical Integrity Testing

Notes about mechanical integrity testing:

The current portfolio of Regional Partnership pilot tests are small enough, in terms of injection rates, that special mechanical integrity testing is not necessary. Only "routine" mechanical testing is being done for these tests.

For Phase III, which will involve injection of over 1,000,000 tons/year in relatively few wells, plans are in place to include in situ tiltmeters and strain gauges (San Juan Basin). Water injection pressure transient tests will be carried out prior to CO_2 injection to characterize state-of-stress and response.

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API Activity on CO_2 Well Construction-Integrity and CO_2 Capture and Geo-sequestration

Co-authors: R. Sweatman, S. Crookshank. M. Parker, S. Meadows, K. Ritter, B. Bellinger

Presented at
EPA CO_2 Geosequestration Workshop on Well Construction and Mechanical Integrity Testing
Albuquerque, New Mexico
14 March, 2007
Organized by:

energy API

API History and Mission

- 1919: API founded as national trade association for US oil and gas industry
- API is only US trade association representing all segments of oil and gas industry
- API represents industry before government, develops standards, and conducts research
- Certification Program for ISO 14001 on Environmental Management System

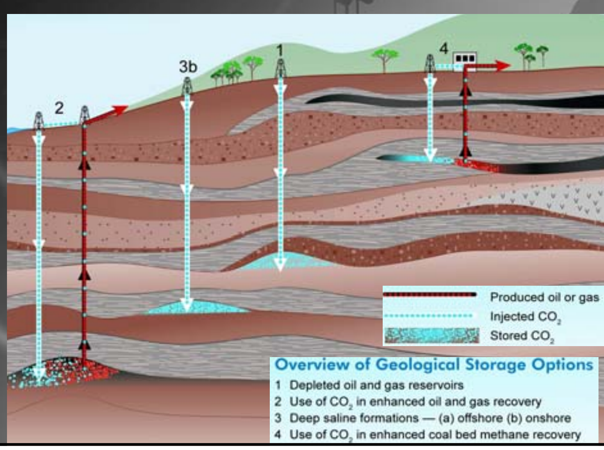
API Standards Process

- **The Process is**
  - Open
  - Transparent
  - Consensus-based

API is an American National Standards Institute (ANSI) accredited Standards Developing Organization

CCS Work Group - Mike Parker, ExxonMobil

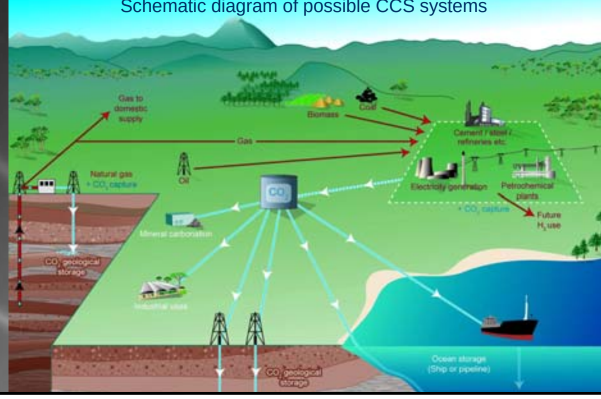
- Upstream Environmental (Water) & Production Experts
- Studying CO_2 Enhanced Oil Recovery Practices
- Working on a Report of Industry Experiences



Guidelines for Emission Reductions from CCS Projects

- **Frede Cappelen, Statoil**
- Joint API/IPIECA Project
- GHG Inventory Experts and CCS Experts
- May, 2007

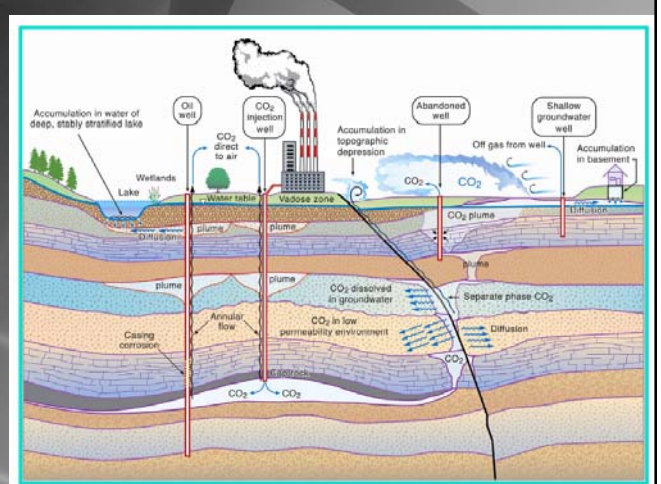
Schematic diagram of possible CCS systems



API/IPIECA CCS Project Emission Reductions

Common issues

- Boundary
- Baseline
- Additionality
- Methodology
- Monitoring

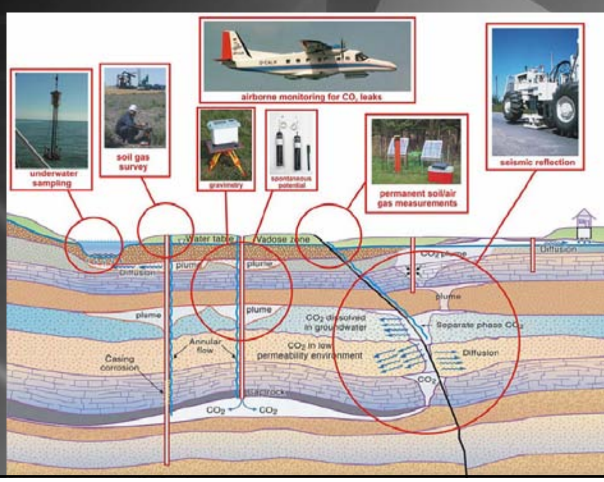


API/IPIECA Project Guidance Objectives

- **Provide guidelines on identifying, assessing, and developing candidate projects that would lead to credible emission reductions**
- **Develop a framework for assessing emission reductions associated with specific project "families", including references to relevant methodologies or guidance**
- **Requires the application of oil industry expertise**
- **Guidance to be regime neutral**

Example Monitoring Techniques

- Tailored to site specific characteristics
- Provide data to update modeling & risk assessment



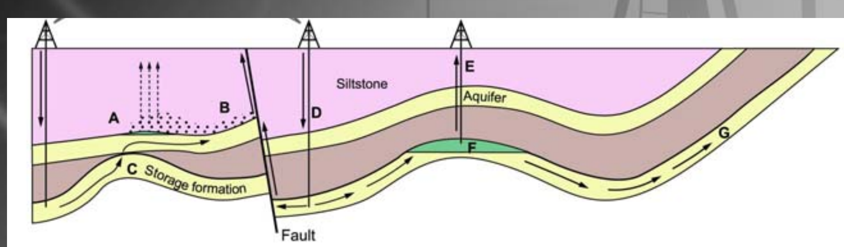
API RP 90 Committee - Phil Smith, Shell

Annular Casing Pressure Management for Offshore Wells

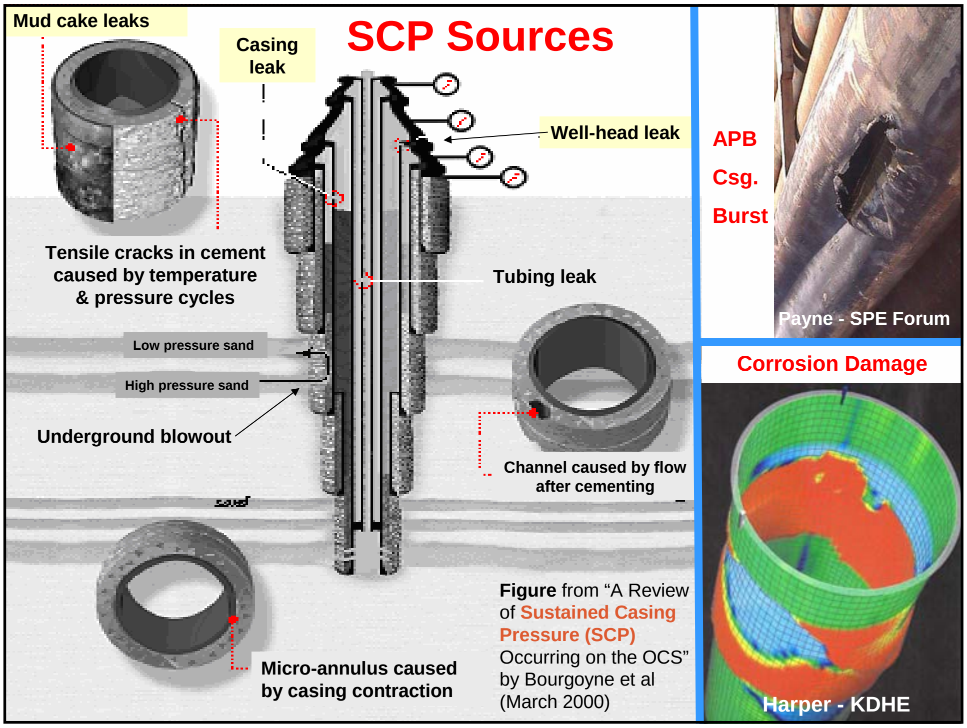
- **Well Planning & Design (refers to API RP-65 for barriers)**
- **Pressure Containment Design Considerations**
- **Maximum Allowable Wellhead Operating Pressure**
- **Detection and Monitoring of SCP and TCP**
- **Diagnostic Testing**
  - **Determines Severity & Need for Remediation**
  - **SCP Pathways & Source Zones (more in RP 65-3)**
- **Well Barriers and Barrier Elements**
- **Casing Integrity Pressure Testing**
- **Record Keeping**
- **Risk Analysis Considerations**

RP 65 Task Group - Ron Sweatman, Halliburton

- Drilling, Production and Other Experts such as Regulators, Academia
- Studying Well Casing Pressure Prevention and Remediation Practices
- Recommended Practices intended for US Federal Regulations
- RP 65-2 (relevant for preventing CO_2 leaks during well construction)
  - Pressure Barrier and other Related Well Construction Practices
  - Passed letter ballot Feb'07 with comments to resolve
- RP 65-3 (includes prevention and remediation of CO_2 leaks)
  - Pressure Barrier Practices for Well Injection, Production and Abandonment
  - Started last year and expect publication in late 2008 or 2009



Potential Escape Mechanisms



RP 65-3 Scope and Objective

Title: **"Practices to Prevent or Remediate Annular Casing Pressure"**

Scope & Objective:

Communicate proven practices to prevent, detect, diagnose, and remediate annular casing pressure (ACP) during well construction, production, injection, & abandonment:

- **Sustained Casing Pressure (SCP) by formation or injected fluids (hydrocarbons, CO_2, H_2S, H_2O, brine, etc.)**
- **Thermal induced ACP (TIACP) caused by trapped fluid pressure inside or near the wellbore**

Include other practices that may:

a) Positively or negatively affect pressure barriers

b) Help avoid or vent TIACP

c) Increase or decrease the occurrence of SCP and TIACP

RP 65-3 Draft Outline

Preventive Practices for Sustained Well Integrity

- Well Planning & Design
  - Avoiding & Venting Annular Pressure Traps
  - Pressure Barrier Selection & Design
  - Corrosion Prevention Methods to Maintain Integrity
- Detection & Diagnostics During Well Construction
  - Find & Record SCP Source Zones
  - Unexpected Annular Pressure Traps (low TOC, etc.)
- Mechanical Barriers (sealing devices & tubulars)
- Cementing Barriers (primary & secondary applications)
- Formation Barriers Near the Wellbore
  - Unplanned Casing Seats Across Weak Zones
  - Unexpected Pore Pressures Higher Than Shoe Tests
  - Borehole Integrity Strengthening Methods
- Chemical Sealant Barriers
  - SCP Source Zone Permeability Barriers
  - Annular Chemical Packers

Preventive Practices (cont'd)

- Well Integrity Verification Evaluation and Testing
  - Types of Tests: Casing & Shoe, Liner Lap, Packer, etc.
  - Positive vs. Negative Pressure Tests
  - Casing Pressure Tests Just After Cementing
  - Cement Evaluation Logs (Refer to API 10TR1)

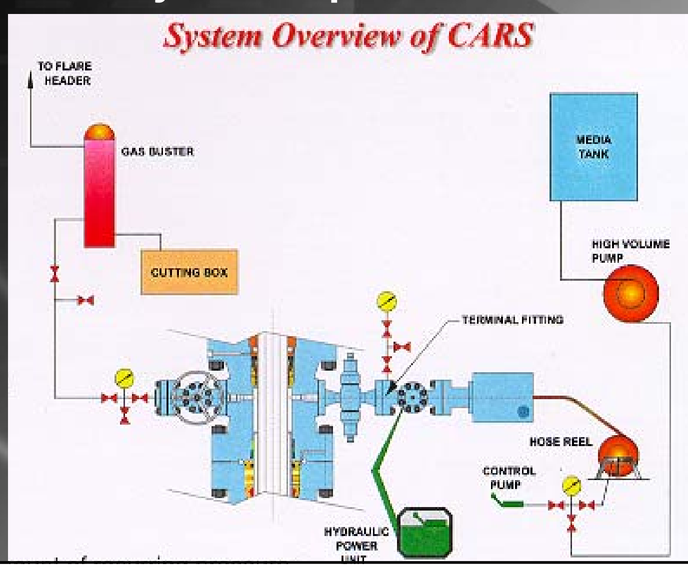
Remedial Well Integrity Practices

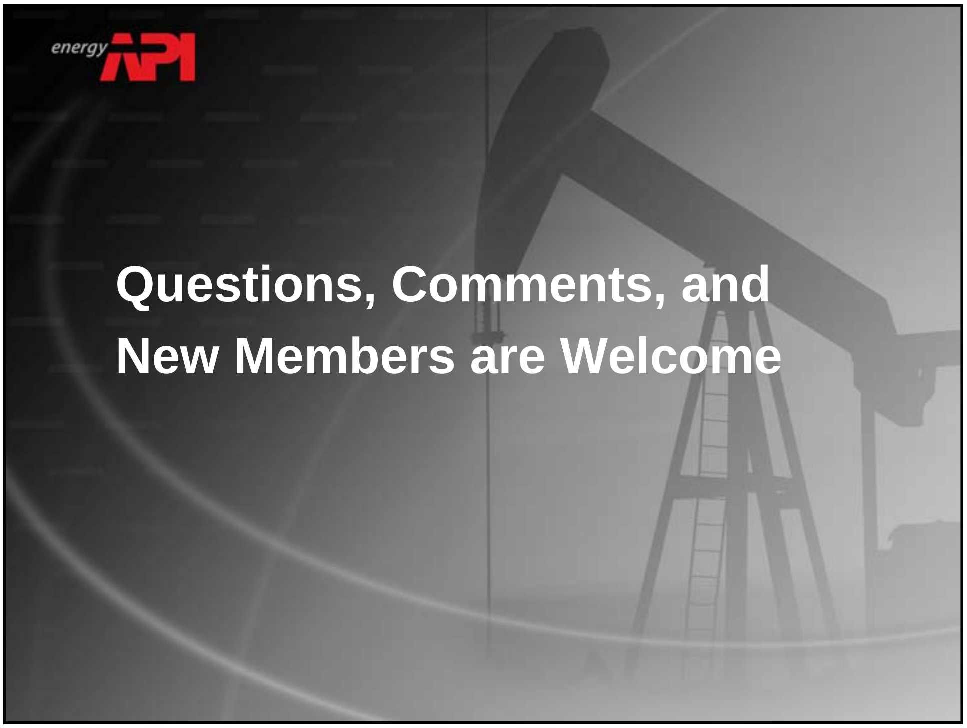
- ACP Detection & Diagnostics (Expand RP 90 Sections)
  - Logging Methods to Identify SCP Flow Paths
  - Casing/Liner Caliper & Inspection Logs
  - Gauge Ring Tests
  - Straddle Packer Pressure Tests
  - Downhole Cameras
  - Pressure & Temperature Monitoring by Permanent Downhole Sensors
  - Others (Preventive Practices above)
- Well Integrity Monitoring After Abandonment
- Annular SCP Flow Path Sealing Methods and Materials
- Rock Barriers (Sealing Methods for Permeability, Fissures, Fractures, etc.)
- Cementing Barriers (Squeeze & Plug Cementing)
- Casing/Liner Pipe Repair Methods and Materials

RP 65-3 Appendices:

- Background: API activity on SCP and TIACP
- Case histories, studies & statistics
- Lessons Learned
- Underground storage history: Acid gas, CO_2, natural gas, brines, etc.
- CO_2 injection well applications: miscible vs. immiscible pressure for EOR, EGR, ECBM, etc.
- References
- Definitions
- Etc.

RP 65 Study - Example of Remediation

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Questions, Comments, and
New Members are Welcome

UIC Program Class I and II EPA Construction and MIT Requirements

EPA Region 6
Brian Graves
UIC Land Ban Coordinator
(214) 665-7193
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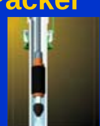
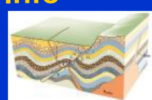
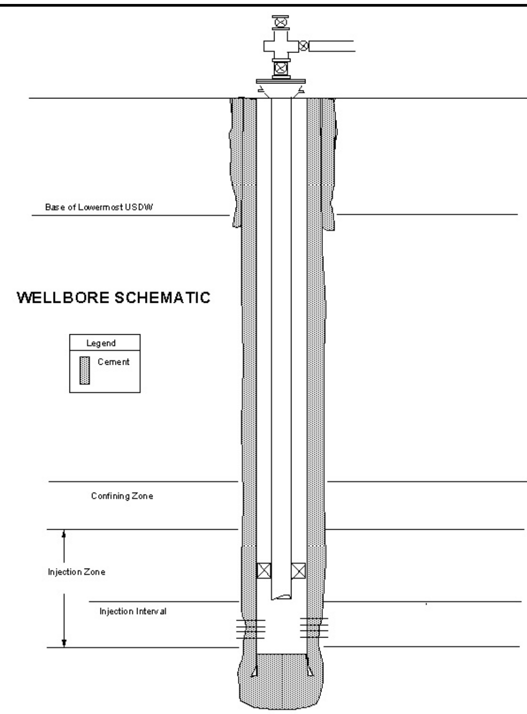
Federal Requirements for Construction (1)

	Class I Nonhazardous	New Class II
Casing and Cement 	• prevent fluid movement into USDWs • designed for well's life expectancy	• prevent fluid movement into USDWs • designed for well's life expectancy
Packer 	• required unless a fluid seal is approved • designed for expected service	• not required
Well Materials and Cementing 	<u>Factors to Consider</u> • injection pressure, fluid, and rate • temperature • well depth • annular pressure	<u>Factors to Consider</u> • internal, external, and injection pressure • axial loading • well and USDW depth • formation fluid and lithology

Federal Requirements for Construction (2)

	Class I Nonhazardous	New Class II
Logs and Tests 	• deviation checks • other appropriate logs and tests i.e., SP, resistivity, caliper, CBL, temperature, porosity, GR	• deviation checks • other appropriate logs and tests i.e., SP, resistivity, caliper, CBL, temperature, porosity, GR
Injection Formation Info 	• pressure and temperature • fracture pressure • fluid properties • matrix properties	• pressure • estimated fracture pressure • injection zone properties



Federal Requirements for Mechanical Integrity Testing (MIT)

	Class I Nonhazardous	New Class II
MIT Part 1 (internal) 	Initial pressure test then 1) monitor annulus pressure or 2) pressure test every 5 years	Initial pressure test then 1) monitor annulus pressure or 2) pressure test every 5 years
MIT Part 2 (external) 	• temperature, noise or other approved log every 5 years	• temperature, noise or other approved log every 5 years or • adequate cement records

Safe Drinking Water Act Section 1422 vs. 1425?

- Section 1422 delegation requires equivalent or more stringent regulation
- Section 1425 allows a state agency related to oil and gas injection activity to make an alternative demonstration which requires "an effective program" to prevent endangerment of USDWs