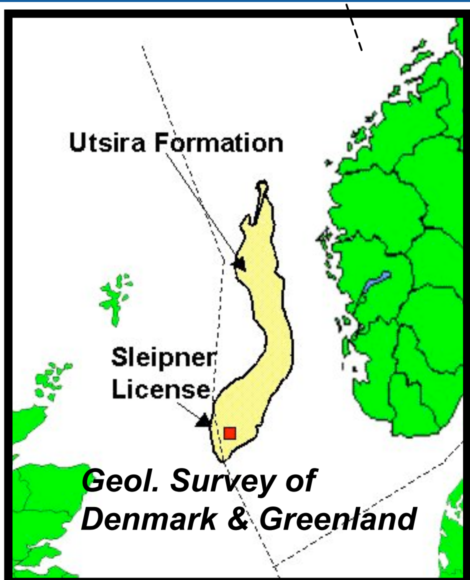
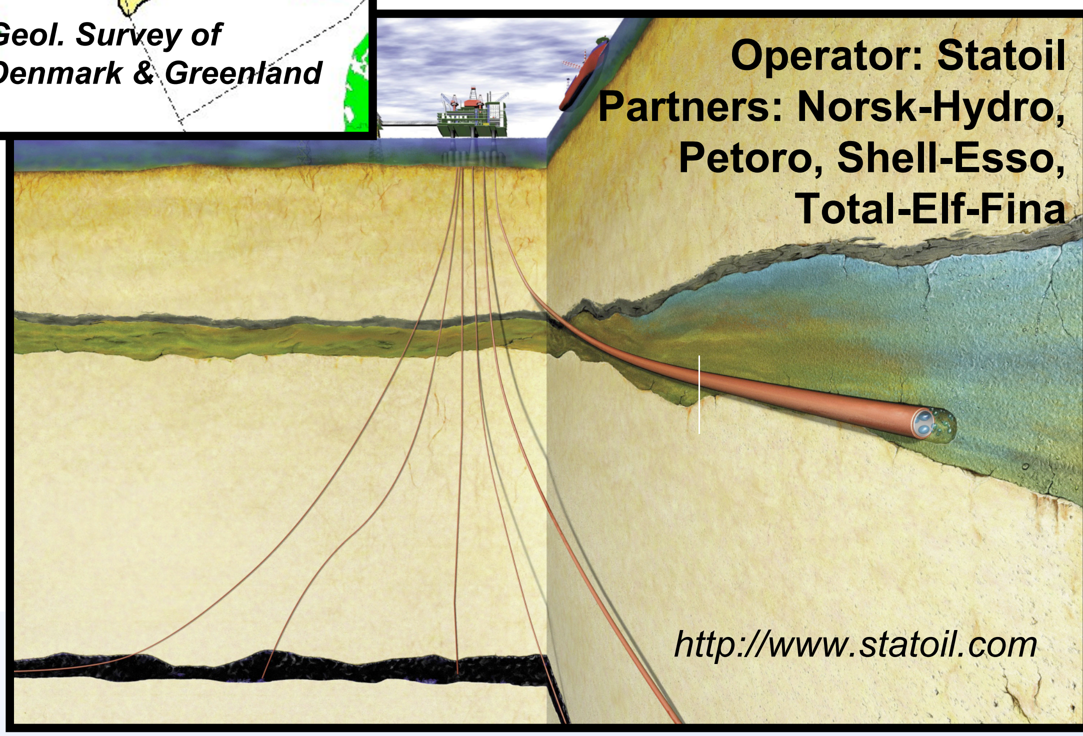
Sleipner Vest project demonstrates first-order viability of commercial storage



1st major large volume CO_2 sequestration, offshore Norway. Active since 1996

Economic driver: Norwegian carbon tax ($50/ton C)
Cost of storage: $15/ton C

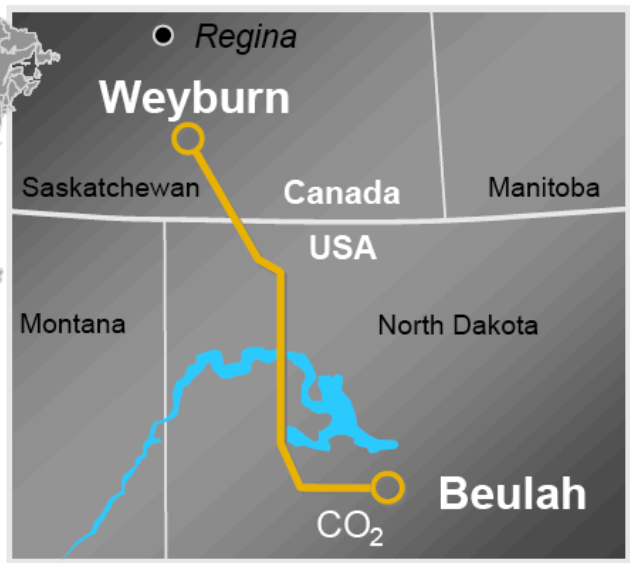


Target: 1 MM t CO_2/yr
So far, 11 MM t

- 30-40% porosity, 200 m thick
- high perm. (~3000 mD)
- 15-36 °C – w/in critical range

Weyburn Enhanced Oil Recovery Project

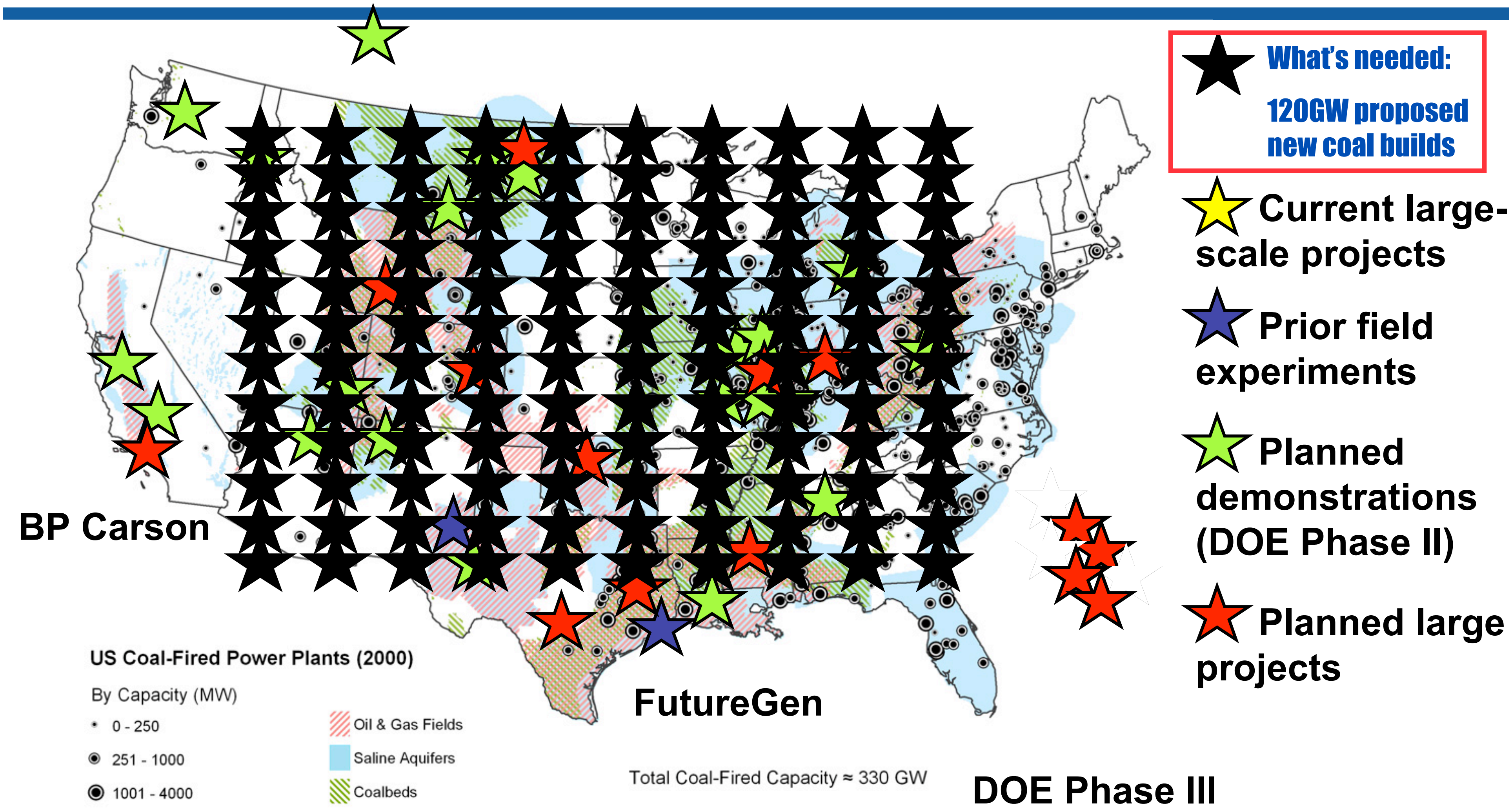
(An Operating Project Maximizing Oil Recovery and CO_2 Storage)



- **Largest CO_2 EOR project in Canada:**
  - **OOIP 1.4 Bbbls**
  - **155 Mbbls incremental**
- **Outstanding EOR response**
- **World's largest geological CO_2 sequestration project**
  - **2.4 MMt/year (current)**
  - **7 MMt to date**
  - **23 MMt with EOR**
  - **<u>55 MMt with EOR/sequestration</u>**

CO_2 from North Dakota gasification plant; 200 mi of pipe

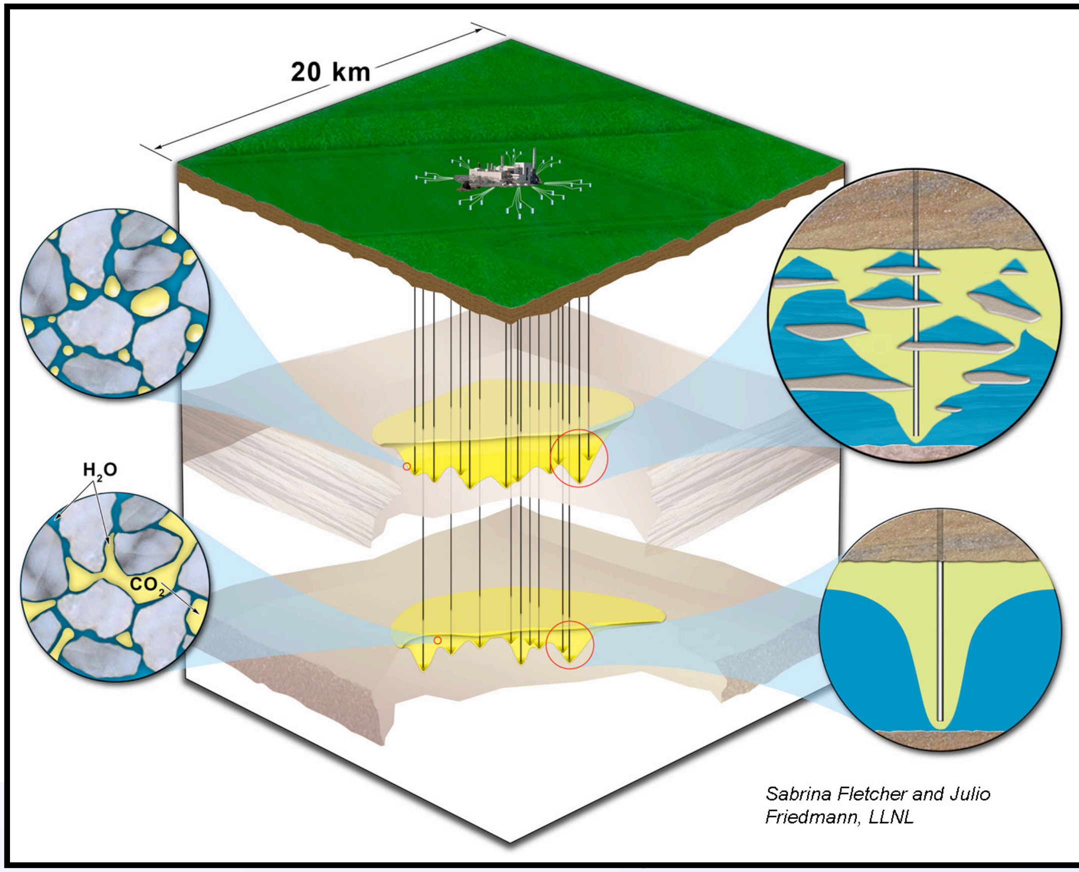
Large projects in the US are announced from many parties in many regions



These projects are proceeding with great uncertainty

Large-scale CCS deployment is the primary challenge and source for concerns

Let's agree that by 2020, all new coal plants will be fitted for CO_2 capture and storage. The scope and scale of injection from a single plant and many plants must be considered.



MIT, in press

One 1000 MW plant:

- 5-8 MM t CO_2/yr
- 120,000-200,000 bbl/d (as supercritical phase)
- After 60 year, 2.8-4 G bbls
- CO_2 plume radius
  - at 10y: ~10 km
  - at 50 yrs: ~30 km
- Many hundreds of wells
- Likely injection into many stacked targets

One Gt/y C abatement requires 600 projects of this size (3600 Sleipners)

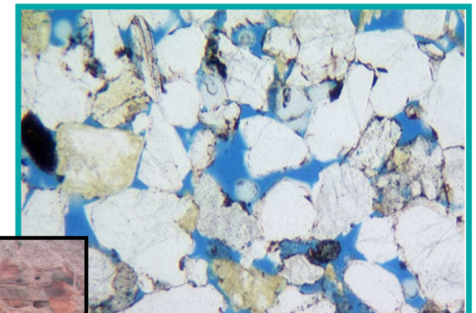
Important steps: Site selection due diligence requires characterization and validation of ICE

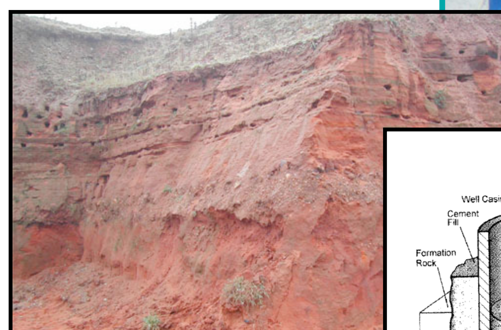
Injectivity ***Capacity*** ***Effectiveness***

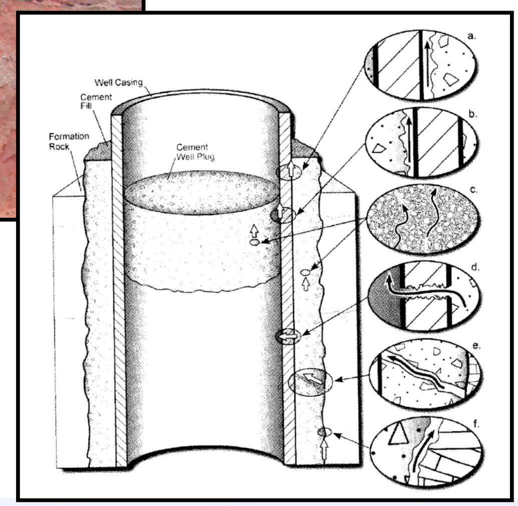
Injectivity
- Rate of volume injection
- Must be sustainable (months – years)

Capacity
- Bulk (integrated) property
- Total volume estimate
- Sensitive to process

Effectiveness
- Ability for a site to store CO_2
- Long beyond the lifetime of the project
- Most difficult to define or defend

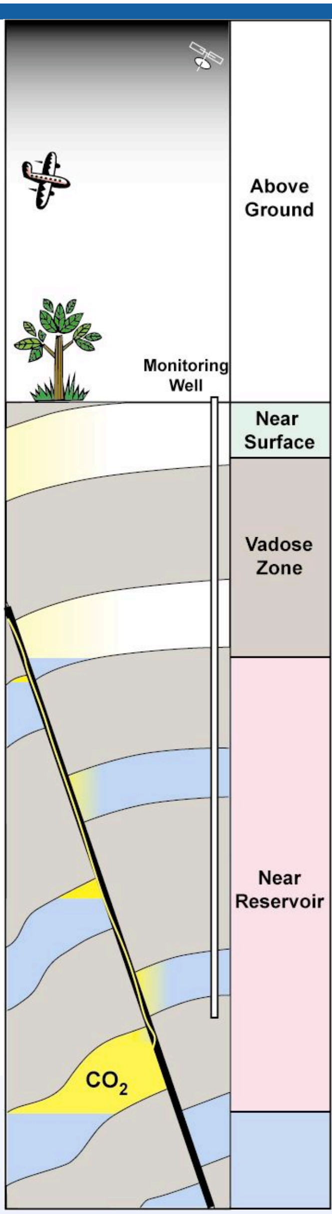






Gasda et. al, 2005

Measurement, monitoring, and verification (MMV) will be required, and at all stages of a project



Assessment and planning

- Site characterization
- Simulation & forward modeling
- Array design and planning

Baseline monitorinng

- May take days to years
- May require reworking wells

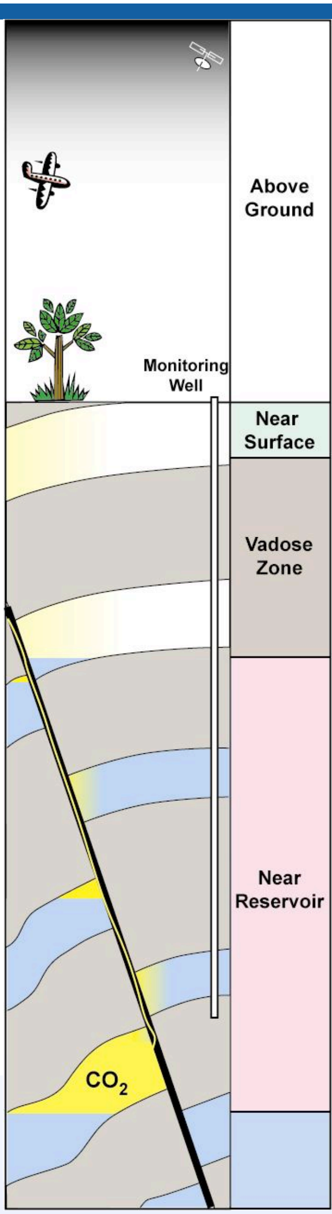
Operational monitoring during injection

- Verify performance against expectations

Closeout and post-injection monitoring

- Surface & subsurface components
- May have additional tools along high-risk zones
- Recurrence and duration determined by site parameters

Measurement, monitoring, and verification (MMV) will be required, and at all stages of a project



Assessment and planning

- Site characterization
- Simulation & forward modeling
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Baseline m

C ... ection

- ... against expectations

Performance-based standards

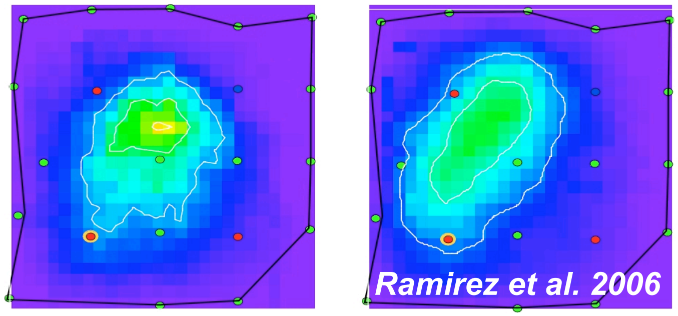
Integration is needed

Closeout and post-injection monitoring

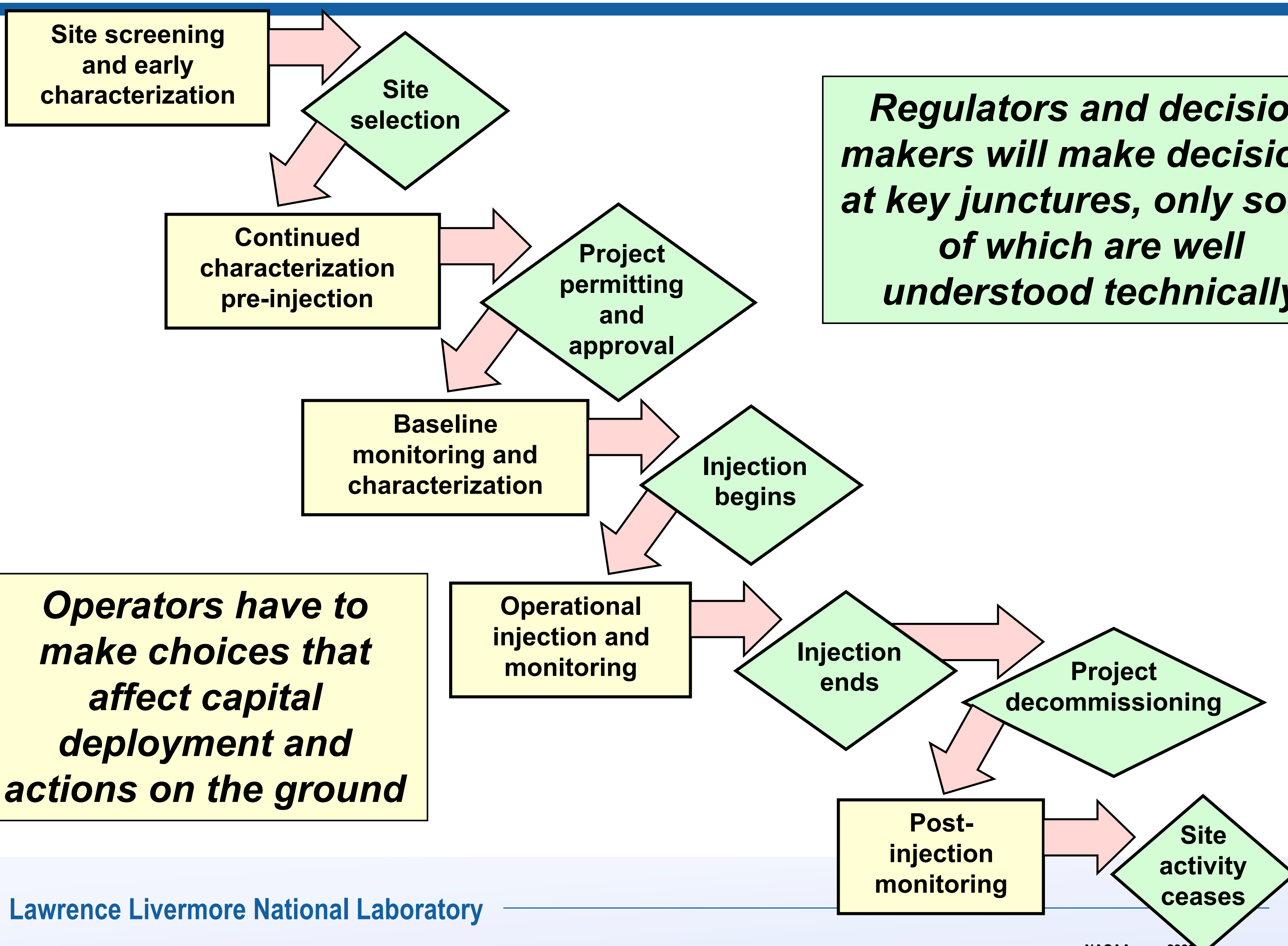
- Surface & subsurface components
- May have additional tools along high-risk zones
- Recurrence and duration determined by site parameters

Many tools exist to monitor & verify CO_2 plumes

Parameter	Best tool	Other tools
Fluid composition	Direct sample	(Surface sampling + simulation)
T, P fieldwide	Thermocouples & pres. sensors	Fiberoptic Bragg grating
Subsurface pH monitoring	pH sensors	
CO_2 distribution	Time-lapse seismic	(microseismic, tilt, VSP, electrical methods)
CO_2 saturation	Electrical methods (ERT)	(advanced seismic)
Surface detection	Soil gas, PFC tracing	(Atmos. eddy towers, FTIRS, LIDAR, hyperspectral)
Stress/strain changes	(Tri-axial tensiometers)	Bragg grating, tilt, InSAR



The drive to deployment has brought focus on the life-cycle of CCS operations and its key issues



Regulators and decision makers will make decisions at key junctures, only some of which are well understood technically

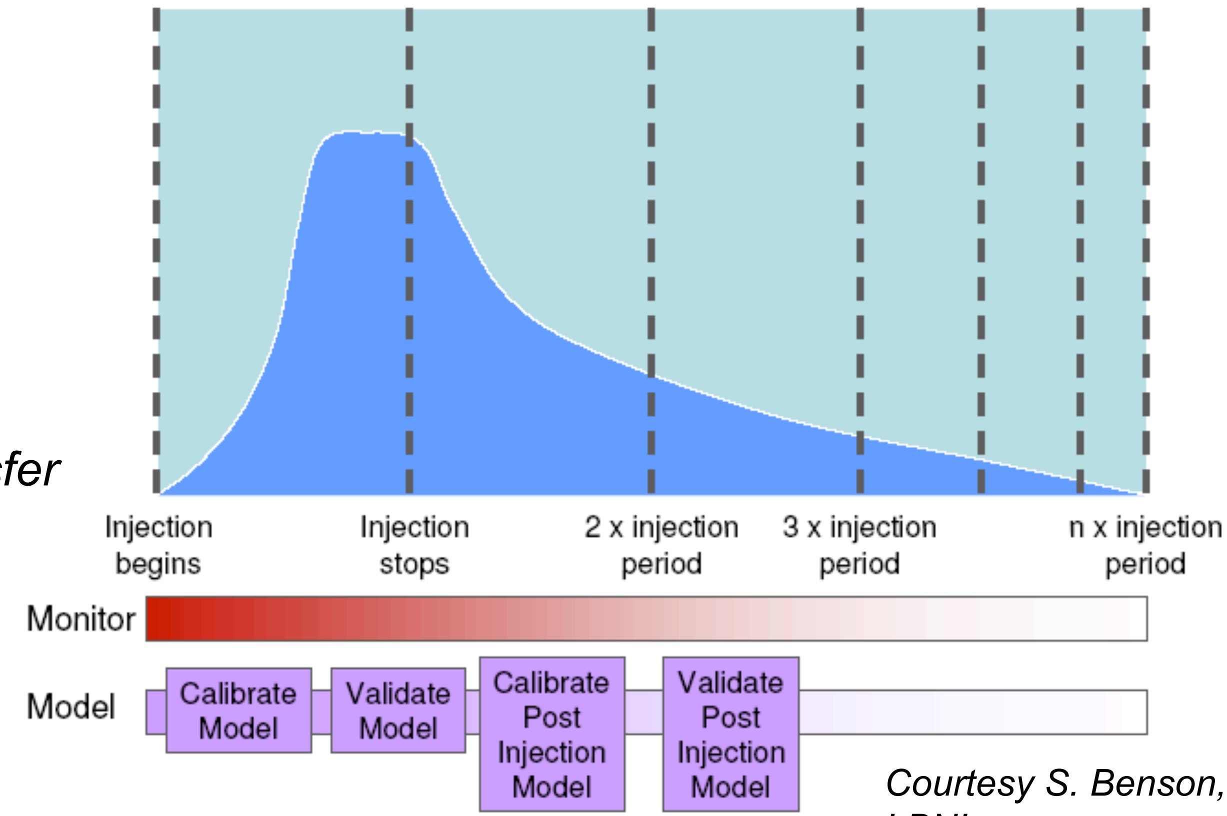
Operators have to make choices that affect capital deployment and actions on the ground

Regulatory, legal and financial frameworks are being developed now

Uncertainties persist in key aspects:

- *What are proper abandonment protocols?*
- *When does monitoring cease?*
- *When does liability transfer to a new party?*
- *Are there unanticipated long-term concerns?*
- *What are the real magnitudes of these risks?*

Conceptual Risk Profile

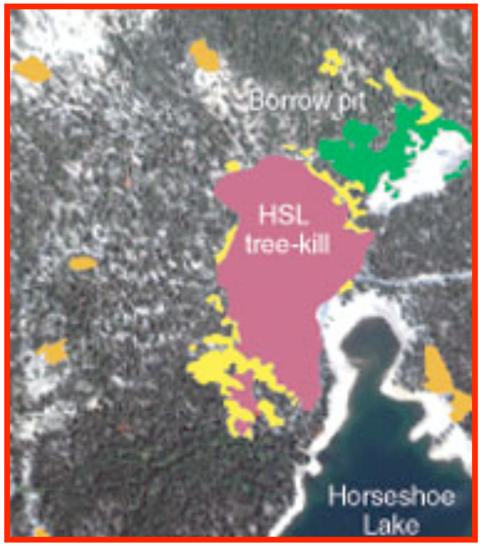


Courtesy S. Benson, LBNL

These uncertainties impede commitment of capitol to operational projects today

Leakage risks remain a primary concern

1) **High atmospheric CO_2 concentrations (>15,000 ppm) can harm environment & human health**
2) **Other potential risks to groundwater, environment**
3) **Effectiveness & potential impact of widespread CO_2 injection**
4) **Economic risks for an operator** (uncertainty in subsurface, liability, and regulations)

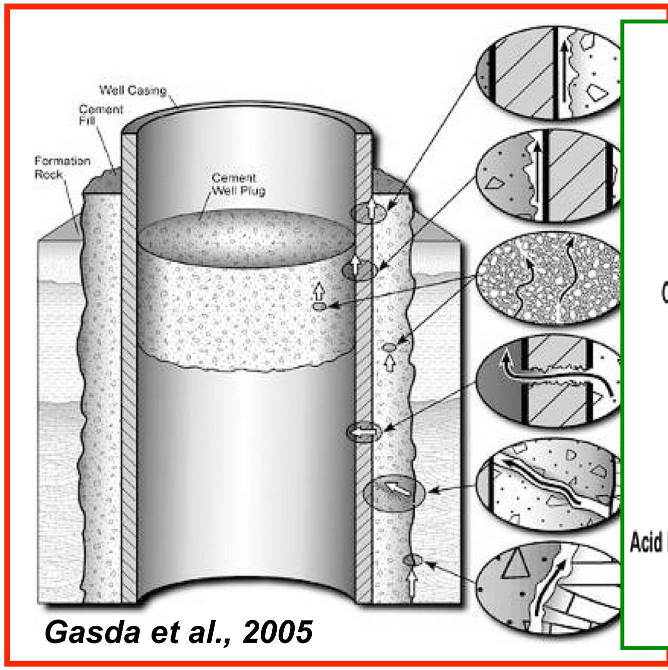


Elements of risk can be prioritized

- Understand high-permeability conduits (wells and faults)
- Predict high-impact effects (asphyxiation, water poisoning)
- Characterize improbable, high-impact events (potential catastrophic cases)

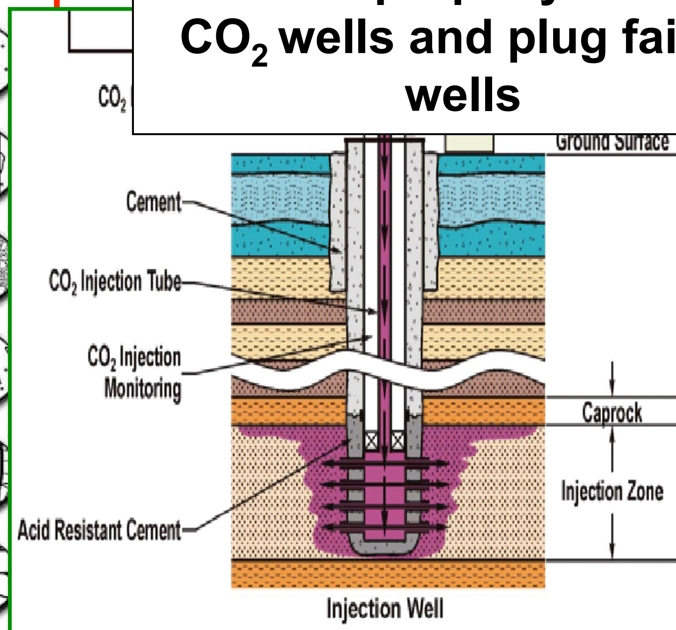
Wells represent the main hazard to GCS site integrity

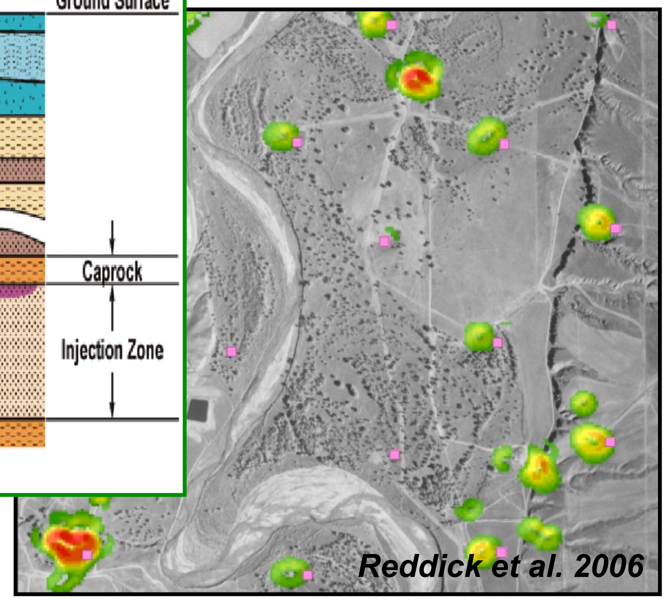
We have some understanding of well failure modes



Gasda et al., 2005

We can properly design CO_2 wells and plug failed wells





Reddick et al. 2006

We can identify and recomplete lost wells

Managing and maintaining well integrity is important to avoiding failure and risk minimization

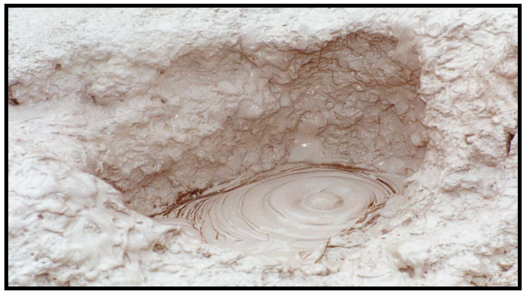
Plugs remain a key concern, particularly for old wells (orphaned and abandoned)

Plug technology has improved over time due to regulation

http://fotos.naturspot.de/bilder/11-336.html

1850's – 1920's

- **Animal Carcasses**
- **Mud**
- **Debris**
- **Nothing**



http://www.richardseaman.com/Travel/NewZealand/NorthIsland/Rotorua/MudPools/SunkenMudPool.jpg

1930's – 1953

- **Mud**
- **Cement with no additives**

http://www.hardwarestore.com/media/product/221101_front200.jpg

1953 – present

- **Standard Portland Cement**
- **Cement with additives**

Ide et al., 2006

Work remains to develop a hazard risk framework that can be regularly employed

The hazards are a set of possible environments, mechanisms and conditions leading to failure at some substantial scale with substantial impacts

Atmospheric release hazards	Groundwater degradation hazard	Crustal deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
		Induced seismicity
		Subsidence/tilt

Friedmann, in press

The hazards must be identified, their risks quantified, and their operational implications clarified

Because of local nature of hazards, prioritization (triage) is important for any case

Hypothetical Case: Texas Gulf of Mexico coast

Atmospheric release hazards	Groundwater degradation hazard	Crustal deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
Pink = highest priority Orange = high priority Yellow = moderate priority		Induced seismicity
		Subsidence/tilt

Friedmann, in press

Part of protocol design is to provide a basis for this kind of local prioritization for a small number of classes/cases

The risks at present appear to be very small and manageable

Analog information abundant

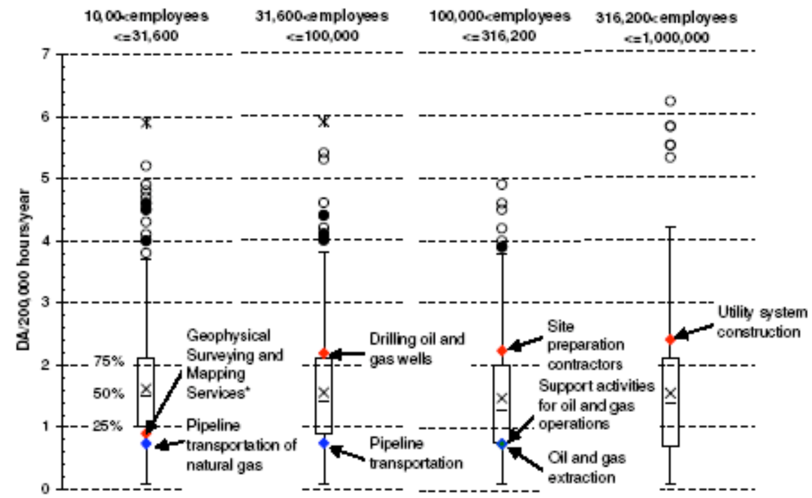
- Oil-gas exploration and production
- Natural gas storage
- Acid gas disposal
- Hazardous waste programs
- Natural and engineered analogs

Operational risks

- No greater than (probably less than) oil-gas equivalents (CO_2 isn't flammable)
- Long experience with tools and methodologies

Leakage risks

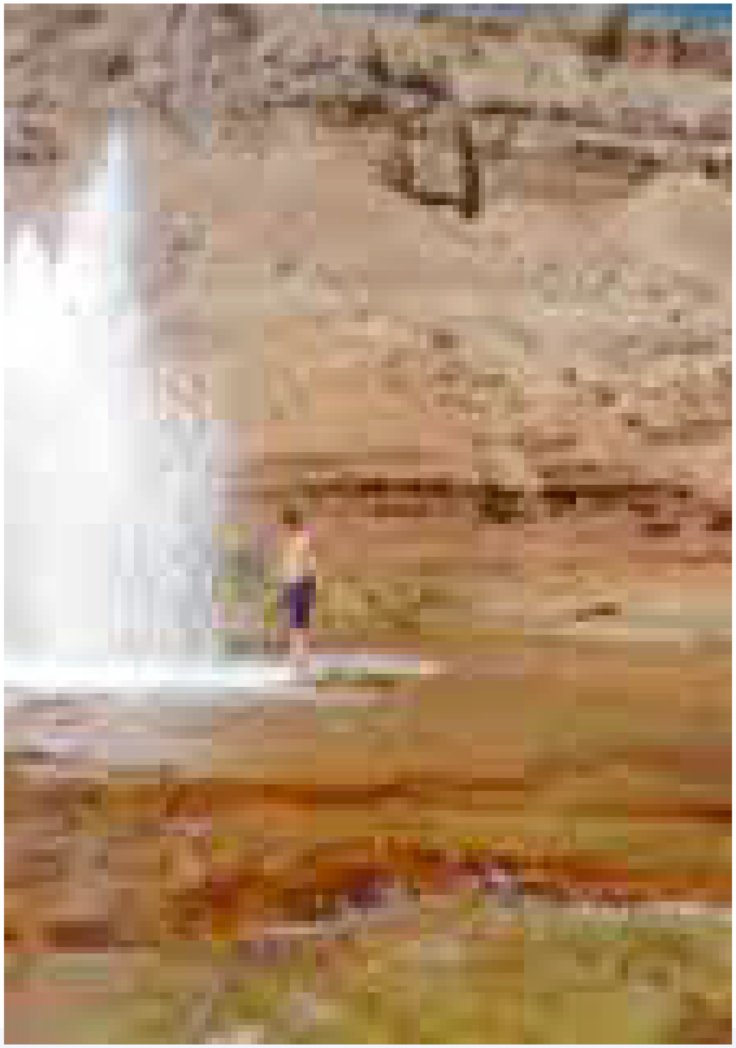
- Extremely small *for well chosen site*
- Actual fluxes likely to be small (health, safety and environmental consequences also small)
- Mitigation techniques exist



Benson, 2006

Bogen et al., 2006

Crystal Geyser, UT: Analog for the worst case scenario



Drilled in 1936 to 801-m depth
Abandoned well initiated CO_2 geysering

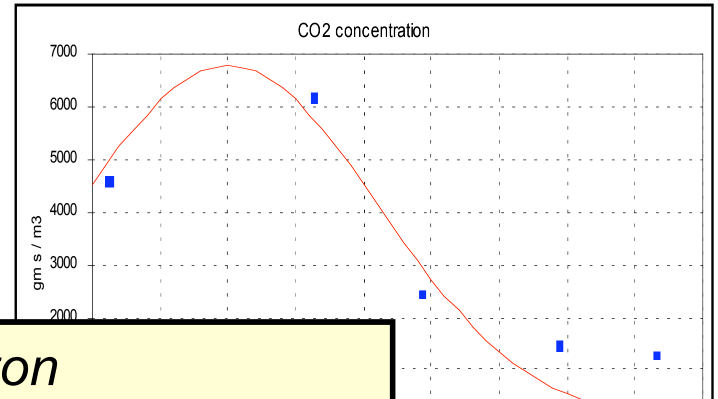
CO_2 flows from Aztec sandstone (high P&P saline aquifer)

LLNL collected flux data (10/04)

- Temperature
- Meteorology (low wind <2m/s)
- 5 eruptions over 48 hrs
- Four eruptions and one pre-eruption event sampled

Crystal Geyser emission data results

		Eruption Interval	CO_2 emission data during eruption	
Eruption	Eruption Character	Duration (hr:min)	Total (metr. ton)	Rate (m.t./ min)
1	moderate	0:07	1.1	0.15
2	*(no observations)* [&]	0:15	*N/A*	*N/A*
3	moderate	2:02	41	0.34
4	explosive	0:10	1.7	0.16
5a [*]	(pre-eruptive)	0:11	0.11	0.010
5	moderate	0:24	1.6	0.07



Short eruptions < 1 ton : Long eruption ~ 41 ton
Daily flux: ~10-25 t (5-41 t)
Annual flux: ~5000-9000 t (<1% of 1 MM t/yr injection)
Never above ~12500 ppm (up to 15000 ppm, no harm at all)

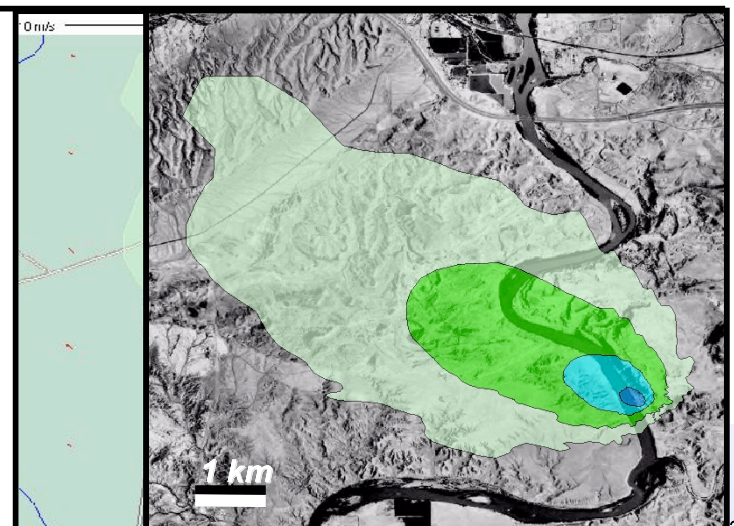
3-D NARAC models of Crystal Geyser CO_2 release set limits on concentrations (i.e., health & safety thresholds) that can guide regulation and monitoring planning.

>100 ppm; 0.05km²

>10 ppm; 0.6km²

>1 ppm; 4.4 km²

>0.1 ppm; 0.05km²



NARAC simulations of the largest hypothetical leakage event suggest only localized danger

Maximum CO_2 flow rate:
7” inside diameter well

Depth (ft)	Flow rate (kg/s)	Flow rate (ton/day)
5036	225	1944
4614	217	1875
5102	226	1952
4882	224	1935

~2x Sheep Mt. event
~50x Crystal Geyser

Simulated hypothetical
Max. flow rate event
Great plains: no wind

This scenario generates maximum credible hazard

Acute (Short-Term) Effects

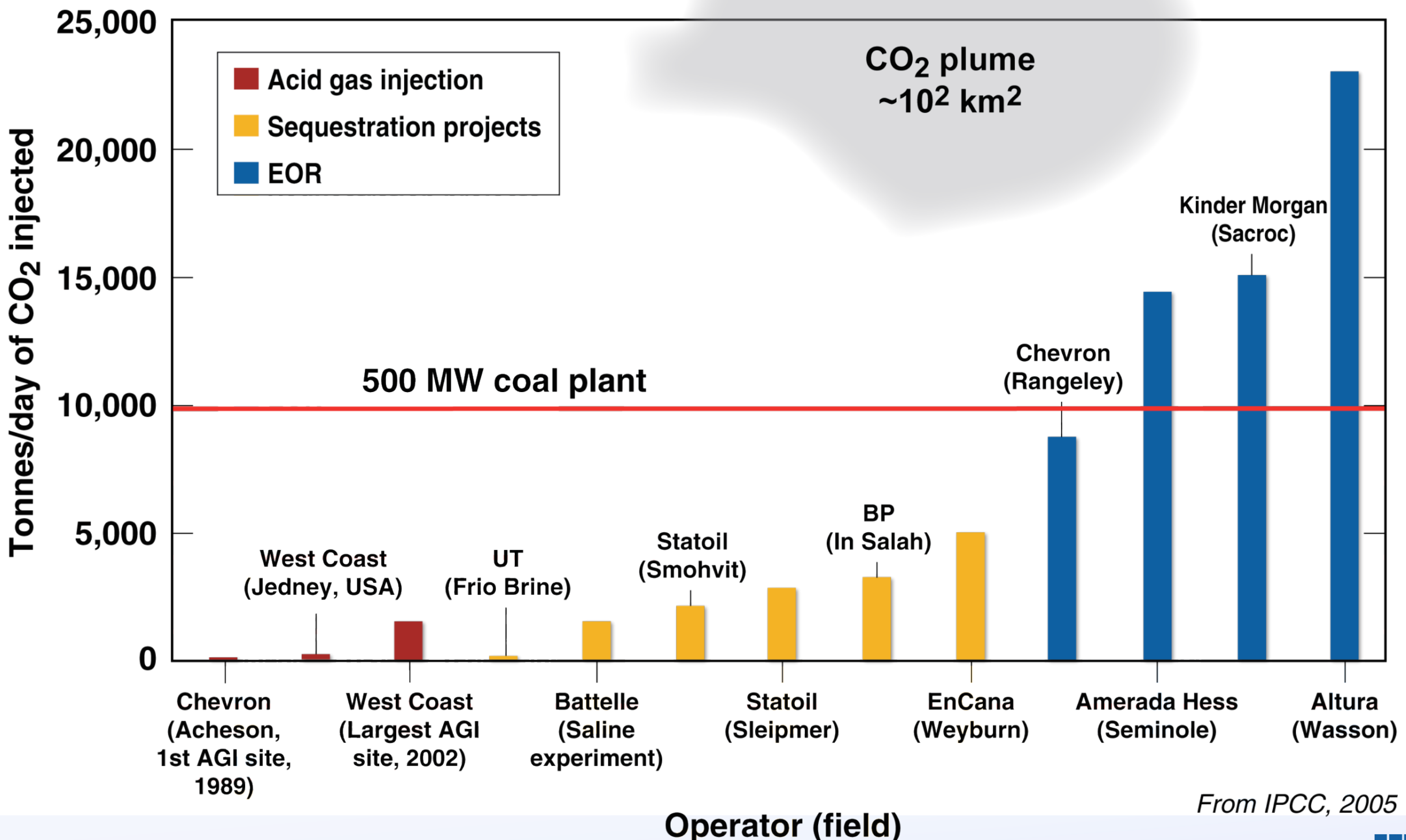
	Description	(ppm) Extent Area	Population Fatalities Casualties
(red)	>TEEL-3: Death or irreversible health effects possible.	>40,000 71.5 m 6,840 m2	0 N/A N/A
(orange)	>TEEL-2 and TEEL-1: Serious health effects or impaired ability to take protective action.	>30,000 87.3 m 9,515 m2	0 N/A N/A

Note: Areas and counts in the table are cumulative. Casualties include both Fatal and Non-Fatal effects.

The toxicity consequences from catastrophic well failure appear to be highly localized.

Over 100 GW of coal-fired capacity are currently on hold: just the site-specific science will be $50-$150M for each site

There is very little experience injecting CO_2 at this scale: confidence-building projects are required



From IPCC, 2005

Courtesy of Roger Aines

Conclusions

- **Current knowledge and experience strongly supports carbon sequestration as a successful technology to dramatically reduce CO_2 emissions.**

Current science and technology gaps appear resolvable

- **Deployment issues, including regulatory, legal, and operational concerns, can be addressed through development of operational protocols advised by science**

- **LARGE SCALE tests are crucial to understanding and guiding successful deployment of carbon capture and sequestration (CCS) and creating appropriate policy/economic structures.**

No test to date is sufficient with respect to scale, duration, monitoring, and analysis.