Title

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Author

Peters, C. A.

Publication Date

2011-04-22

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Catherine A. Peters[a,]*, Patrick F. Dobson[b], Curtis M. Oldenburg[b], Joseph S. Y. Wang[b],
Tullis C. Onstott[a], George W. Scherer[a], Barry M. Freifeld[b], T.S. Ramakrishnan[c],
Eric L. Stabinski[c], Kenneth Liang[c], Sandeep Verma[c]

[a]*Dept. of Civil & Environmental Engineering, Princeton University, Princeton, NJ 08544 USA*
[b]*Earth Sciences Division 90-1116, Lawrence Berkeley National Laboratory, Berkeley CA 94720 USA*
[c]*Schlumberger-Doll Research Center, 1 Hampshire Street, Cambridge, MA 02139 USA*

Abstract

LUCI, the Laboratory for Underground CO_2 Investigations, is an experimental facility being planned for the DUSEL underground laboratory in South Dakota, USA. It is designed to study vertical flow of CO_2 in porous media over length scales representative of leakage scenarios in geologic carbon sequestration. The plan for LUCI is a set of three vertical column pressure vessels, each of which is ~500 m long and ~1 m in diameter. The vessels will be filled with brine and sand or sedimentary rock. Each vessel will have an inner column to simulate a well for deployment of down-hole logging tools. The experiments are configured to simulate CO_2 leakage by releasing CO_2 into the bottoms of the columns. The scale of the LUCI facility will permit measurements to study CO_2 flow over pressure and temperature variations that span supercritical to subcritical gas conditions. It will enable observation or inference of a variety of relevant processes such as buoyancy-driven flow in porous media, Joule-Thomson cooling, thermal exchange, viscous fingering, residual trapping, and CO_2 dissolution. Experiments are also planned for reactive flow of CO_2 and acidified brines in caprock sediments and well cements, and for CO_2-enhanced methanogenesis in organic-rich shales. A comprehensive suite of geophysical logging instruments will be deployed to monitor experimental conditions as well as provide data to quantify vertical resolution of sensor technologies. The experimental observations from LUCI will generate fundamental new understanding of the processes governing CO_2 trapping and vertical migration, and will provide valuable data to calibrate and validate large-scale model simulations.

Keywords: Leakage; buoyancy; Joule-Thomson; experimental; storage

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* Corresponding author. Tel.: +1-609-258-5645; fax: +1-609-258-2799.
E-mail address: cap@princeton.edu

1. Introduction

Geologic carbon sequestration is one of the methods to reduce anthropogenic emissions of CO_2 and has the potential to mitigate the principal driver of global climate change. Geologic carbon sequestration involves capture, injection, and sequestration of large quantities of CO_2 into deep geologic formations. The benefits of geologic carbon sequestration would be negated if CO_2 leaks out of the targeted formation. At present, our understanding of CO_2 trapping and flow of leaking CO_2 relies on simulation and theoretical constructs rather than observation. Furthermore, parameters used in the simulations are based on measurements conducted on a small length scale. As a result, there is substantial uncertainty in our ability to predict the likelihood of leaks, the extent of leaked CO_2 that could reach the land surface, and the time frame for this transport.

In this paper, we present an overview of a planned experimental facility for controlled experimental study of CO_2 flow at vertical length scales that are realistic for geologic sequestration conditions. The proposed new facility is called LUCI, Laboratory for Underground CO_2 Investigations. The facility will be part of DUSEL, the Deep Underground Science and Engineering Laboratory, being built in the Homestake gold mine in South Dakota, USA. Here we describe the design and the motivating science for the experimental facility.

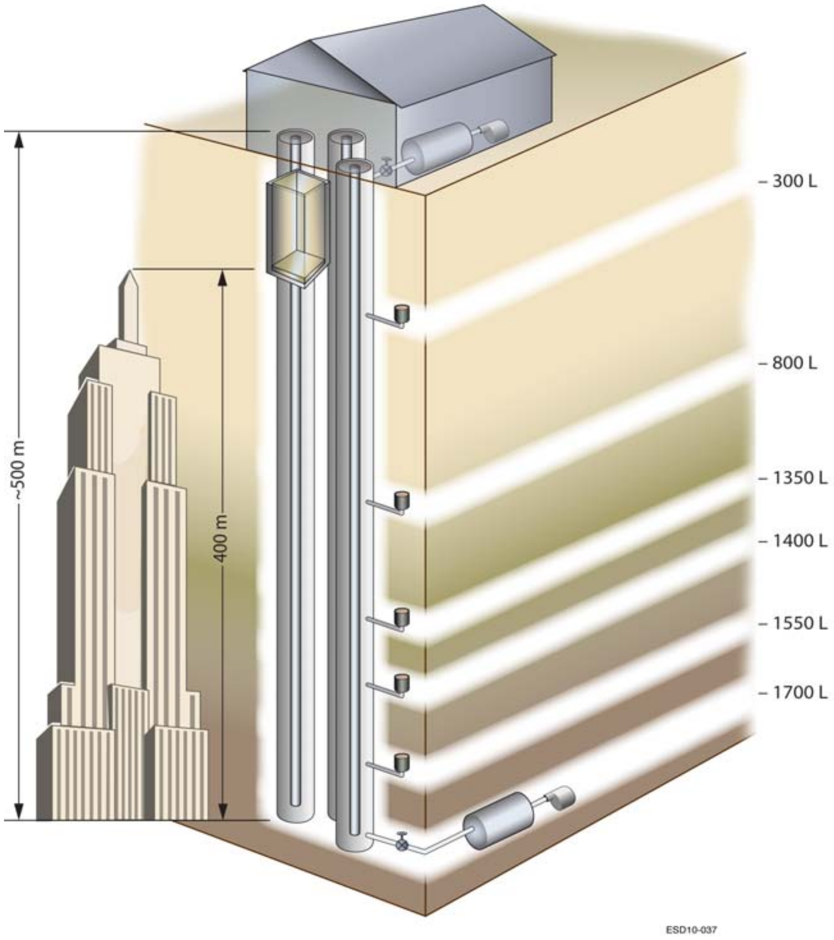

Figure 1. A graphical depiction (not to scale) of the LUCI experimental facility, showing the three vertical columns, the surface building, and the access drifts. The Empire State Building is depicted to indicate the vertical extent of this facility.

2. Plans for the LUCI Experimental Facility at DUSEL

LUCI is being designed for experiments to study CO_2 flow as it moves vertically through unconsolidated porous media, and the mechanisms that serve to trap it under impermeable layers. The facility will include three pressure vessels each having a length of ~500 m and a diameter of ~1 m (Figure 1). The vessels will have an inner column that will be used for sensors, similar to a monitoring well. The annular space between this column and the outer vessel walls will be filled with brine and sand or other relevant granular material that mimics the strata encountered in sedimentary basins prior to CO_2 injection. Thermal and pressure gradients along the length of the columns will be controlled to simulate real subsurface conditions. The columns will be highly instrumented to allow unprecedented monitoring of the governing thermal, physical, and chemical processes.

The vessels will be supported within a newly excavated 3m x 3m vertical shaft, and will extend from the land surface down to the 1700 ft (518 m) level (Figure 2). Within DUSEL, the new vertical shaft will be located ~150 m from one of the existing vertical mine shafts, the Ross Shaft. At the top, a LUCI surface building will be constructed. It will have rigging capabilities, and will house the tops of the columns, fluid containment vessels, materials preparation vessels, and ventilation system. Key to the experimental goals is the ability to make measurements and sample fluids along the lengths of the flow columns. The location of the shaft was selected with this in mind to enable access to the vessels at intermediate points between the top and bottom. Intermediate access will be possible from the levels at 300 ft (91 m), 800 ft (244 m), 1250 ft (381 m), 1400 ft (427 m), and 1550 ft (472 m) (Figure 2). At these levels, new excavations will connect existing drifts with the new shaft. In addition, access to the columns will be possible from an Alimak vertical transporter, which will climb and descend along a track attached to the wall of the shaft. Our current estimation is that the DUSEL CO_2 experimental facility will cost between \$40 and \$60 million U.S. dollars and it will take 2 ½ years to construct, once the DUSEL facility is ready. The earliest possible completion date is 2016.

The scale and accessibility of this facility will permit measurements that cannot be done in a conventional lab. The unique capabilities of LUCI will be:

- The ability to study CO_2 flow and reaction over pressure and temperature variations that span supercritical to and subcritical conditions.
- The ability to study flow and reaction over long length scales that allow observation of the difficult-to-model processes of channeling, backflow, and residual trapping.

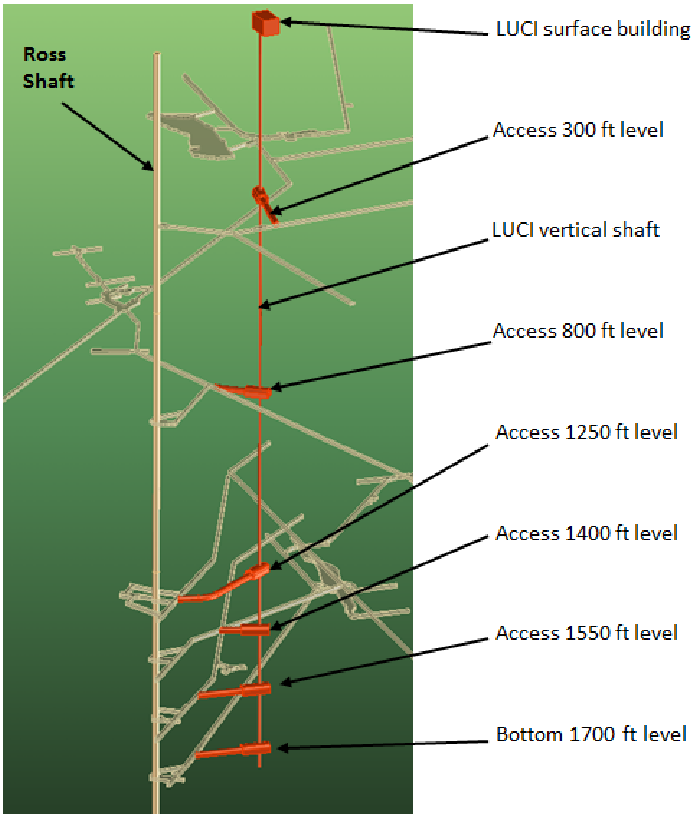

Figure 2. A diagram of the shafts and drifts in the Homestake mine near the Ross Shaft. Shown in red is the new 500 m vertical shaft planned for the LUCI facility and the planned horizontal excavations providing access from existing drifts. Graphic produced by Dave Plate (LBNL Engineering Division).

- The ability to create permeability heterogeneities to mimic those that exist in sedimentary basins and study their effects on flow and trapping.
- The potential for extensive instrumentation to directly sample and observe pressure and thermal gradients, gas and fluid flow, geochemistry, and geomicrobiology.
- The use of redundant approaches for verification and development of monitoring technologies.

3. Review of the relevant physics of CO_2 phase properties and buoyant rise of leaking parcels

The physics of vertical flow of buoyant CO_2 parcels is governed by processes occurring at multiple length scales. At the small length scales, corresponding to pore sizes, CO_2 flow is controlled by the displacement of fluid-fluid interface menisci, while at the 100 m scale CO_2 buoyancy is controlled by gradients in temperature and hydrostatic pressure.

At the depths considered for CO_2 injection and storage (below 1 km), hydrostatic pressure is greater than 100 bar and temperatures are typically greater than 35°C [1]. Figure 3 shows the phase states and densities of CO_2 for conditions corresponding to depths ranging from 400 m to 1400 m. In geologic carbon sequestration, CO_2 would be supercritical, having a density close to that of liquid CO_2 and a compressibility close to that of gaseous CO_2. Because the relevant pressure and temperature conditions are not far from the critical point of CO_2 (at 74 bar and 31°C), there is a large range in potential fluid densities under geologic storage conditions, from roughly 400 to 700 kg/m^3. Despite this large range, the densities are all substantially less than the density of the resident brines. The CO_2 will tend to flow upwards and form a CO_2 plume under an impermeable confining layer. If the plume of CO_2 encounters contiguous faults or permeable regions in the confining layer (e.g., Zhang et al. 2009 [2]; Wollenweber et al. 2010 [3]) or poorly-sealed abandoned wells [4], it can escape from the injection formation.

As CO_2 approaches shallower depths it may accelerate due to the increased buoyancy that comes from expansion of CO_2 from supercritical to subcritical conditions [5-6]. If the parcel rises quickly, adiabatic expansion and associated Joule-Thomson cooling would tend to mitigate the density difference [6]. The trailing surface of CO_2 may leave behind a residual saturation of isolated CO_2. Another possibility is the dissolution of CO_2 as it encounters fresh brines [7], a process heavily dependent on the interfacial surface area between the two fluids.

In the following discussion, we focus only on the impact of density variation, ignoring the added complexities from residual saturation trapping and CO_2 dissolution. In Figure 3, Scenario 1 represents the case of a rising parcel of CO_2 starting at a depth of 900 m at 45°C, with a geothermal gradient of 25°C per km and a land surface temperature of 22°C. The path indicated in Scenario 1 is for the case in which the CO_2 parcel has perfect heat exchange with its surroundings, thus experiencing the same change in temperature as its surroundings. Along this path, the CO_2 phase density changes from 400 kg/m^3 to 200 kg/m^3 over the first 250 m, indicating increasing buoyancy as the parcel rises.

Scenario 2 represents the case of a parcel of CO_2 starting at a depth of 1200 m, from a colder formation at 40°C. This could occur in a region where the land surface temperature is 10°C but with the same geothermal gradient of 25°C per km. While the pathway depicted in Scenario 2 also represents the case of perfect heat exchange with the surroundings, the variation in density along this path is very different from that in Scenario 1. The density at the origin is 740 kg/m^3, so it is much less buoyant than in Scenario 1, and the density does not change over the first 550 m of rise because the thermal gradient coincides with the isopycnic (constant density) contour. Thus the rise would not accelerate while the CO_2 is supercritical or liquid. However, at a depth of 620 m, the CO_2 fluid would boil as it passes from liquid to gas, suddenly expanding to a density of 250 kg/m^3. As a result, it would be suddenly much more buoyant and its rise would accelerate.

The extent to which a rising parcel of CO_2 will exchange heat with its surroundings depends on the size of the parcel, its surface area, its velocity, and the thermal conductivity of the fluids and rock matrix. Less than perfect heat exchange would mean that the rising parcel of CO_2 will be cooler than the surroundings. For example, Scenario 3 describes a case closer to adiabatic expansion. The substantial cooling along this trajectory means that rise velocity would be less accelerated along this path compared to Scenario 1, which shares the same starting point.

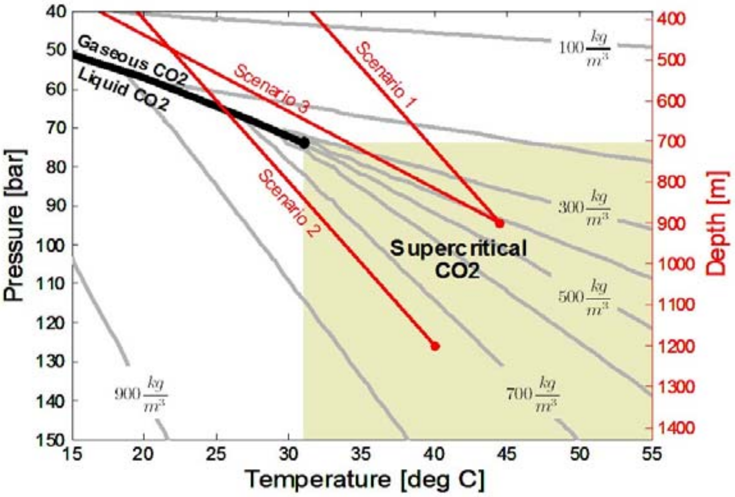

Figure 3. Phase diagram for CO_2 at pressures and temperatures near the critical point and for depths relevant for geologic storage. The supercritical region is indicated. Grey curves are isopycnic (constant density) contours, computed as described in Crandell et al. [26]. Red curves indicate three possible scenarios for the pressure and temperature variation experienced by a rising parcel of CO_2.

The primary motivation for experiments at the LUCI facility is to develop a more accurate understanding of these behaviors resulting from a combination of dynamics of flow and expansion of CO_2 as it migrates upwards. The understanding of interdependence of buoyancy-driven flow, Joule-Thomson cooling, thermal exchange, viscous fingering, residual gas trapping, CO_2 dissolution and its effect on native fluids is incomplete, and to date experimental observations are lacking. Experiments conducted at LUCI over large vertical distances and under controlled conditions will therefore provide much needed input for modeling.

4. Suite of planned experiments

As part of the suite of planned experiments, the primary experiment will simulate a leak in which CO_2 changes from a supercritical fluid to a subcritical gas as it flows up the column. For this experiment, a column will be filled with unconsolidated quartz sand and brine. A slug of CO_2 will be released into the bottom of the vessel, and its phase transitions and rise velocity will be observed. The physical processes described in the previous section will be investigated, such as the extent to which the acceleration is mitigated by Joule-Thomson cooling. Both pressure and temperature will be measured along the column through distributed sensing devices. Periodic logging through the central “well” will be conducted to infer CO_2 saturations.

In other experiments, CO_2-water-rock interactions will be examined. In this type of experiment, a column will be filled with layers of sand and consolidated, fractured sedimentary rock segments. The low pH resulting from CO_2 dissolution in formation brines may lead to dissolution of feldspars, zeolites and other aluminosilicates, and can lead to precipitation of clay minerals and carbonates [8-9] The impermeability of cap rocks may be compromised by such reactions [10], or fractures in cap rocks may self-seal due to precipitation [12]. Additional processes that may be studied include the counter-imbibition of brine as the upward moving CO_2 dries the sand column akin to near-wellbore evaporation of water.

Another type of experiment will investigate the reactions of CO_2/brine with well cements. Because mature sedimentary basins have a century-long history of oil and gas exploration and production, they are penetrated by large numbers of existing wells. These existing wells represent potential leakage pathways for CO_2. Experiments under downhole conditions show that well cement is unstable with respect to carbonated water, but may have an extended life with dry CO_2 and to a lesser extent with moist CO_2 [12-16]. Release and expansion of gas could also lead to severe chilling and the formation of plugs of dry ice; this could result in a cycle of periodic plugging and release as has been observed on occasion during CO_2 flooding for EOR [17]. The corrosion reaction products might also tend to plug the leak and form a protective rind, as suggested by lab-scale experiments [18] as well as by examination of 30-year old well cements [19].

Finally, the effects of anaerobic, thermophilic bacteria on CO_2 conversion to methane and carbonate will be investigated. In these experiments, segments of a column will be filled with organic-rich shales. At the depths being targeted for geologic carbon sequestration, anaerobic thermophilic microbial communities are known to exist [20]. The metabolic potential is large because the electron-donating organic matter and oxidized substrates in these formations are not in equilibrium. The reaction rates are limited, however, by slow mass transfer across the subsurface strata containing the different species [21]. Subsurface injection of CO_2 is expected to impact this lethargic subsurface microbial ecosystem by increasing bioavailability of organic matter (e.g., as in the Frio CO_2 injection, Kharaka et al. 2006 [22]). The rates and extent of microbial immobilization of CO_2 is difficult to predict because our knowledge of anaerobic microbial processes is based upon studies of water-saturated systems, not a mixed CO_2/water system at high pressure [23].

5. Validation of technologies for in-well monitoring

We plan to employ a comprehensive suite of geophysical sensors that are primarily used within the oil and gas field for geological, petrophysical, and reservoir characterization. The deployment of geophysical logging instruments in the inner "well" will allow detailed monitoring of conditions in the annular flow and reaction regions of the flow columns, while also allowing validation of the instrumentation itself.

Existing sensor technology and inversion may be modified to be sensitive to the presence of CO_2. Based on measurement physics, the downhole sondes may be broadly classified into five groups: Nuclear (neutron, gamma ray, neutron-gamma ray spectroscopy), acoustic, electrical (passive and active electrode, and induction), NMR, and pressure and fluid testing. Some of these may be deployed as semi-permanent instrumentation (e.g., pressure and temperature).

The most capable tools (to date) for detecting CO_2 from within a cased-hole belong to the nuclear-based family. With the current nuclear tools capable of measuring the neutron capture cross-section, we can detect the absence of Cl^- or brine adjacent to the well, thus inferring CO_2 by subtraction. In a time-lapse mode, quantitative saturation estimates are possible [24-25]. The application is limited to moderately saline aquifers (>30,000 ppm) with sufficient porosity (>0.1). With additional nuclear measurements such as the hydrogen index, it is possible to extend the range and also obtain the saturation of CO_2 independently. Although nuclear tools have been implemented historically to determine saturation profiles around casing, other methods may also be utilized. For example, acoustic sondes, chiefly sonic (1-20 kHz) and ultrasonic (100s of kHz) transducers and receivers, can be used to image fluids by using differences in acoustic impedance. Similarly, Nuclear Magnetic Resonance (NMR) measurements can be used to determine the pore volume and infer characteristic pore sizes. In an electromagetically unshielded borehole, NMR measurements may also be used to delineate the vertical saturation profile.

6. Summary

The planned LUCI experimental facility is crucial for bridging the gap between bench-scale measurements, simulations, and field-scale demonstration. The LUCI facility will be the only large-scale laboratory for controlled study of geologic carbon sequestration in the world. The experimental observations from LUCI will generate fundamental new understanding of the processes governing CO_2 trapping and vertical migration, and will provide valuable data to calibrate and validate large-scale model simulations. These experiments will also be a guide to quantify vertical resolution of many of these sensor technologies.

7. Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-0919140 to Princeton and Grant No. CMMI-0965552 to LBNL. We thank Dave Plate, Rohit Salve, Tom Trancynger, Kathy Hart, Jaret Heise, and other members of the DUSEL and Sanford Lab staff for their support in this work. LBNL work was also partially supported by Contact No. DE-AC02-05CH11231.

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