Carbon Management and Underground Coal Gasification

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Conclusions regarding UCG and CCS

Important synergies between UCG and CCS

Low-cost syngas provides cost-competitive opportunities for CO_2 capture & separation

Siting, monitoring, and key hazard assessment requirements for UCG support CCS and visa versa

Commercial-scale demos possible

CO_2 storage in the cavity is not commercially ready

Best Practices in Underground Coal Gasification: Pending DOE-FE Report

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

Underground coal gasification produces syngas with low capital and low operating cost

Gasification occurs in situ. The technology is well tested >40 years

Environmental benefits

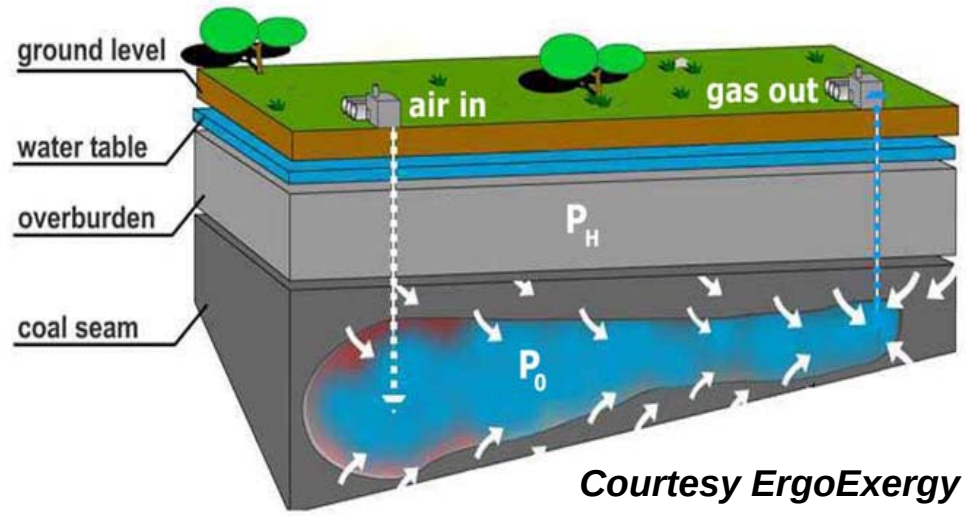
- No mining
- Much less pollution (no SO_x, NO_x; less mercury, particulates)
- Low-cost H_2 production

Economic benefits

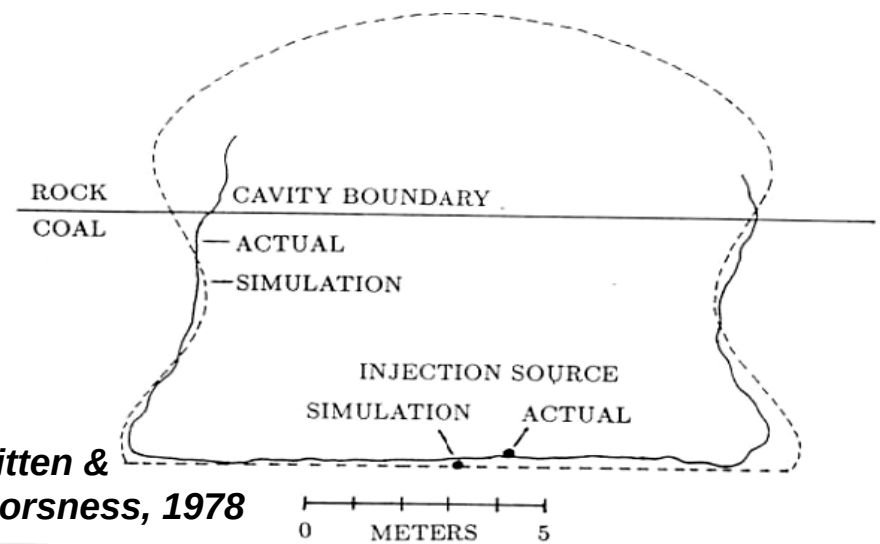
- No gasifier purchase, operation
- No coal purchase or transport
- Low-cost power generation

Carbon Management

- Lower cost CO_2 separation
- Good coincidence between UCG and sequestration sites



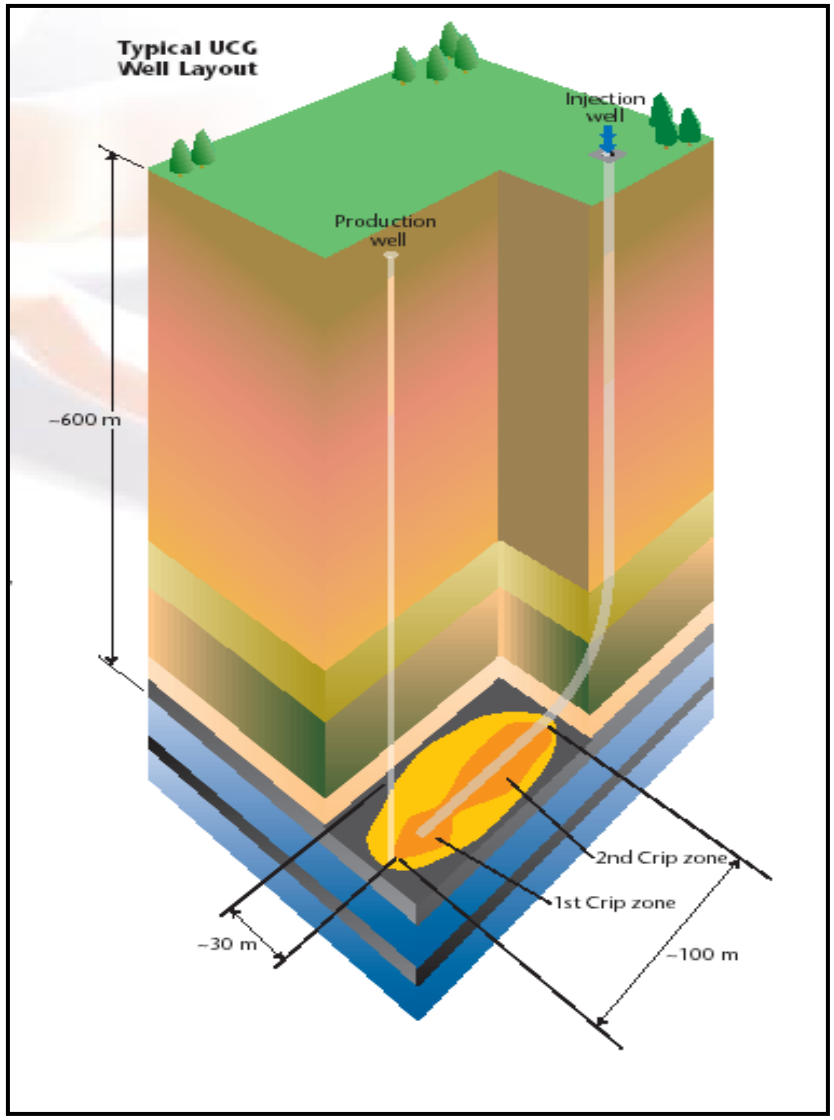
Courtesy ErgoExergy



Britten & Thorsness, 1978

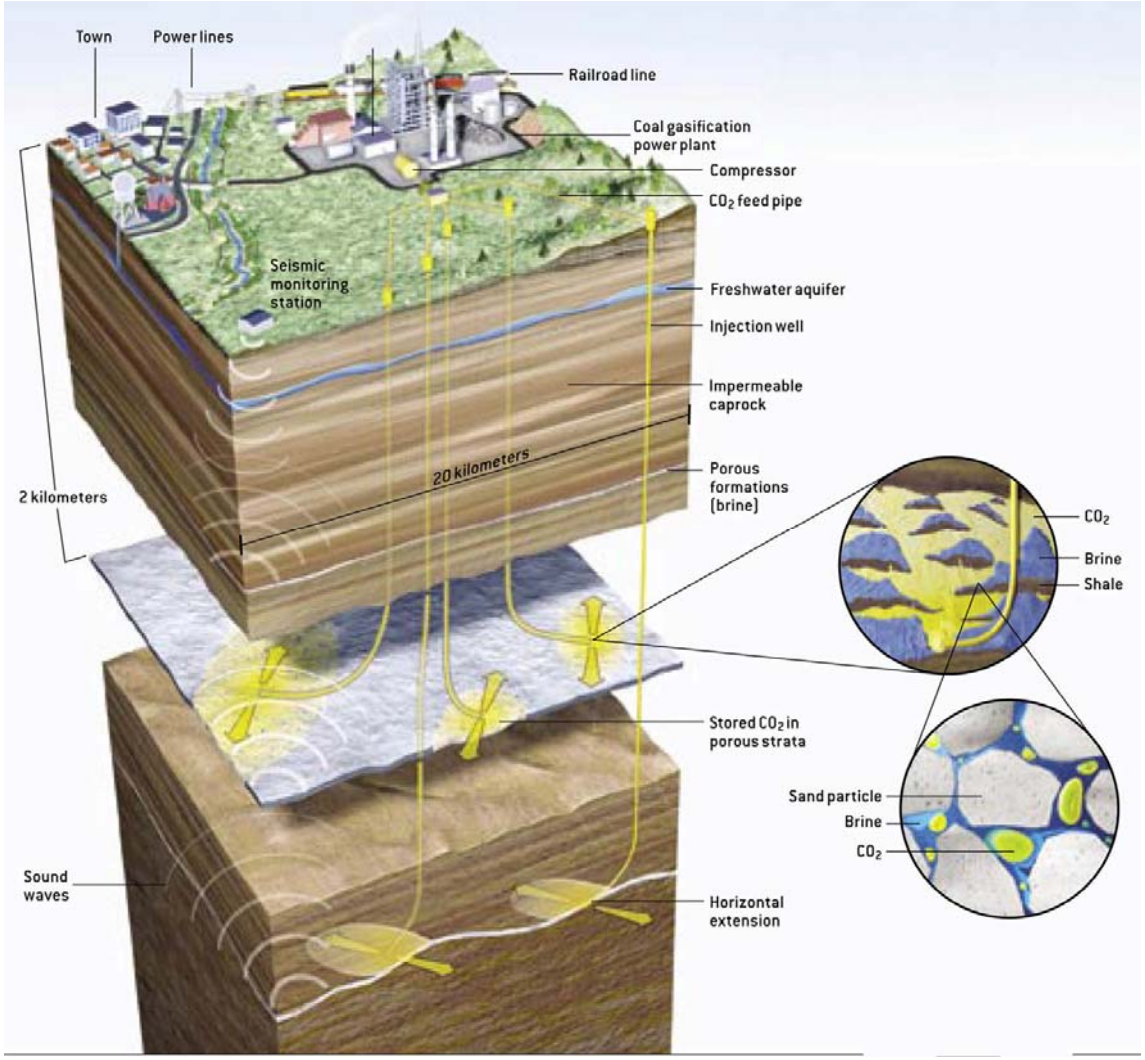
DOE/LLNL has been active in UCG for over three decades

- Invented the CRIP (controlled retractable injection point) process (1974-1985)
- Conducted a number of field tests (Hoe Creek, Hanna, Centralia)
- Developed cavity growth models (Thorseness and Britten, 1989)
- Developed a CFD-based model of the UCG process and integrated it with Aspen Plus (Wallman 2004)
- Currently expanding the CFD model to include additional phenomenology
- Developed a large suite of tools for environmental assessment
- Developed methodologies for process control monitoring
- Applied carbon management and CO_2 sequestration expertise to UCG (Blinderman & Friedmann, 2006)



Carbon dioxide can be stored in geological targets, usually as a supercritical phase

Carbon capture and storage (CCS) has emerged as a new field aimed at reducing greenhouse gas emissions, chiefly CO_2, through geological sequestration.

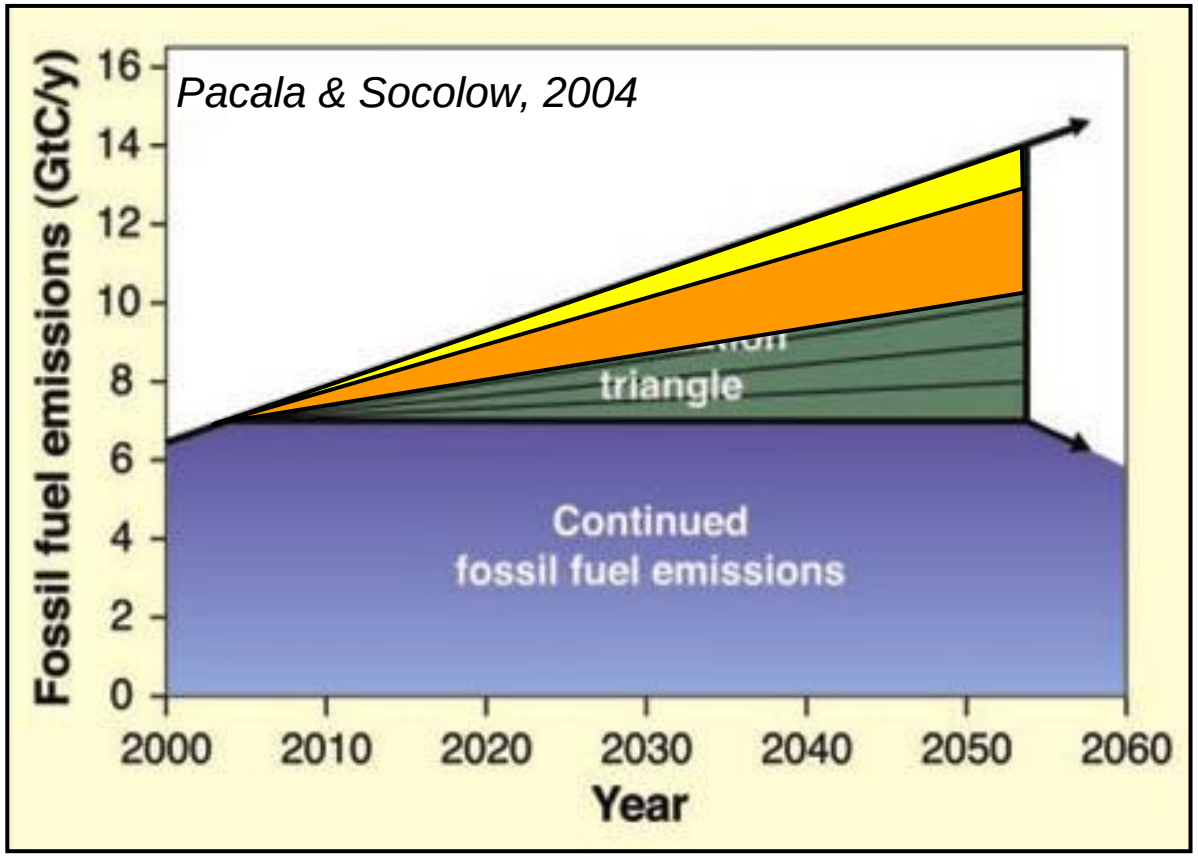


Saline Aquifers
Depleted Oil & Gas fields
(w/ or w/o EOR and EGR)
Unmineable Coal Seams
(w/ or w/o ECBM)

These formations are likely to be found near coal seams chosen for UCG

Competitive carbon-capture economics and coincidence of storage targets make UCG + CCS an attractive carbon management package

CO_2 Capture & Sequestration (CCS) can provide 15-50% of global GHG reductions



- *ACTIONABLE*
- *SCALEABLE*
- *COST-EFFECTIVE*

- **A key portfolio component**
- **Cost competitive to other carbon-free options**
- **Uses proven technology**
- **Applies to existing and new plants**
- **Room for cost reductions (50-80%)**

Carbon management requires both CO_2 capture (separation) and CO_2 storage

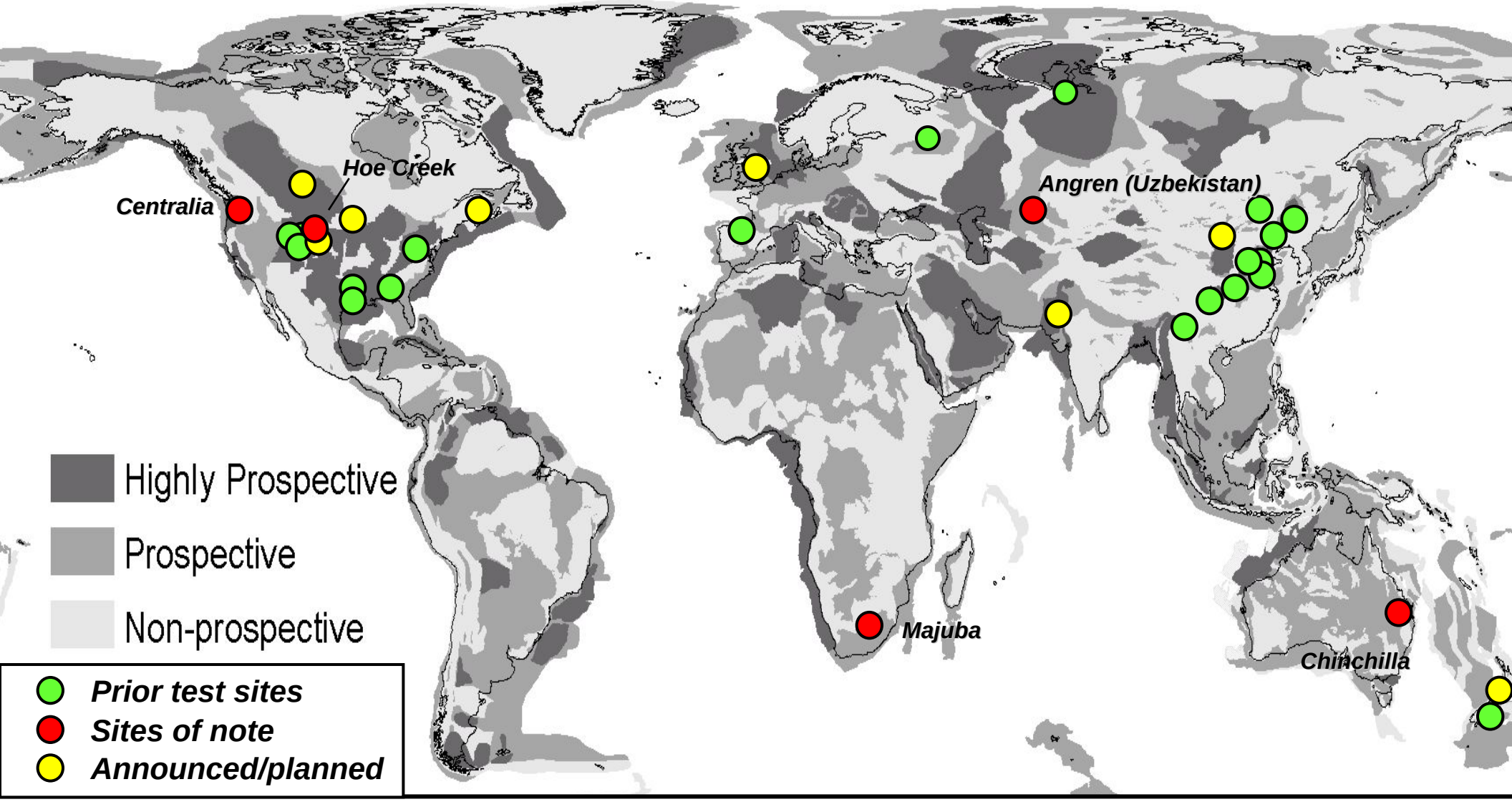
LLNL's capture program combines conventional & unconventional approaches:

- **Conventional**: ASPEN analysis of surface processes
  - (e.g., Selexol, PSA, water-gas shift)
- **Unconventional**: Advanced membranes, novel engineering concepts (e.g., down-hole water-gas shift)

Our current CO_2 storage program focuses on four components:

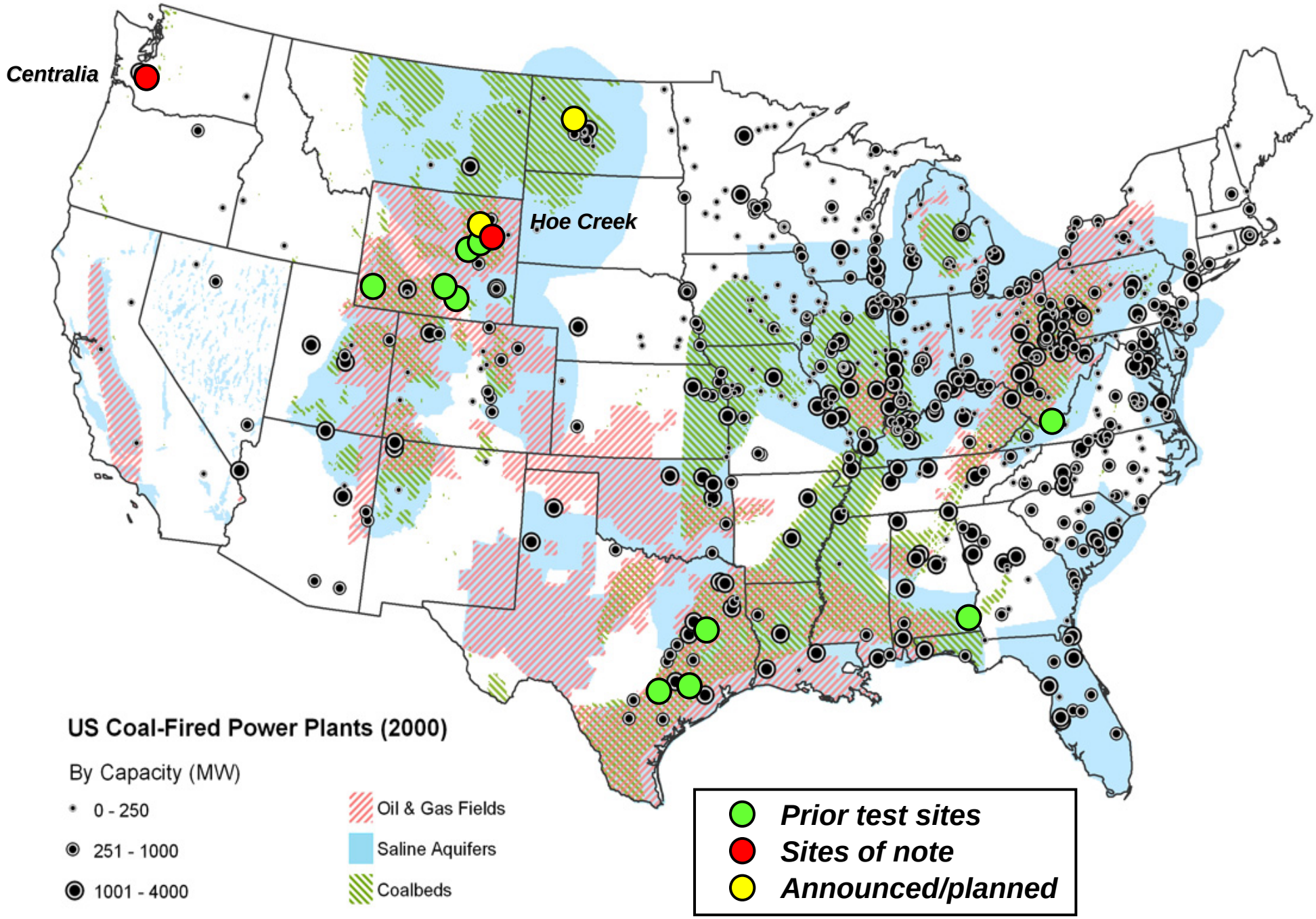
- **Advanced simulation**: Integrated hydrological, geochemical & geomechanical processes
- **Monitoring and verification:** Technology to detect CO_2 and to integrate many monitoring data streams
- **Site characterization:** Capacity estimation, hazard identification and assessment.
- **Risk quantification**: Source-term definition, GIS-based risk screening, constraint of operational protocols

There's a high coincidence of prospective and highly prospective CO_2 storage sites and UCG sites



Over 33 US, 66 FSU projects, and 20 other international pilots

There's a high coincidence of prospective and highly prospective CO_2 storage sites and UCG sites



UCG provides unique new strategies for carbon capture and separation

Partial decarbonization: CO_2 Separation from raw syngas

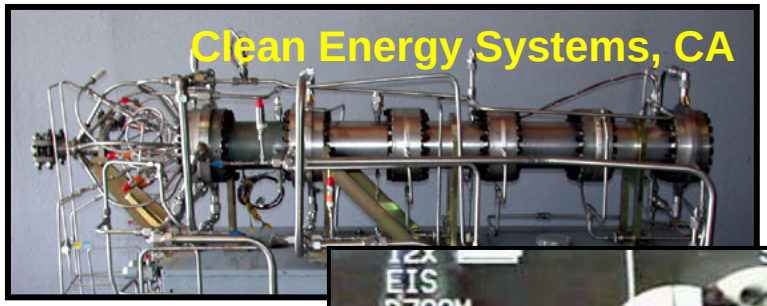
- conventional (e.g. Selexol)
- downhole: LLNL Proprietary

Full carbon separation

- Pre-combustion (water-gas shift+Selexol)
- Post-combustion (e.g., MEA)
- Air Separation and oxyfiring

Separation Technology:

- Chemical sorption (e.g., amines, selexol, chilled ammonia)
- Cryogenic separation (incl. hydrate separation)
- Pressure Swing Adsorption (e.g., Rectisol)
- Adv. membrane separation (e.g., SLIP, ion-transfer)



Energetics of CO_2 removal from UCG syngas

Data from Halmann & Steinberg, 1999

Basis: 100 kgmole syngas, at 10 atm, produced by oxygen gasification

H_2	36.1	CO	18.5
CO_2	36.1	Other	9.3

*Energy content of syngas (@248 BTU/scft) = 57.2*100 = 5720 KWH*

O_2 used = 27.3 kg moles; Energy needed for O_2 = 384 kWH (0.44 kWH/kg O_2)

Case 1: No shift, remove CO_2 from raw syngas

Removal of CO_2 by improved amines absorption (better w/ Selexol):

*energy required = 0.11*2.2*36.1*44*.9=346 kWH*

*Total energy penalty for CO2 removal: 346/5720 = **6%***

Case 2: syngas after complete shift: (H_2=54.6; CO_2= 54.6; other=9.3)

Removal of CO_2 by improved amines absorption:

*energy required = 0.11*2.2*54.6*44*.9=524 kWH*

*Total energy penalty for CO2 removal: 524/5720 = **9%***

Case 3: Oxyfired combusion of raw syngas (e.g., in CES power block)

*Energy needed for O_2 = (0.44*18.1*36) + (0.44*9.25*36) = 438kWH*

O_2 required for stoichiometric conversion = 18.1 mole + 9.25 moles O_2

*Total energy penalty for total O_2 production: 438/5720 = **8%***

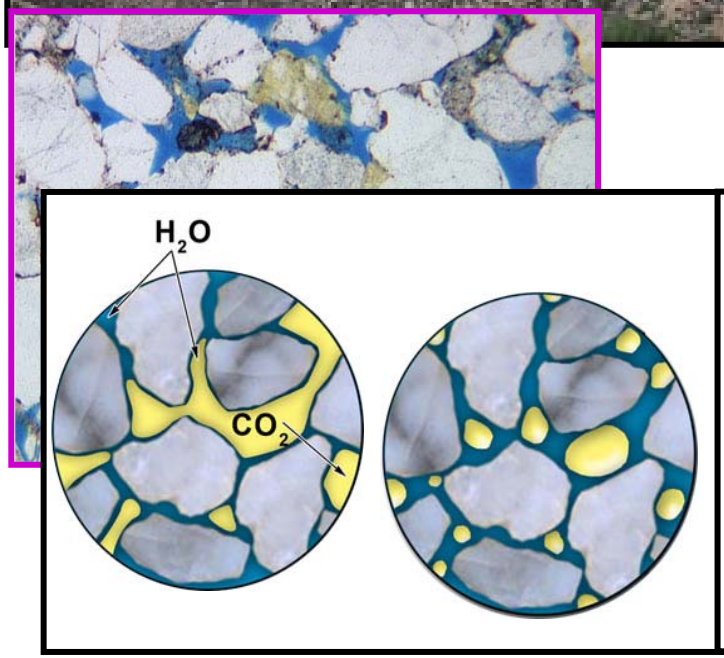
Storage mechanisms are reasonably well understood

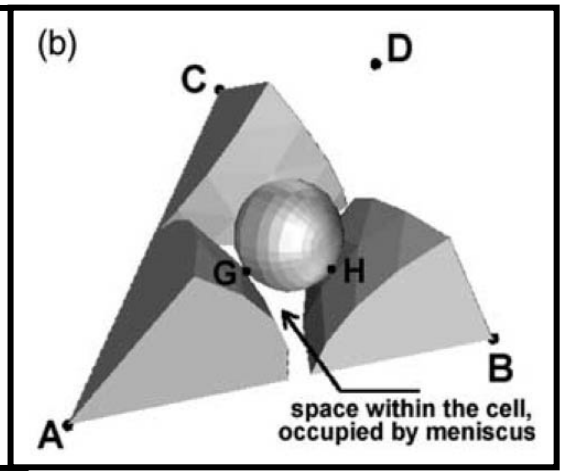
Physical trapping
- Impermeable cap rock
- Either geometric or hydrodynamic stability

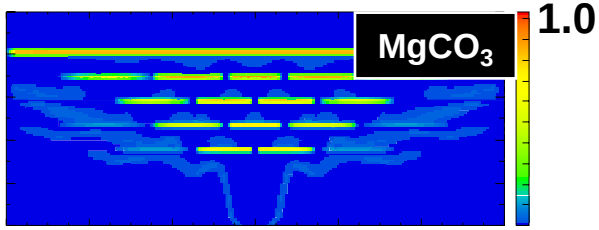
Residual phase trapping
- Capillary forces immobilized fluids
- Sensitive to pore geometry (<25% pore vol.)

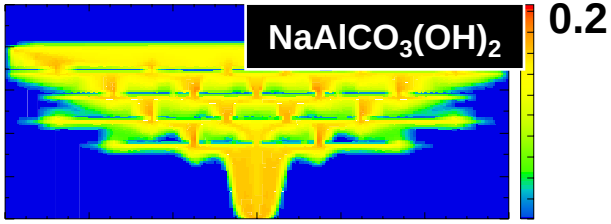
Solution/Mineral Trapping
- Slow kinetics
- High permanence

Gas adsorption
- For organic minerals only (coals, oil shales)

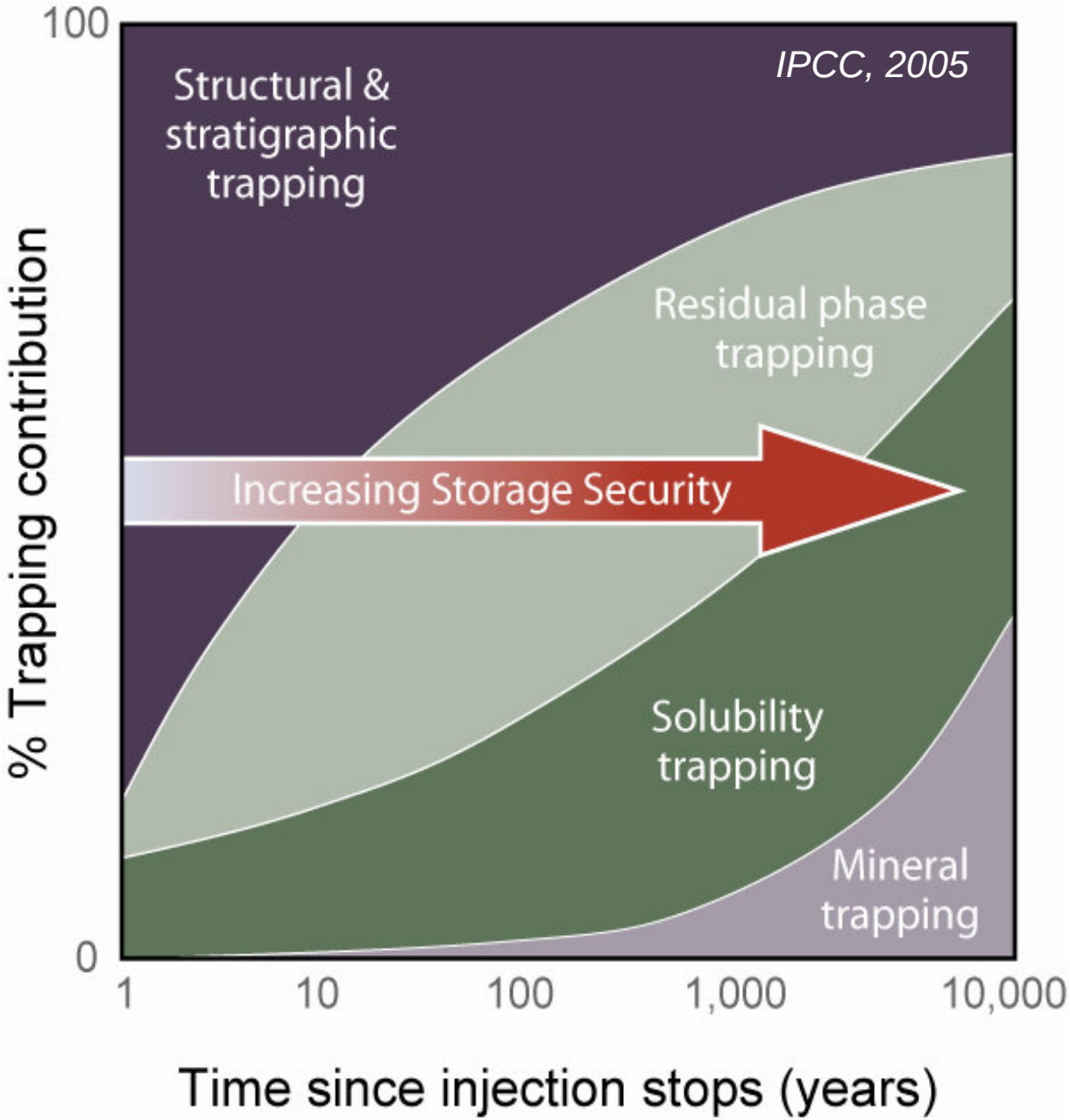








The crust is well configured to trap large CO_2 volumes indefinitely



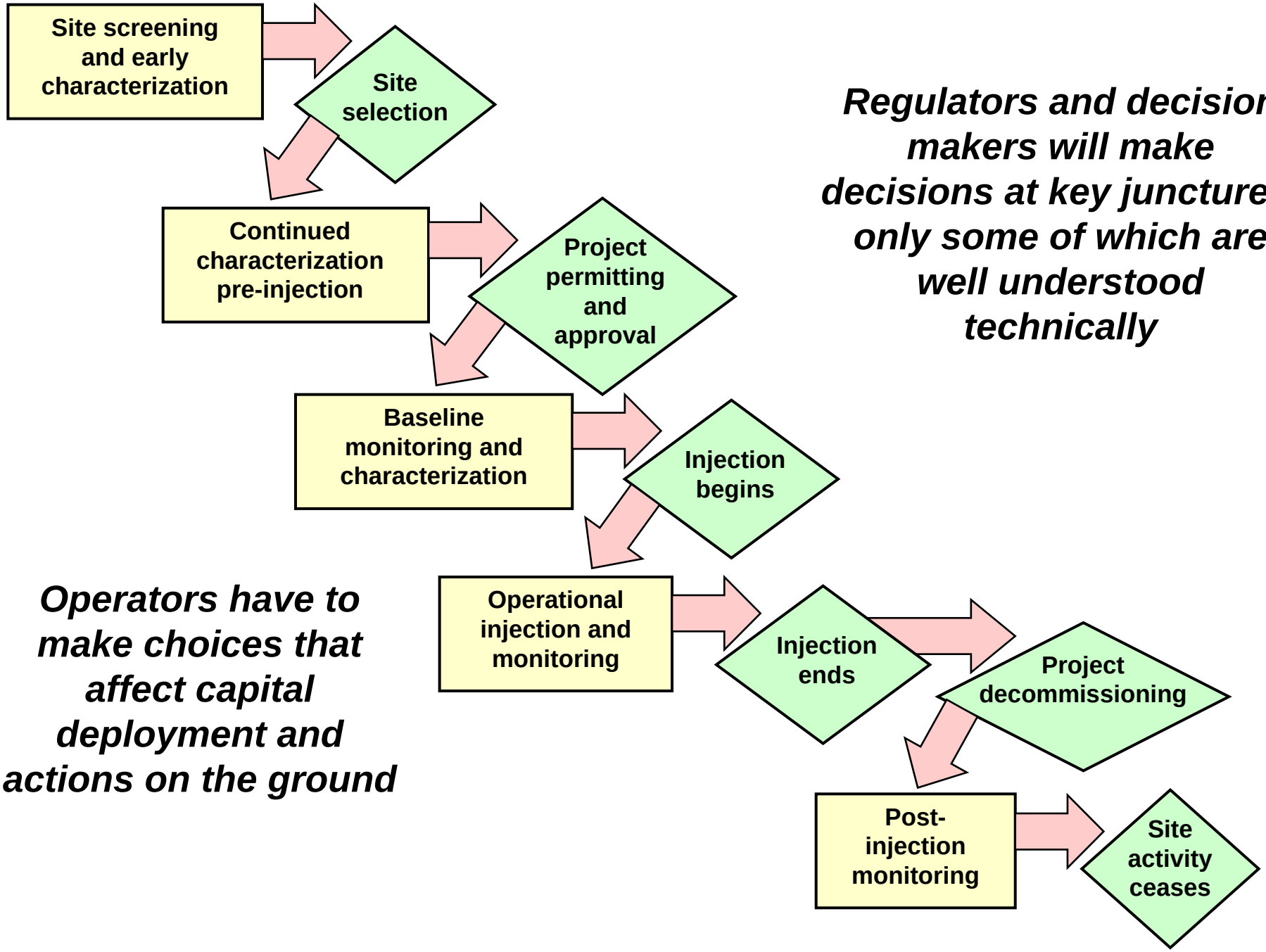
Because of multiple storage mechanisms working at multiple length and time scale, the shallow crust should attenuate mobile free-phase CO_2 plumes, trap them residually, & ultimately dissolve them

This means that over time risk decreases and permanence increases

What are the key issues with sequestration as relates to UCG?

- **Sequestration resource: How much and where?**
- **Site selection: What does a specific site need?**
  - **Injectivity**
  - **Capacity**
  - **Effectiveness**
- **Monitoring & Verification**
- **Hazards and risks**
- ***THE MAIN ISSUE IS SCALE!!***
  - **Need >1mT/yr injection for 50 – 70 yrs (200 mw power plant)**
  - **Mechanics– integrity (effectiveness)**
  - **Affect of heterogenity – larger volume, more hetergeneities contacted --- performance (capacity, injectivity)**

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

Site selection due diligence requires characterization & validation of ICE

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

Injectivity

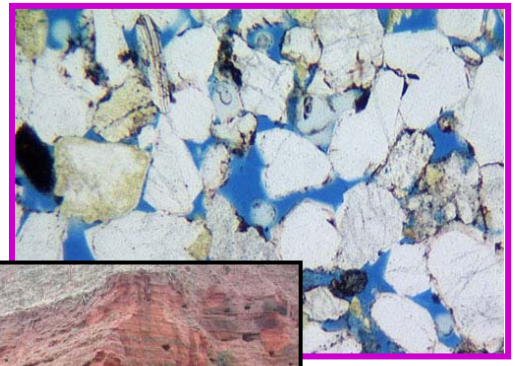
- Rate of volume injection
- Must be sustainable
  - (test for months – use for years)

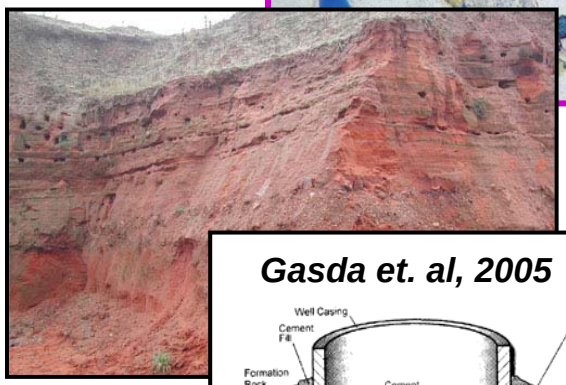
Capacity

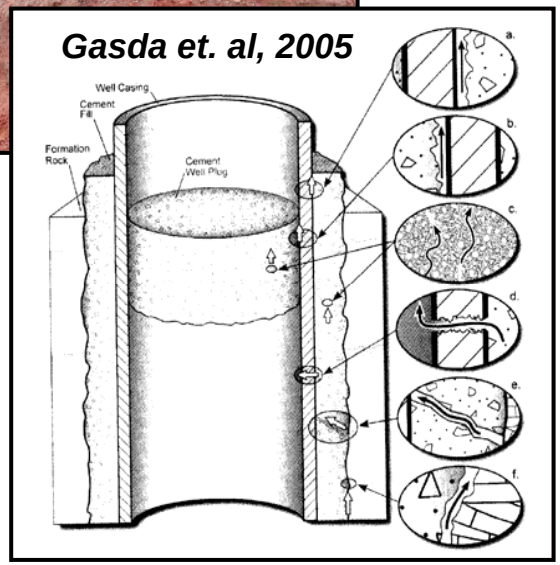
- Bulk (integrated) property
- Total volume estimate
- Sensitive to trapping mechanisms

Effectiveness

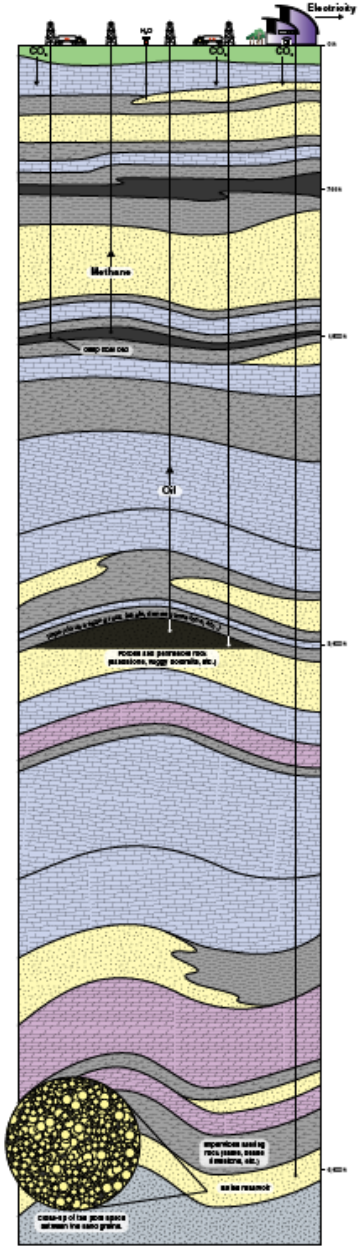
- Ability for a site to store CO_2
- Long beyond the lifetime of the project
- Most difficult to define or defend

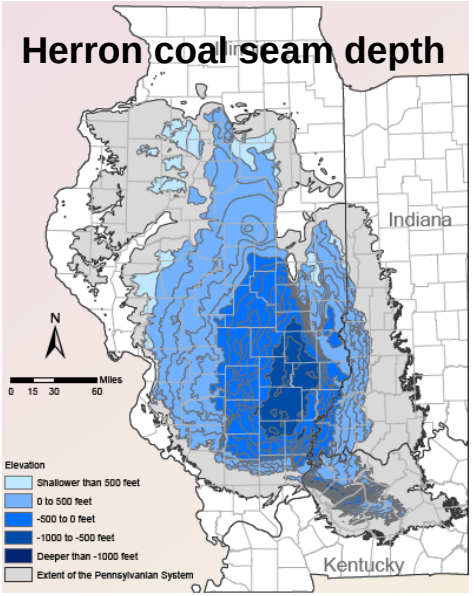


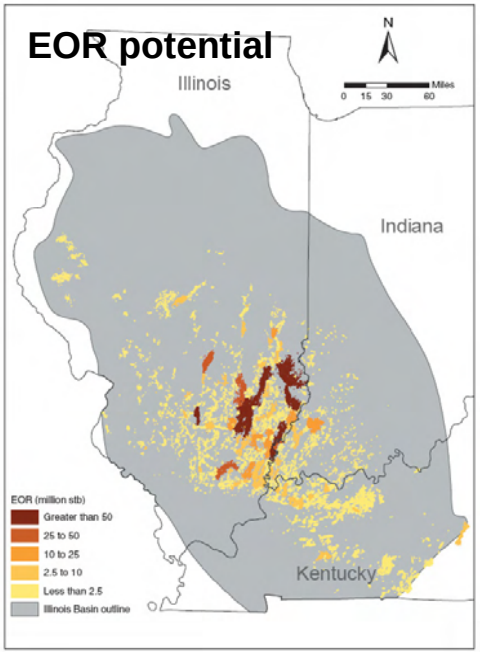




Many aspects of CCS site selection have special relevance to UCG site selection







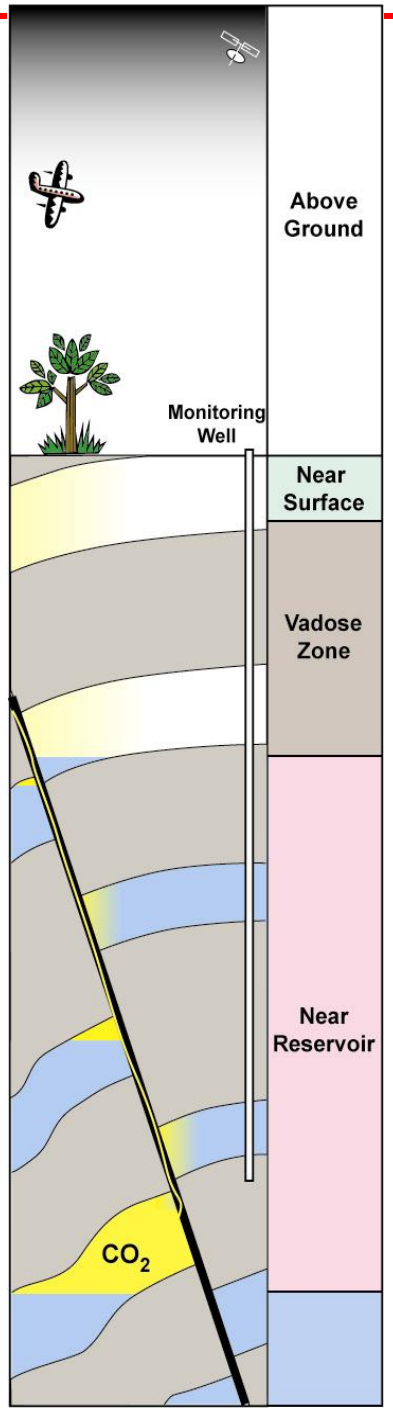
Overlying coals:

- "Fail-safe" filters for CO_2 leaks
- Good UCG containment helps CCS
- Coincidence of thick, deep seams and EOR/Saline Form. units

Infrastructure and economics

- Share pipeline rights of way
- Partial/complete CO2 capture streams for EOR
- Shared monitoring network
- Potential for joint permitting

Once injection begins, monitoring and verification (M&V) is required



MMV serves these key roles:

- Understand key features, effects, & processes
- Injection management
- Delineate and identify leakage risk and leakage
- Provide early warnings of failure
- Verify storage for accounting and crediting

Currently, there are abundant viable tools and methods; however, only a handful of parameters are key

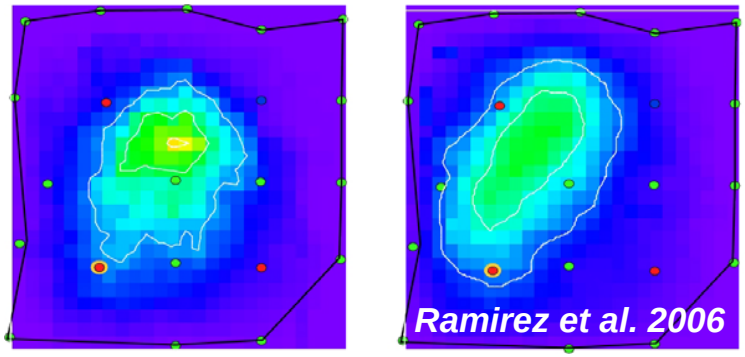
- Direct fluid sampling via monitoring wells (e.g., U-tube)
- T, P, pH at all wells (e.g., Bragg fiberoptic grating)
- CO_2 distribution in space: various proxy measures
  (Time-lapse seismic clear best in most cases)
- CO_2 saturation (eg Electrical Resistance Tomography)
- Surface CO_2 changes, direct or proxy
  (atmospheric eddy towers best direct; LIDAR may surpass)
  (perfluorocarbon tracing or noble gas tracing best proxies)
- Stress changes (tri-axial tensiometers)

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

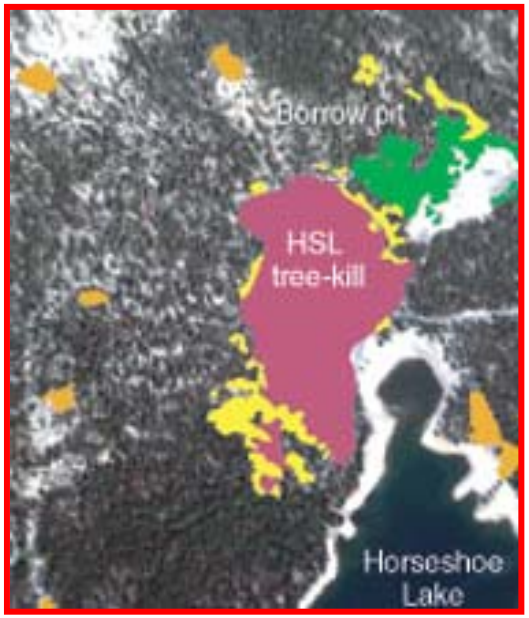
Tools that could monitor UCG process could also be used to monitor CCS, and visa versa

~4600 m^3 of CO_2 injected ~6300 m^3 of CO_2 injected



Leakage risks remain a primary concern

1) High CO_2 concentrations (>15,000 ppm) can harm environment & human health.
2) There are other potential risks to groundwater, environment
3) Concern about the effectiveness & potential impact of widespread CO_2 injection
4) Economic risks flow from uncertainty in subsurface, liability, and regulations



Elements of risk can be prioritized

- Understanding high-permeability conduits (wells and faults)
- Predicting high-impact effects (asphyxiation, water poisoning)
- Characterizing improbable, high-impact events (potential catastrophic cases)

The focus for CO_2 storage operations should be HAZARDS first, RISKS second

HAZARDS are easily mapped & understood, providing a concrete basis for action

RISK = Probability * consequence

RISKS are often difficult to determine

- **Hard to get probability or consequence from first principles**
- **Current dearth of large, well-studied projects prevents empirical constraint**

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	Groundwater degradation	Crustal deformation
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

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

Friedmann, 2007

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

Hypothetical Case: Texas GOM 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

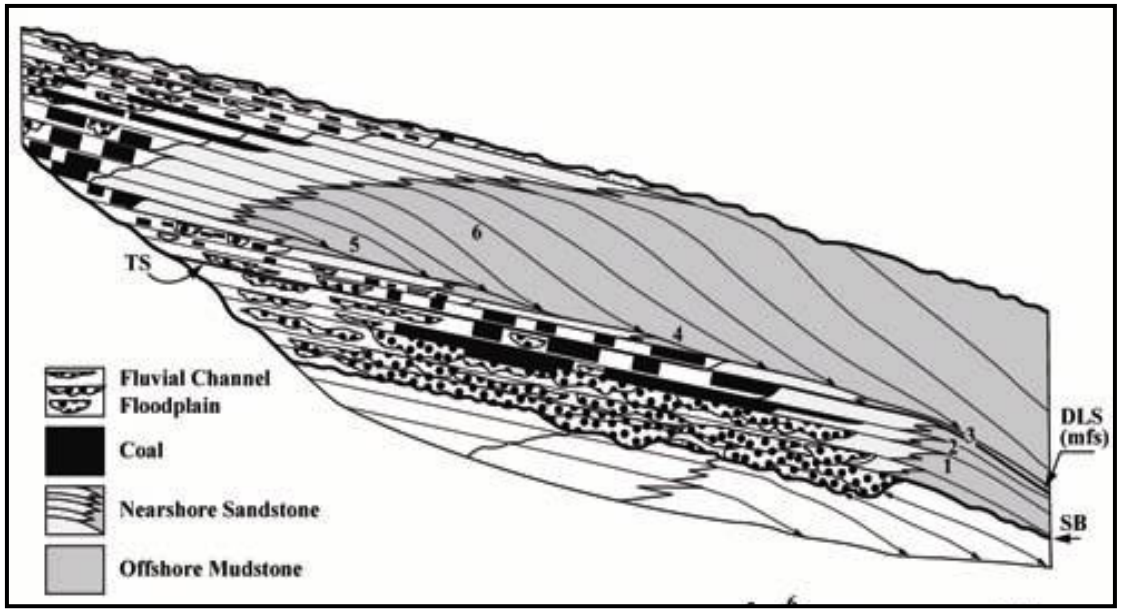
Part of protocol design is to provide a basis for this kind of local prioritization for a small number of classes/cases

Environmental Issues In UCG

- **Migration of VOCs into potable groundwater**
- **Organic compounds derived from coal and solubilized metals from minerals migrating into groundwater**
- **Upward migration of contaminated groundwater due to:**
  - Thermally-driven flow away from burn chamber
  - Buoyancy effects from fluid density gradients resulting from changes in dissolved solids and temperature
  - Changes in permeability of reservoir rock due to UCG.

LLNL has outlined criteria for site selection and planning with environmental concerns in mind

- **Geological Assessments**
  - **Structural**
  - **Stratigraphic**
  - **Hydrologic**
- **Contaminant Transport Prediction**
  - **Potential contaminant types from coal and rock mineral compositions**
  - **Contaminant behavior under UCG burn and post-burn conditions**



Stratigraphic category	Lateral Isolation	Overlying Unit Character	Relative Risk
1	Low	Sand-prone	High
2	Low	Shale-prone	Moderate
3	High	Shale-prone	Low
4	Moderate	Shale-prone	Moderate
5	Moderate	Sand-prone	High
6	Low	Sand-prone	High

CO_2 storage within UCG reactor zones: Caveats

UCG processes cause thermal, geomechanical, and geochemical changes to the reservoir:

- Heating/quenching effects on fractures and rock properties
- Enhanced permeability from acid leaching of ash, tars, char, coal, rock minerals
- Changes in fluid density from temperature and TDS
- Increased solubility of organic contaminants in CO_2
- Increased solubility of metals in acid groundwaters

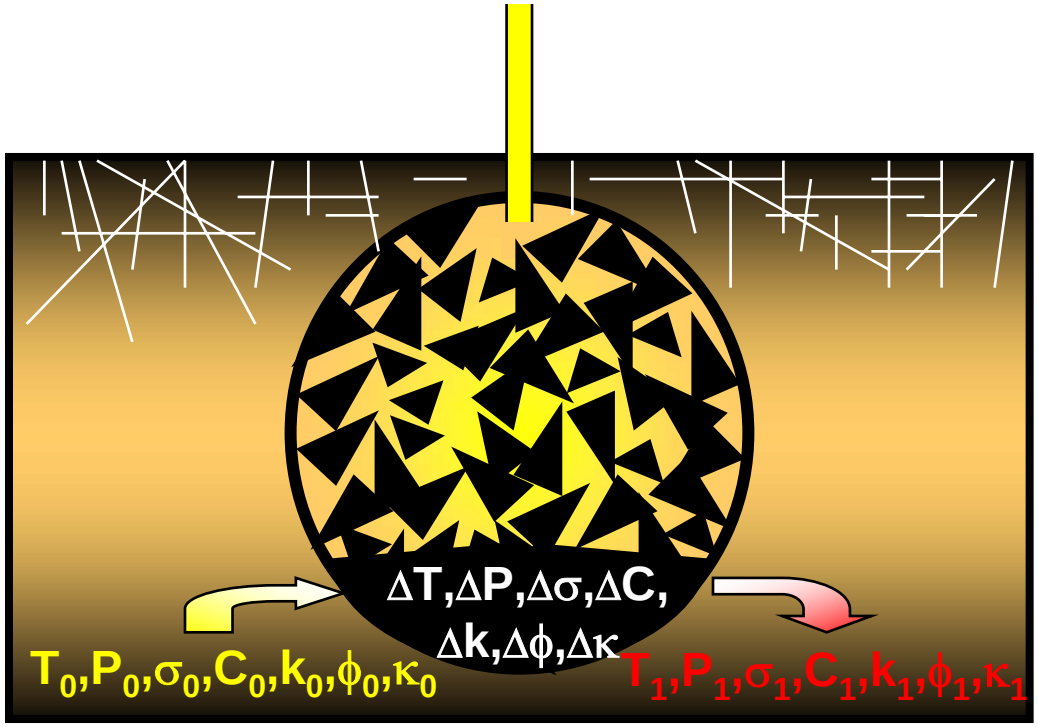
These concerns are credible.

The scientific or empirical basis to quantify these risks has not yet been established.

The potential advantages & disadvantages suggest a targeted research program

Key scientific concerns should be addressed in lab, simulation, and field-based investigations

- **T-P-D constraints for effective storage operation**
- **Geomechanical response**
- **Environmental risk from displaced UCG zone water**
- **Geochemical effects**
- **Long-term fate of CO_2**



These concerns can be addressed quickly and effectively with a research agenda involving experiments, coupled-process simulations, and field injections, monitoring, and verification

Modeling Demonstrates Complexity of Managing Environmental Risk

- **The complexity of UCG systems requires use of hydrological, geochemical and geomechanical models to capture:**
  - generation and behavior of contaminants within the burn chamber,
  - enhanced vertical hydraulic conductivity of the rock matrix above the burn chamber as a result of collapse and fracturing, and
  - buoyancy-driven upward flow of groundwater in the vicinity of the burn chamber toward potable water resources at shallower depths

- **The CFD process models and the Aspen Plus models need to be integrated with the environmental models**
  - Balancing gasifier operational pressure against hydrologic pressure and other gradients in the field to prevent outward contaminant migration.

Conclusions regarding UCG and CCS

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Low-cost syngas provides cost-competitive opportunities for CO_2 capture & separation

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