CO_2 as Cushion Gas for Compressed Air Energy Storage

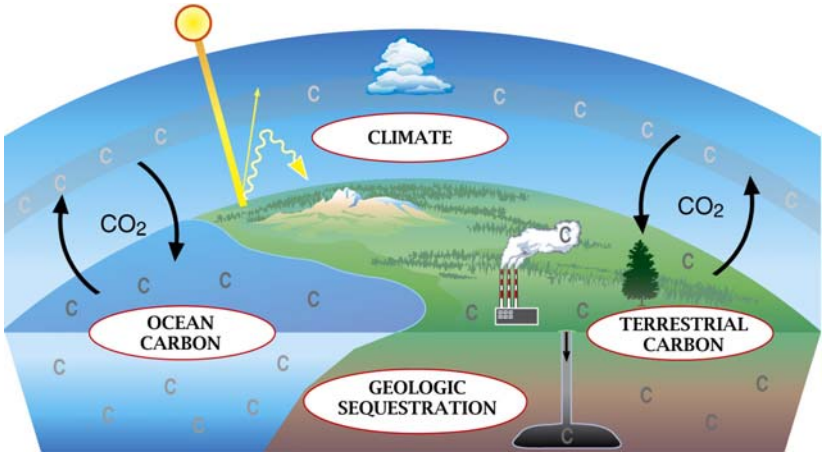
Curtis M. Oldenburg

Lehua Pan

Earth Sciences Division
LBNL

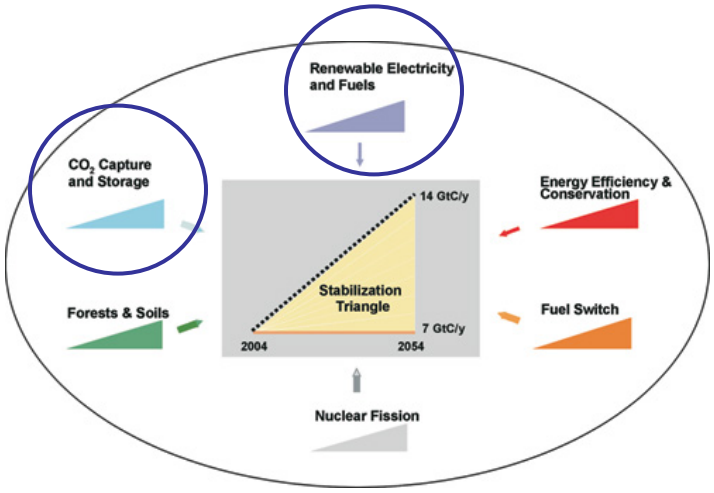
January 21, 2011

Carbon Cycle 2.0 LDRD Seminar Series
ALS User Support Building (15-253)



Source: Margaret Torn (LBNL)

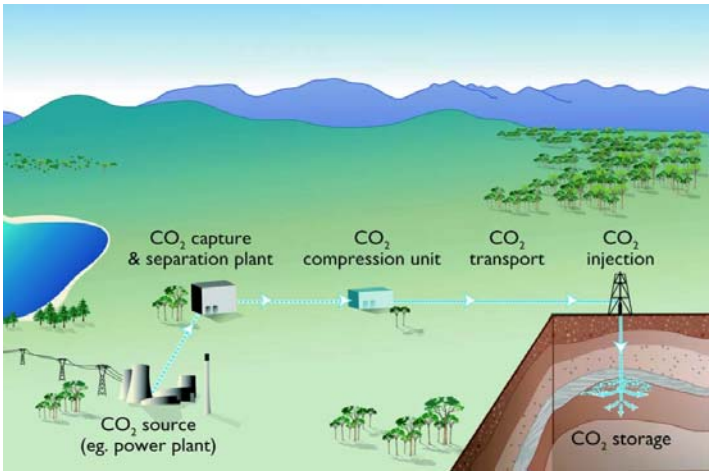
Options Available



http://www.princeton.edu/~cmi/resources/stabwedge.htm

3

Carbon Capture and Storage (CCS)

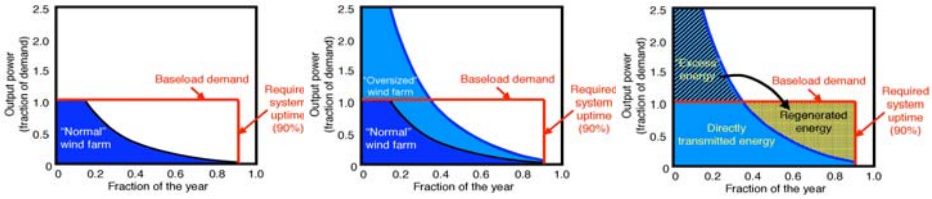


(From IPCC Special Report on CO_2 Capture and Storage)

Renewables Need Energy Storage

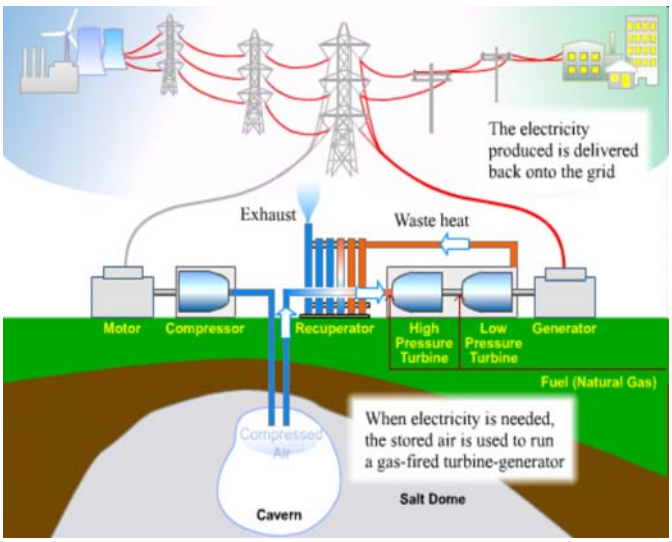
Figure 2: Timescales of natural cycles of renewable energies

Source: International Energy Agency (IEA), Variability of wind power and other renewables: Management options and strategies, IEA Publications, June 2005.



Source: Samir Succar, IAC Workshop, October 2005.

Diabatic Cavern CAES Schematic



http://web.ead.anl.gov/saltcaverns/overview/index.htm

State of the Art

- Today there are two CAES plants world-wide.
  - Huntorf, Germany (290 MW, in operation for 30 yrs)
    - Two solution-mined salt caverns
    - 48-66 bar, for black start of nearby nuclear plant
  - McIntosh, Alabama (110 MW, in operation for 20 yrs)
    - Solution-mined salt cavern
    - 45-74 bar, supply for network of coal plants

Compressed air locomotive operated at the Homestake mine from 1928-1961.

Recover Heat of Compression

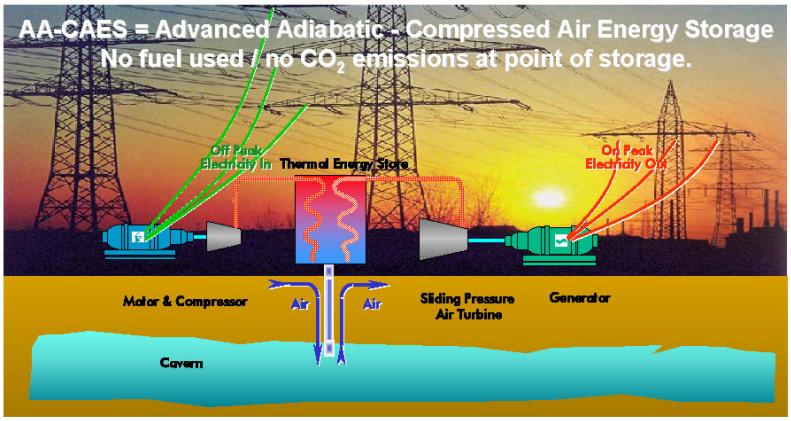


Figure 1. Schematic arrangement of the main elements of an Adiabatic CAES plant

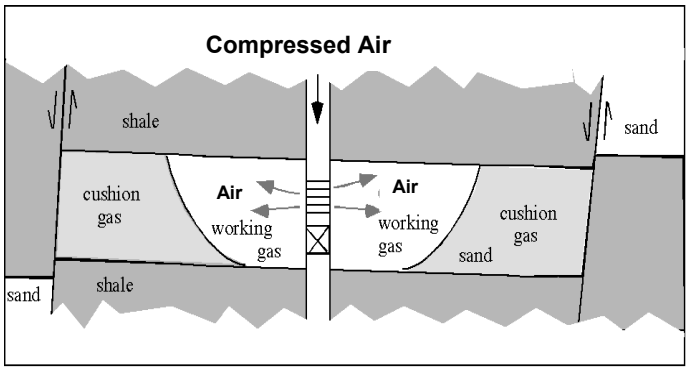
(From Bullough et al., 2004)

Advancing the State of the Art

- Neither of the existing plants has anything to do with renewables.
- Both are in caverns.
- Cavern volumes are limited.
- Aquifers and depleted-reservoirs are available for CAES, but have not been used to date.
- An analogue of CAES is natural gas storage which is done in aquifers and depleted reservoirs.
- Alternative cushion gas has been used in natural gas storage (specifically, N_2).
- Use of non-air cushion gas for CAES is novel.

Cushion and Working Gas

- Production of air from the reservoir relies on presence of a cushion gas (gas that is not produced, but whose pressurization drives working gas out of reservoir).

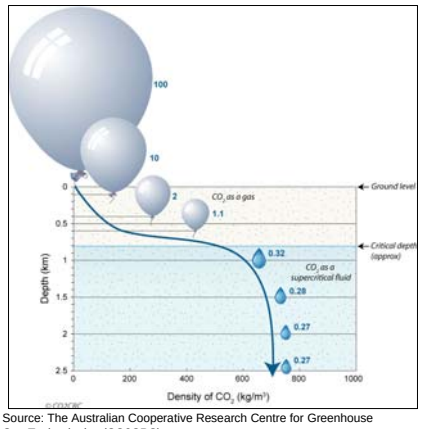


Oldenburg, C.M., *Energy&Fuels*, *17*(1), 240–246, 2003.

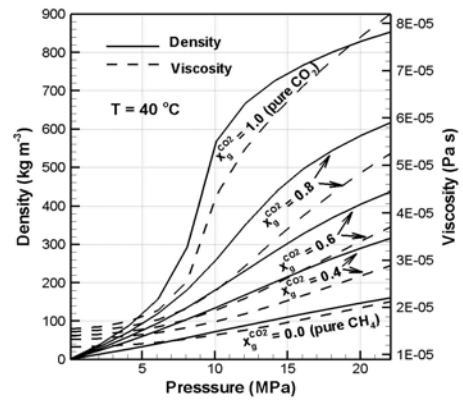
Enhancement of CAES Using CO_2

- **CO_2 around its critical pressure behaves like a super-cushion**

Oldenburg, C.M., *Energy&Fuels*, *17*(1), 240–246, 2003.



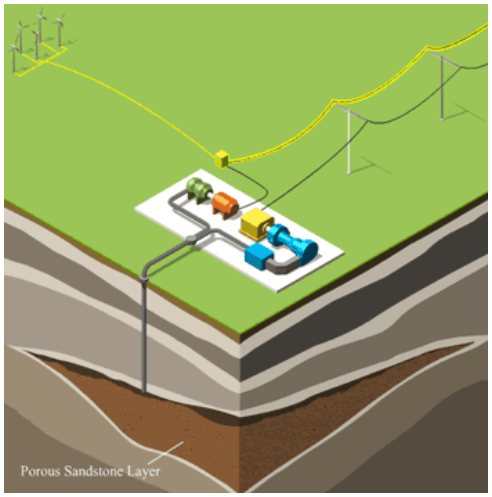
Source: The Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)



Advancing the State of the Art

- Neither of the existing plants has anything to do with renewables.
- Both are in caverns.
- Cavern volumes are limited.
- Aquifers and depleted-reservoirs are available for CAES, but have not been used to date.
- An analogue of CAES is natural gas storage which is done in aquifers and depleted reservoirs.
- **Alternative cushion gas has been used in natural gas storage (specifically, N_2).**
- **Use of non-air cushion gas for CAES is novel.**

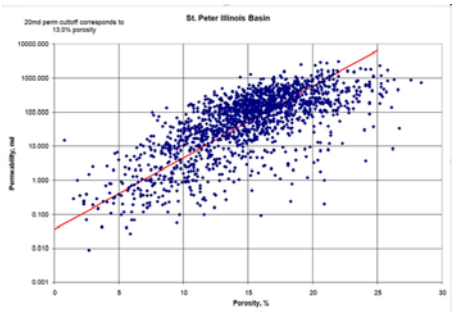
CAES in Aquifers or Depleted Reservoirs



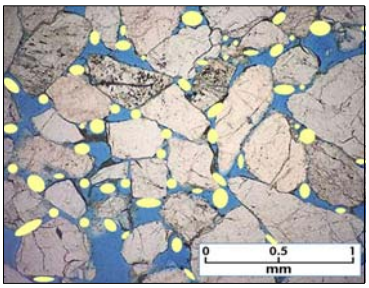
http://www.isepa.com/about_isep.asp

Aquifers ≠ Caverns

- Pore space (porosity)
- Permeability
- Two-phase flow
  - Capillary forces (wetting phase, non-wetting phase)
  - Relative permeability

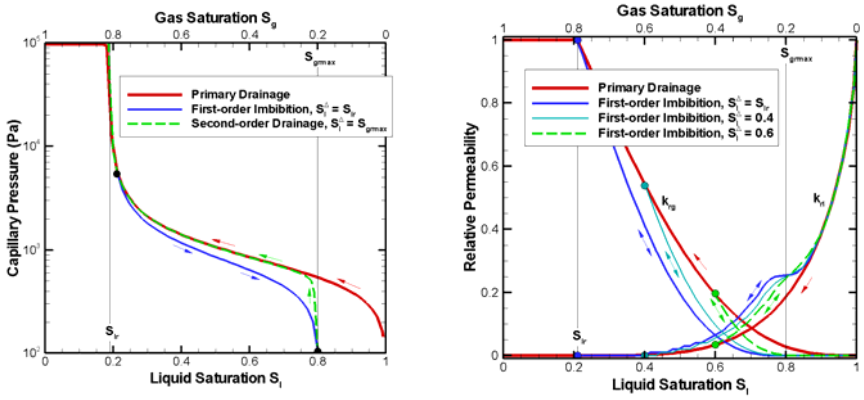


Source: Leetaru et al. http://knoxstp.com/reservoir.htm



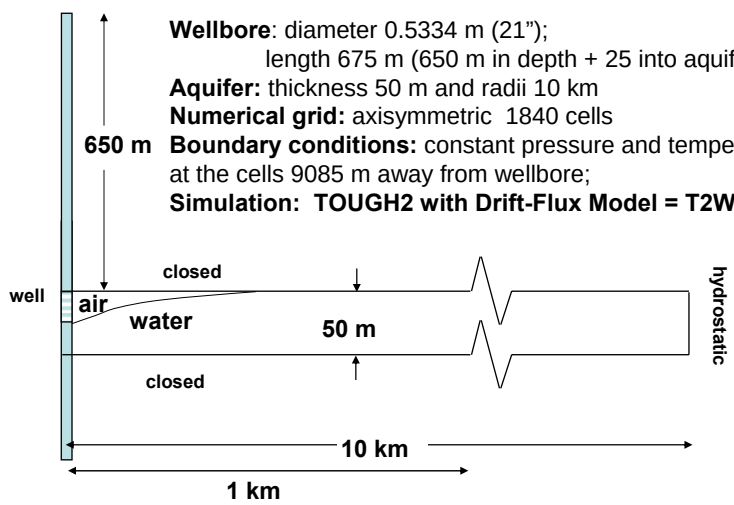
Source: John Beyer (LBNL)

P_{cap} and k_{rel} Curves



Source: Christine Doughty (LBNL)

Simulation of Aquifer-CAES



Wellbore: diameter 0.5334 m (21”);
length 675 m (650 m in depth + 25 into aquifer);
Aquifer: thickness 50 m and radii 10 km
Numerical grid: axisymmetric 1840 cells
Boundary conditions: constant pressure and temperature at the cells 9085 m away from wellbore;
Simulation: TOUGH2 with Drift-Flux Model = T2Well

The TOUGH Codes

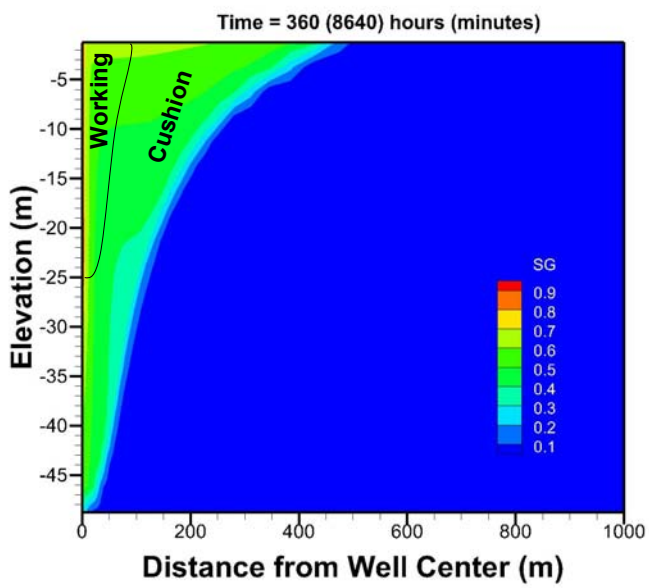
- TOUGH: Transport Of Unsaturated Groundwater and Heat

multidimensional	1D, 2D, 3D
multiphase	liquid, gas, NAPL
multicomponent	water, air, VOC, radionuclides
nonisothermal	heat
flow and transport	multiphase Darcy law
fractured-porous media	dual-ϕ, dual-k, MINC, ECM

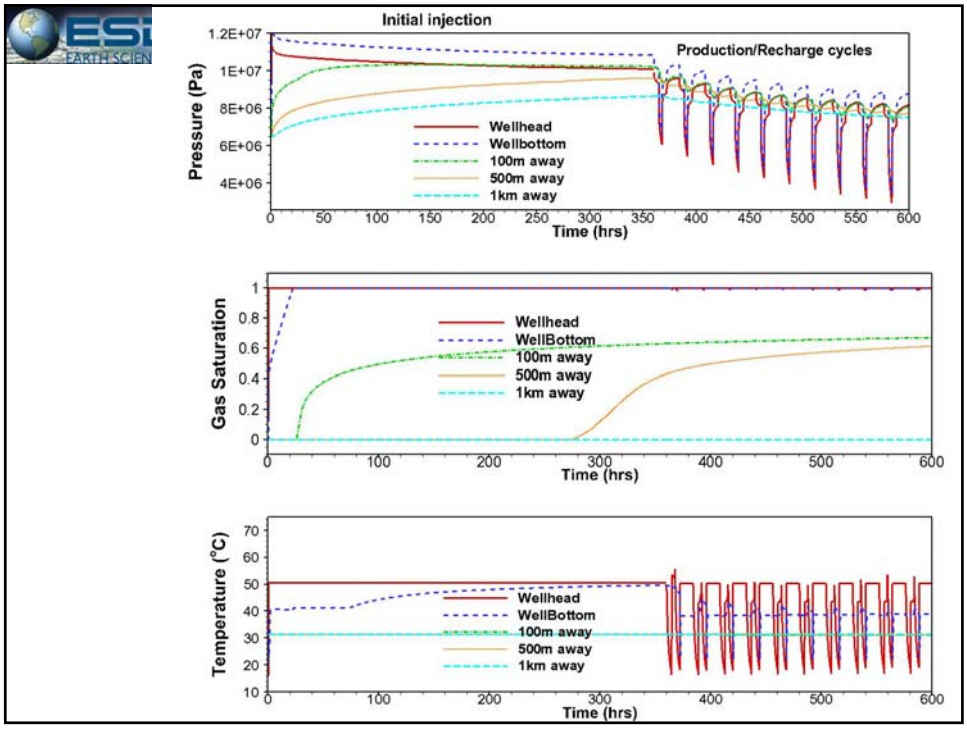
EOS: Accurate description of thermophysical properties

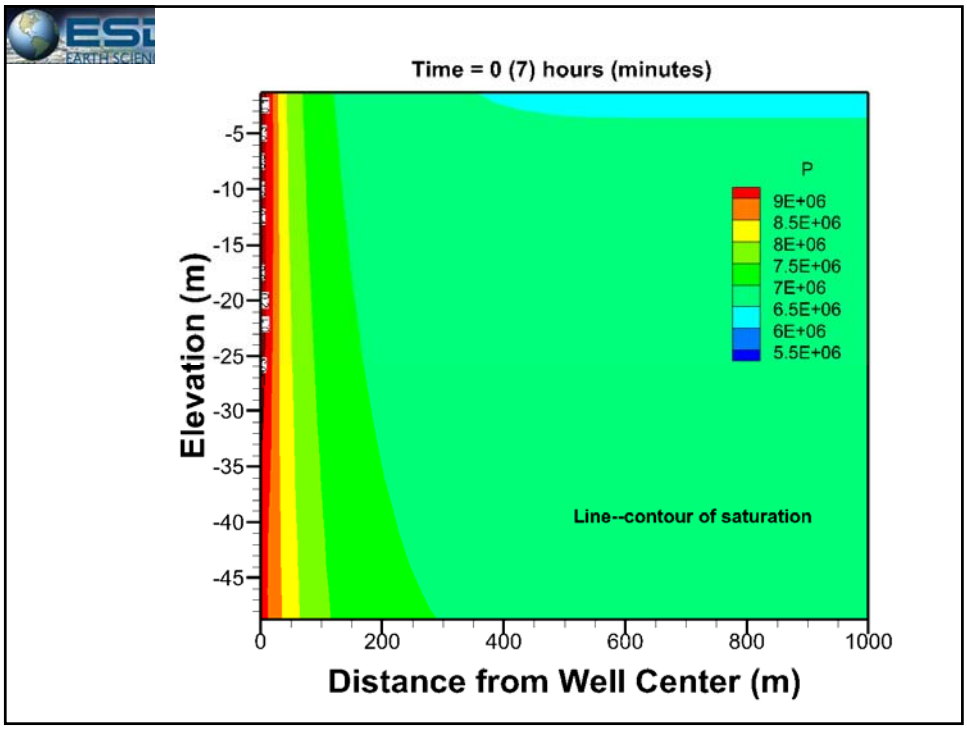
http://esd.lbl.gov/TOUGH2/

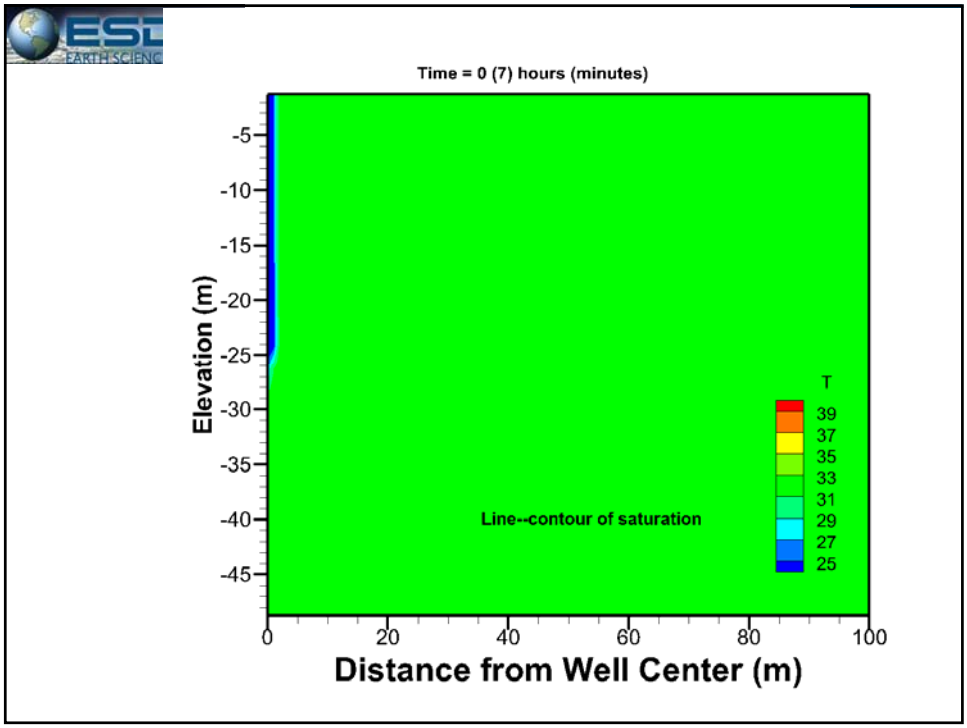
http://esdtools.lbl.gov/gaseos/

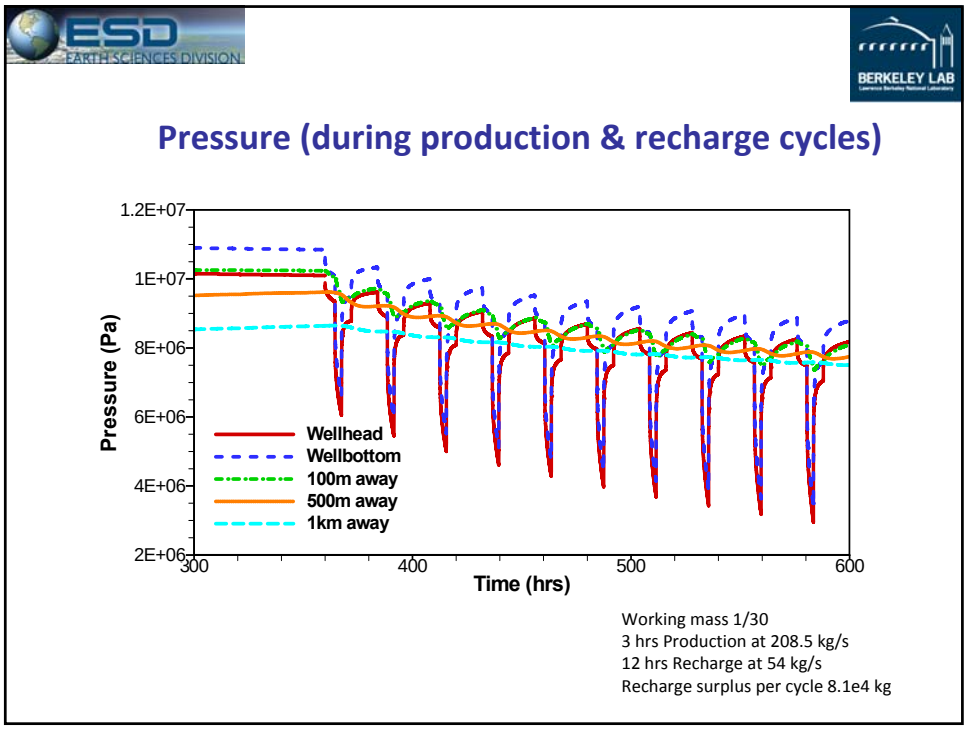


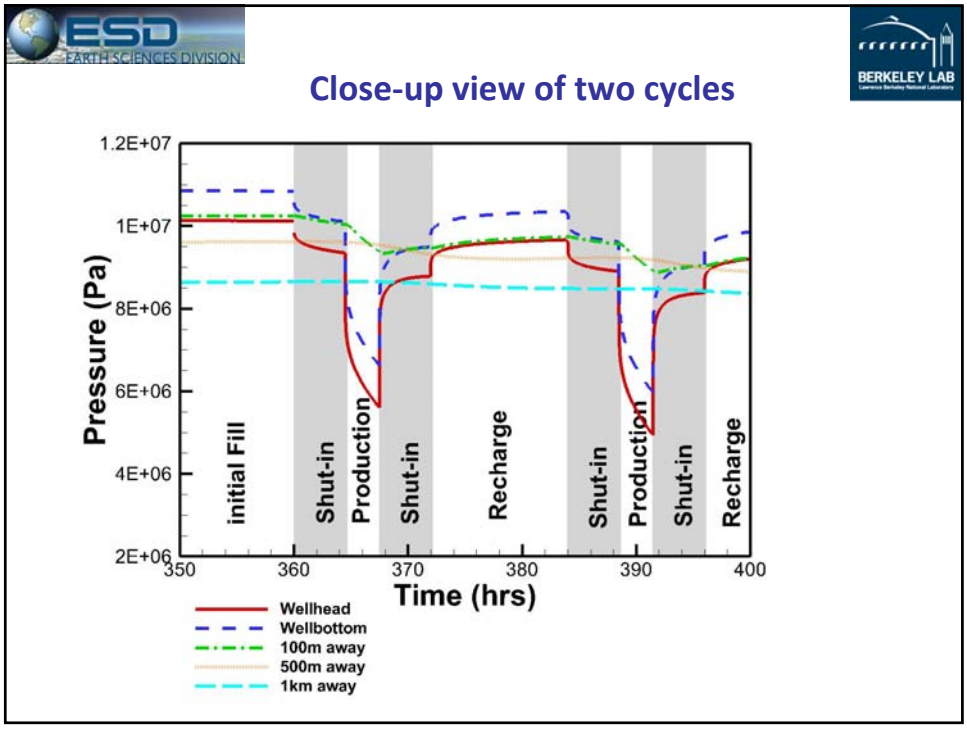
Note:
- **30 times as much air in the bubble compared to working gas**
- **Two-phase zone**
- **Bubble evolves (flattens) over time.**

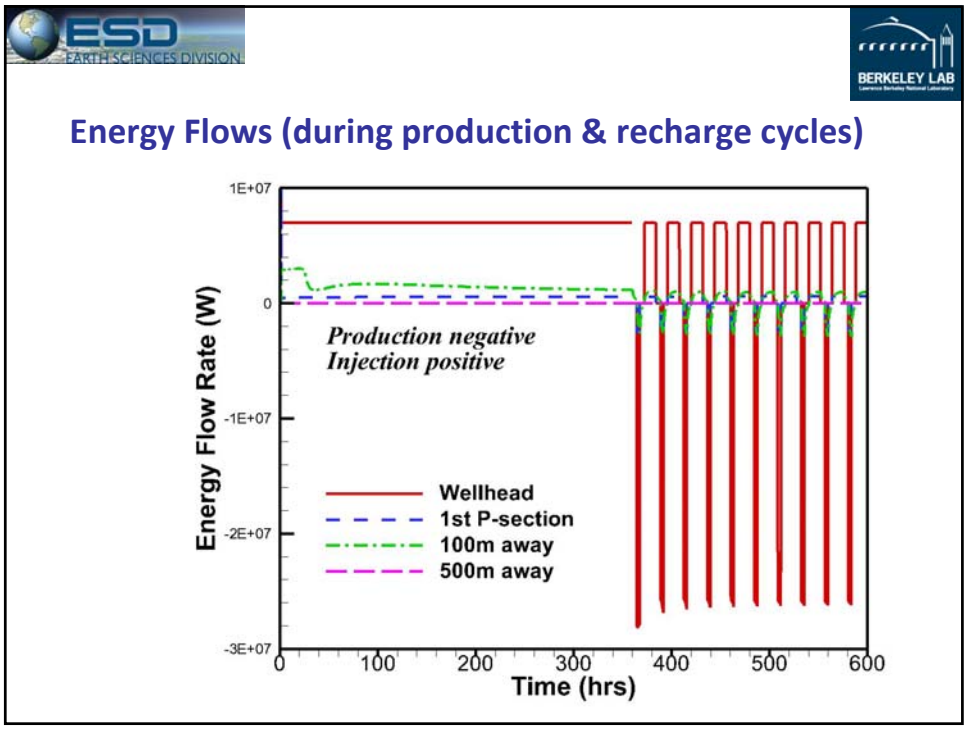

Initial injection
Production/Recharge cycles
Pressure (Pa)
Time (hrs)
Wellhead
Wellbottom
100m away
500m away
1km away
Gas Saturation
WellBottom
Temperature (°C)


Time = 0 (7) hours (minutes)
P
9E+06
8.5E+06
8E+06
7.5E+06
7E+06
6.5E+06
6E+06
5.5E+06
Line--contour of saturation
Elevation (m)
Distance from Well Center (m)

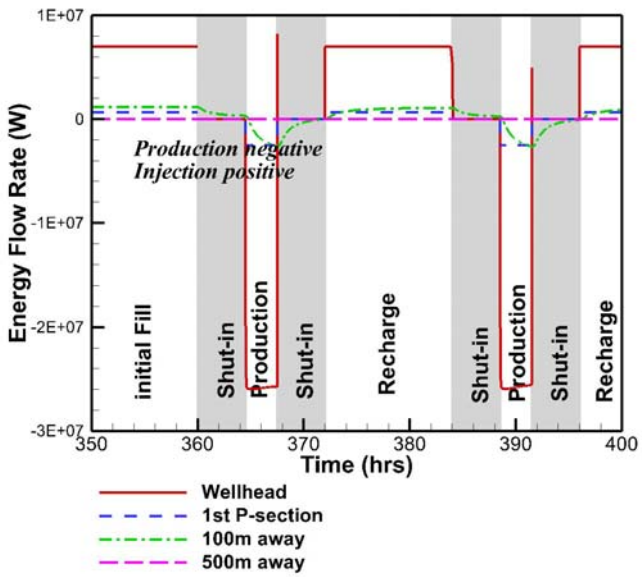

Time = 0 (7) hours (minutes)
Elevation (m)
-5
-10
-15
-20
-25
-30
-35
-40
-45
0
20
40
60
80
100
Distance from Well Center (m)
T
39
37
35
33
31
29
27
25
Line--contour of saturation


Pressure (during production & recharge cycles)
Pressure (Pa)
1.2E+07
1E+07
8E+06
6E+06
4E+06
2E+06
300
400
500
600
Time (hrs)
Wellhead
Wellbottom
100m away
500m away
1km away
Working mass 1/30
3 hrs Production at 208.5 kg/s
12 hrs Recharge at 54 kg/s
Recharge surplus per cycle 8.1e4 kg


ESD
EARTH SCIENCES DIVISION
BERKELEY LAB
Close-up view of two cycles
Pressure (Pa)
1.2E+07
1E+07
8E+06
6E+06
4E+06
2E+06
350
360
370
380
390
400
Time (hrs)
initial Fill
Shut-in
Production
Shut-in
Recharge
Shut-in
Production
Shut-in
Recharge
Wellhead
Wellbottom
100m away
500m away
1km away

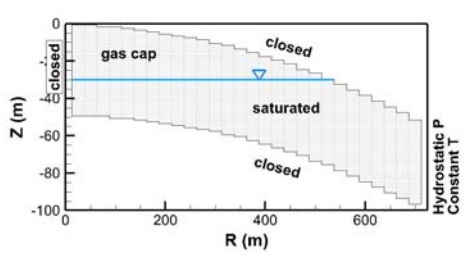

ESD
EARTH SCIENCES DIVISION
BERKELEY LAB
Energy Flows (during production & recharge cycles)
Energy Flow Rate (W)
1E+07
0
-1E+07
-2E+07
-3E+07
Production negative
Injection positive
Wellhead
1st P-section
100m away
500m away
0
100
200
300
400
500
600
Time (hrs)

Close-up view of two cycles



Preliminary Simulation of Gas-Reservoir CAES with CO_2 as Cushion Gas

Aquifer: thickness 50 m and radius 725 m
Numerical grid: axisymmetric 1449 cells
Boundary conditions: constant pressure and temperature at the down-dip water leg boundary.
Wellbore: diameter 0.5334 m (21”);
length 675 m (650 m in depth + 30 m into aquifer) (**not yet implemented**);



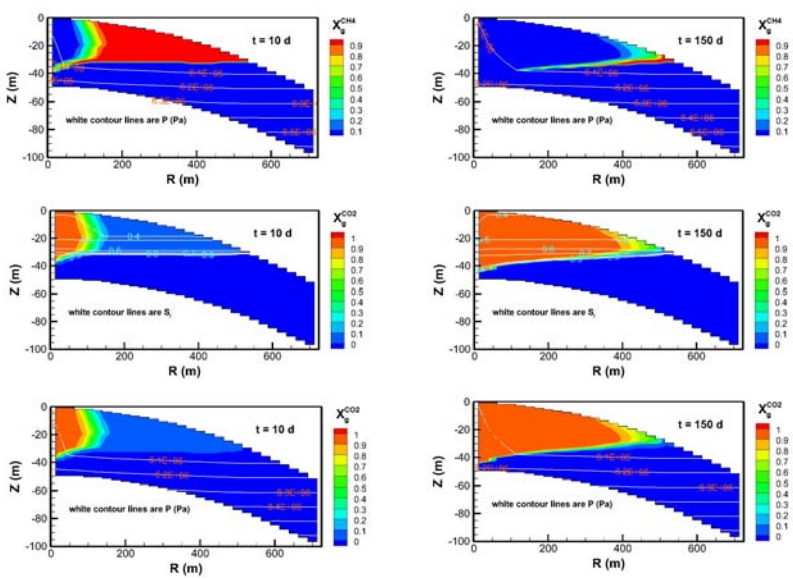
Details of Gas-Reservoir CAES Simulation

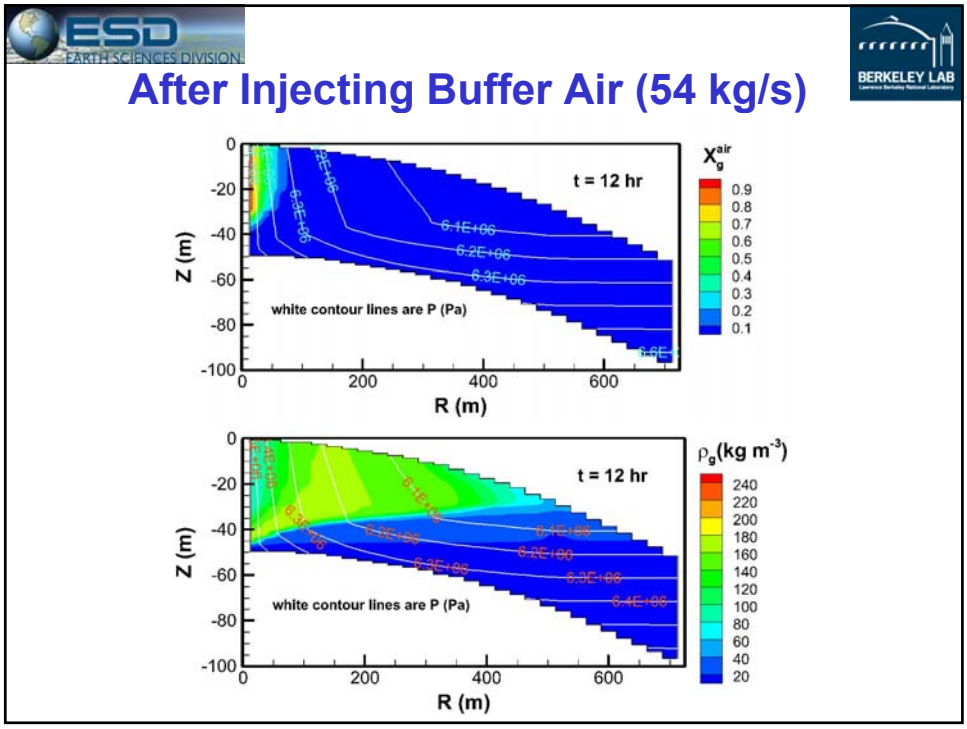
Simulation: TOUGH2 with Drift-Flux Model for wellbore flow = T2Well*
Injection: Into the top 30 gridblocks on the LHS
Initial fill of CO_2: 21.7 kg/s for 180 days (total of 0.7 Mt CO2)
Inject air buffer: 12 hours at 54 kg/s
Inject air working gas: 6 hours at 810 kg/s
Inject air working gas: 12 hours at 540 kg/s
Production of air working gas: 6 hours at 104.25 kg/s
Recharge: 12 hours at 540 kg/s
Initial condition: hydrostatic pressure and uniform temperature
Boundary conditions: constant pressure and temperature at down-dip edge of structure; wellhead is prescribed injection (air) rate with enthalpy of 0.13005E+06 J/kg or production (mass) rate.

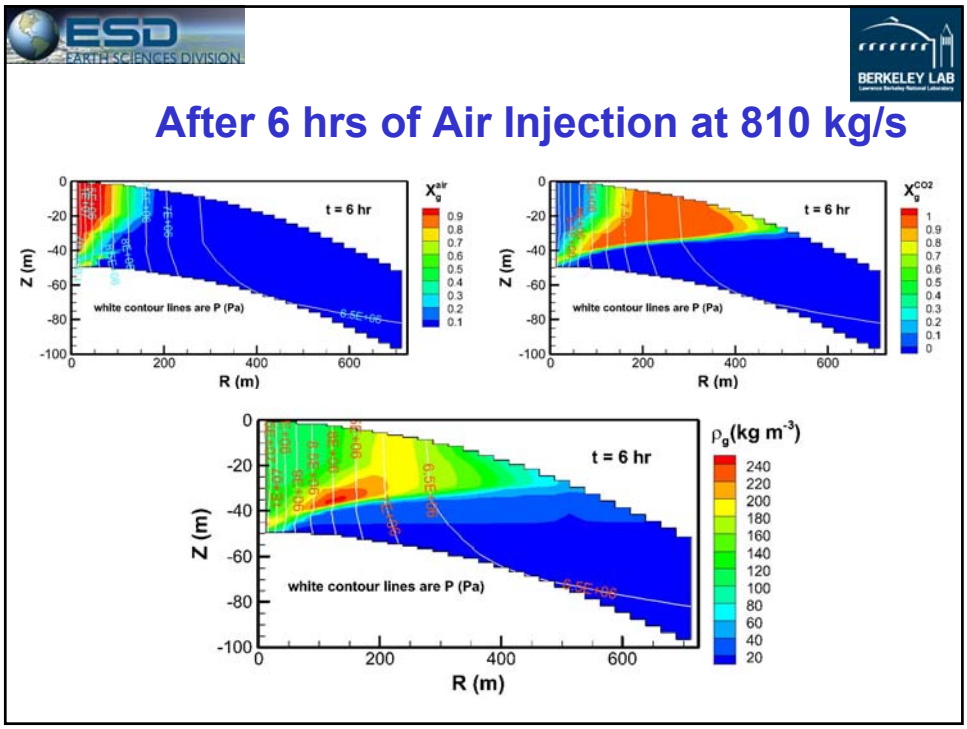
Schedule:
TBD

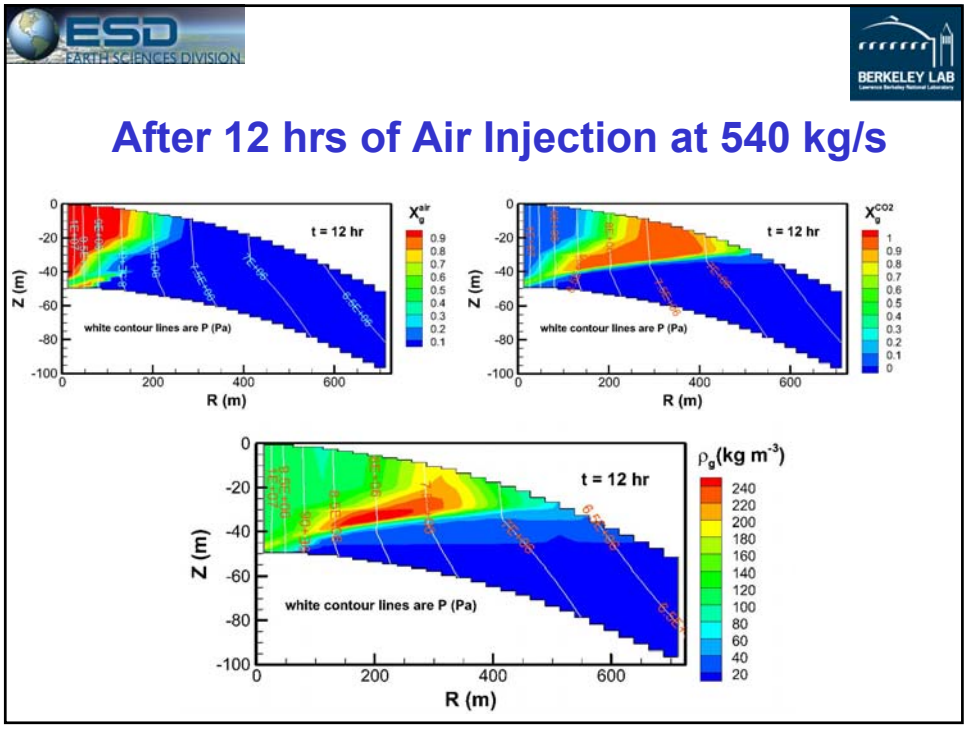
***Pan, L., C.M. Oldenburg, Y.-S. Wu, and K. Pruess, Wellbore flow model for carbon dioxide and brine, *Energy Procedia*, GHGT9 conference, Nov. 16-20, 2008, Washington DC. LBNL-1416E.**

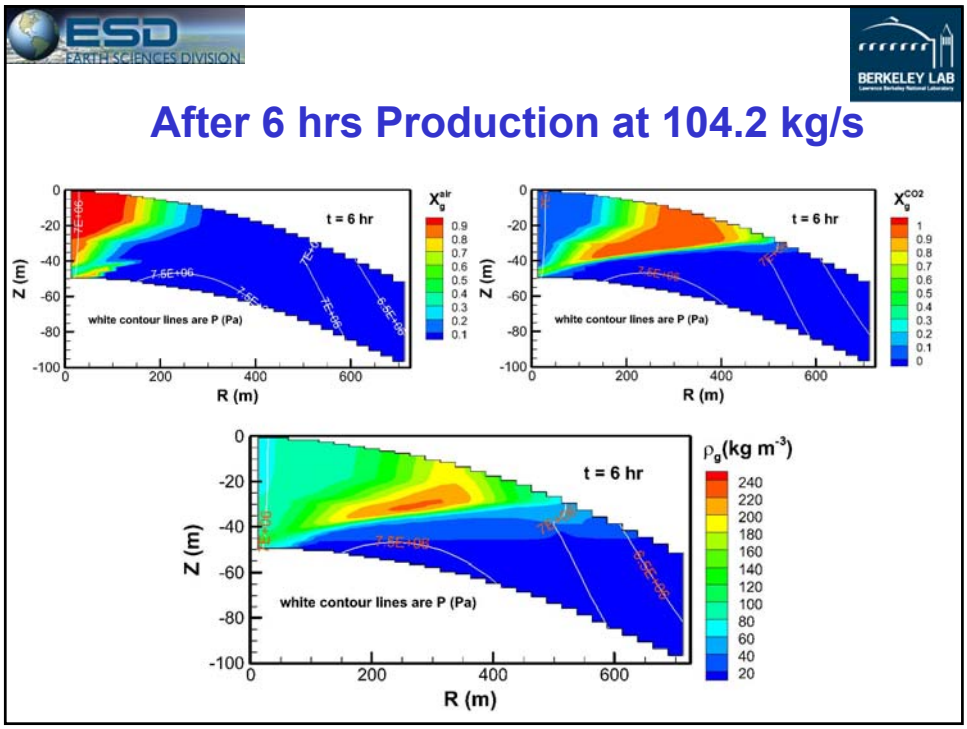
Initial Fill with CO_2 (CH_4 Recovery)



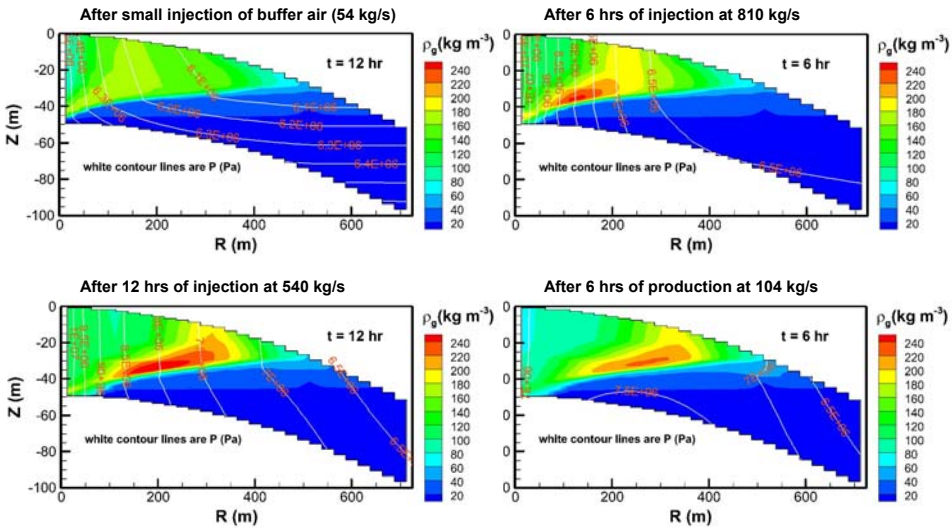

ESD
EARTH SCIENCES DIVISION
BERKELEY LAB
After Injecting Buffer Air (54 kg/s)
t = 12 hr
white contour lines are P (Pa)
Z (m)
R (m)
X_g^{air}
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
6.1E+06
6.2E+06
6.3E+06
t = 12 hr
white contour lines are P (Pa)
Z (m)
R (m)
ρ_g(kg m^{-3})
240
220
200
180
160
140
120
100
80
60
40
20


ESD
EARTH SCIENCES DIVISION
BERKELEY LAB
After 6 hrs of Air Injection at 810 kg/s
t = 6 hr
white contour lines are P (Pa)
Z (m)
R (m)
X_g^{air}
t = 6 hr
white contour lines are P (Pa)
Z (m)
R (m)
X_g^{CO2}
t = 6 hr
white contour lines are P (Pa)
Z (m)
R (m)
ρ_g(kg m^{-3})


ESD
EARTH SCIENCES DIVISION
BERKELEY LAB
After 12 hrs of Air Injection at 540 kg/s
t = 12 hr
white contour lines are P (Pa)
Z (m)
R (m)
X_g^{air}
X_g^{CO2}
ρ_g(kg m^{-3})


ESD
EARTH SCIENCES DIVISION
BERKELEY LAB
After 6 hrs Production at 104.2 kg/s
t = 6 hr
white contour lines are P (Pa)
Z (m)
R (m)
X_g^{air}
X_g^{CO2}
ρ_g(kg m^{-3})

Density Evolution



Conclusions

- Climate change motivates CCS and increased use of renewables.
- Renewables need energy storage (e.g., CAES) to meet baseload requirements.
- CCS can potentially be coupled with CAES.
- Price on carbon would subsidize CAES project.
- CAES could benefit by super-cushion properties of CO_2.
- We are evaluating the benefits and risks of using CO_2 as a cushion gas.

Acknowledgments

This work was supported in part by the Office of Science, U.S. Department of Energy, and by the Assistant Secretary for Fossil Energy (DOE), Office of Coal and Power Systems, through the National Energy Technologies Laboratory (NETL), and by Lawrence Berkeley National Laboratory under Department of Energy Contract No. DE-AC02-05CH11231 .