**National Science Foundation**

# Deep Underground Science & Engineering Laboratory (DUSEL)

## AC-GEO Subcommittee Science Review

## PANEL REPORT

**April 1, 2011**

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**National Science Foundation**

**Deep Underground Science & Engineering Laboratory (DUSEL)**

**AC-GEO Subcommittee Science Review**

## Background

The Deep Underground Science and Engineering Laboratory (DUSEL) has been envisioned as a world-class underground national laboratory supporting unique science and engineering research. The DUSEL laboratory, consisting of the facility, its infrastructure and a suite of experiments, has been under preparation for consideration as a Major Research Equipment and Facilities Construction (MREFC)[3] project at NSF.

The selection of the former Homestake gold mine in Lead, South Dakota as the sole site for further design and development of a DUSEL was made in July 2007. The site selection process was governed by NSF DUSEL Solicitation 3 (S3)[1]. A subsequent DUSEL Solicitation 4 (S4)[2] provided funding for planning and development of designs for potential DUSEL experiments.

Together, the S3 and S4 solicitation processes supported the development of initial project plans that would define the cost, schedule, scope, staffing requirements, and other parameters that would enable the construction of an appropriately mature MREFC proposal[3]. The ultimate goal of the S4 process, which funded nine (9) physics experiment design teams and seven (7) geosciences/engineering experiment design teams, is the potential inclusion of these experiments (or a subset of these experiments) in the proposal for the MREFC project to construct the DUSEL. Of the seven geosciences/engineering experiment design projects, six were selected for review by the AC-GEO Subcommittee to evaluate their geoscience opportunities. The remaining project, which addresses cavern design and engineering, is reserved for a separate technical review.

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[1] DUSEL Solicitation 3 (S3), NSF 06-614, http://www.nsf.gov/pubs/2006/nsf06614/nsf06614.pdf.
[2] DUSEL Solicitation 4 (S4), NSF 09-500, http://www.nsf.gov/pubs/2009/nsf09500/nsf09500.pdf.
[3] Preparation for potential MREFC projects is guided by the Large Facilities Manual (LFM), NSF 07-38, http://www.nsf.gov/pubs/2007/nsf0738/nsf0738.pdf.

## Charge to the Review Panel

The AC-GEO subcommittee review has been focused exclusively on the potential transformative geoscience that could be accomplished in a DUSEL, as delineated by the geoscience design teams as well as other potential experimental opportunities. The subcommittee is to review neither the MREFC facility construction plans nor the overall management or operations and maintenance of DUSEL. The subcommittee is also not to make budgetary recommendations. Specifically, the subcommittee was charged with:

1. Reviewing and assessing the science opportunities, experimental designs, and cost analysis of the geoscience design teams at the Homestake DUSEL.

2. Assessing the suitability of a deep mine for these experiments. Is a deep mine location required and, if so, is Homestake the best location given the international context of underground science?

3. Recommending other potentially transformative geoscience opportunities that can only be accomplished at the proposed Homestake DUSEL.

4. Reviewing and assessing the proposed selection process (on-ramps and off-ramps) to be used by NSF for geoscience experiments in the DUSEL facility.

Panel review materials for each of six S4 geoscience design projects consisted of a proposal, PI annual reports, PI presentations, and the interim panel review report, as well as broad community workshop reports that identified the science opportunities at a DUSEL (e.g., *EarthLab*, *Deep Science*). These materials were made available to the subcommittee via a secure website before the meeting.

The subcommittee met at the FDIC L. William Seidman Training Center in Arlington, VA over Feb. 16-18, 2011, and communication continued thereafter by e-mail and conference calls. This report includes findings and recommendations to the Advisory Committee for Geosciences on the basis of extensive discussion and information provided by the review materials.

## Developments in Funding and Context of this Review

Between the time that the AC-GEO Subcommittee was established (October, 2010) and the time that the subcommittee first met, several developments took place that changed the context of the subcommittee's charge and deliberations. On Feb. 16, the first day of the subcommittee's meeting, NSF personnel informed the subcommittee of significant findings by the National Science Board's Committee on Programs and Plans. Furthermore, the subcommittee was informed that NSF funding for DUSEL in the 2012 federal budget request submitted to Congress had recently been dropped. Specifically:

> "on December 2$^{nd}$ the National Science Board's *Committee on Programs and Plans* voted not to recommend the proposed DUSEL bridge award to the full National Science Board. National Science Foundation staff will be working with their counterparts at the Department of Energy, the University of California, Berkeley and other stakeholders to assess next steps."

Consequently, the President's rollup of the FY2012 budget request issued on Feb. 14, 2011 (*nsf.gov/about/budget/fy2012/pdf/fy2012_rollup.pdf*) made the following statement:

> "Deep Underground Science and Engineering Laboratory (DUSEL): NSF eliminates funding for DUSEL, which had been pursued in conjunction with the U.S. Department of Energy's (DOE) Office of Science. This termination is based on National Science Board reviews that concluded the cost and scope of DUSEL were inconsistent with the agency's role in advancing fundamental research and education across many fields and disciplines. NSF will continue to solicit proposals for future particle physics research. No funding is required in FY 2012 for DUSEL."

Following discussion of these developments, the AC-GEO subcommittee concluded that DUSEL geoscience experimental facilities and projects should still be evaluated as outlined in the original charge. However, the scientific opportunities should be evaluated in the context that future changes in funding or redistribution of facilities and research costs between NSF and DOE may correct the problems identified by the National Science Board. Evaluations are made in this report, assuming that the DUSEL facility re-emerges as a scientific priority. The subcommittee also discussed any experimental facilities and science opportunities that may be competitive for NSF support and could potentially go forward without the full development of DUSEL as a large-scale underground laboratory. These are identified, assuming that safe access to the Homestake mine is maintained (using current safety and access procedures at DUSEL; *http://sanfordundergroundlaboratoryathomestake.org/index.php?option=com_content&view=article&id=222&Itemid=24*).

## Review Summary

A number of opportunities have been identified for scientific discoveries at DUSEL geosciences laboratory facilities that are transformative. These include studies of deep subsurface life, measurement of high frequency seismic signals that cannot be made at the Earth's surface, and scaling of mechanical, hydraulic, and geochemical processes, given that the experimental facilities are successful in providing new, revealing observations and measurements that improve theory and the ability to predict properties and processes in the Earth.

Basic geoscience experimental facilities are mandatory if not necessarily transformative, should DUSEL be built and operated safely. These include, but are not limited to, the installation of strain meters, tiltmeters, and seismic instruments to monitor strains, loading, seismic velocity changes, and small earthquake and rock burst responses to dewatering, excavation and long-term operation of experimental DUSEL facilities.

A few projects were identified that could potentially go forward within FY2012, whether or not DUSEL is established as a large-scale underground laboratory. These include installation of one or more broadband seismometers and strain monitoring, both of which are time-sensitive, and more focused geobiology sampling and monitoring in advance of the establishment of DUSEL geoscience laboratories. Installation of a broadband seismometer could be tied into the transportable seismic array of EarthScope. US Array transportable array stations are currently located in South Dakota but will be moved out in future years (*http://earthscope.org/current_status/*). Similarly the network of strain meters would measure a transient signal from dewatering of the mine, a signal that is maximum now and will decay over time. In addition to time-sensitive instrument installations, a few very high frequency seismometers could be used to detect small events triggered by tides and passing strong surface waves. Early deployment of a few high frequency instruments may allow more rational deployment at a later time, should DUSEL be fully funded. Also, given that subsurface microbial communities can be sampled with current mine access and safety precautions, some of this work can go forward by way of competitive proposals and existing NSF programs, without full funding of DUSEL facilities.

The panel identified some experimental facilities that require significantly more analysis and development of safety protocols. These include special considerations where nitrogen gas may displace breathable air in confined spaces of the Homestake mine or carbon dioxide may leak, endangering staff and scientists of a number of DUSEL experimental facilities.

The panel also identified a number of geoscience opportunities that are not included in the present set of experimental laboratory designs. These include detection of geoneutrinos, hydrogeologic scaling and anisotropy studies, low-temperature abiotic geochemical studies, development of environmentally sustainable mining practices, and testing of new types of chemical and biological sensors.

A potentially significant opportunity may be realized if geoneutrinos (produced by decay of heat-producing isotopes in the Earth, $^{238}U$ and $^{232}Th$) can be detected. Geoneutrinos provide a direct measurement of the heat production of the solid Earth; thus, their numbers have implications for the energy budget and thermal history of the planet. However, unless there are advances in the technology of measuring directional geoneutrinos, this should be thought of primarily as a physics experiment, with limited contributions to geoscience. Accuracy is much lower than estimates of the heat production obtained from other methods, and the signal is likely to be dominated by geometrically complex continental sources in the DUSEL setting.

Underground laboratory facilities may also allow studies of subsurface fluid flow scaling. This is touched on in two existing facilities designs but hydrological scaling isn't fully developed in the reports that were reviewed. For example, effective permeabilities at different scales could be measured, correlated with fracture maps, and modeled in three dimensions. In addition to questions of scaling, effective permeabilities in foliated, fractured media are likely to be anisotropic. Facilities at DUSEL could include three dimensional fluid sampling, pore pressure testing, and observations and mapping of fracture networks.

The geoscience experimental facilities at DUSEL are designed to investigate high temperature geochemical processes and low temperature biological processes, but underground facilities also have the potential to contribute to understanding abiotic rock-water interactions at low temperatures. Geochemical studies could include reaction rates and scaling of solute transport at temperatures of ~100C over extended periods of time.

There are also research opportunities in developing environmentally sound metal sulfide mining practices and testing of chemical and biological sensors, which may not be transformative but could be of high societal impact or drive technical advances. Improvements in mining practice that enable mineral extraction and processing without major cleanup operations after mining operations cease could lead to sustainable resource development and improvements in mine engineering practice. Many of the experimental facilities at DUSEL could also benefit from application and testing of new types of chemical and biological sensors, some of which are described in the reports reviewed. These include sensors designed to monitor T, P, pH, CO, $CO_2$, $CH_4$, and $H_2S$.

In general, a number of physics experiments at DUSEL may collect data that have geological implications but are not of interest in particle physics. For example a gravity wave detector may be used as a seismometer, and a number of detectors may collect what is considered noise in the physics community, but may be regarded as useful geophysical measurements, if continuous data are collected and archived.

The subcommittee is in agreement with prior evaluations of DUSEL laboratory facilities, which concluded that a coordinator should be appointed, counseled by an advisory team that includes principal investigators of established DUSEL facilities. Given the wide-ranging activities of the different laboratories, it will be important to provide oversight for experimental operations, safety, and timing of excavations, instrument installation, monitoring, and experimentation. In addition, coordination of data streams and data archiving need to be addressed. Incoming data from DUSEL labs should be coordinated with IRIS, UNAVCO, and other national data repositories. DUSEL data sets should also include detailed geologic mapping and information regarding the history of mining operations, as well as core descriptions and any archived cores.

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**Deep Underground Science & Engineering Laboratory (DUSEL)**

**AC-GEO Subcommittee Science Review**

**Lead PI Names:** **Herbert Wang**
**Dante Fratta**

**Institution:** **University of Wisconsin**

**Title:** **Fiber-Optic Strain Monitoring of Rock Masses in Large Underground Facilities**

**Experiment Overview**

This laboratory facility is designed to measure rock deformation underground in order to understand how strain varies over different scales of space and time. It is also designed to advance the technologies used for rock deformation measurement by providing a platform for development and use of new strain measurement technologies using fiber-optics. The project takes advantage of the planned DUSEL underground laboratory as a site for deploying a network of sensors (strain and temperature meters, tiltmeters, and other instruments) to characterize the deformation associated with loading and unloading. Because the primary sources of strain are due to hydrologic loading and unloading, the strain measurements will primarily have implications for the hydrologic system in the region. A corresponding set of measurements will be made in a separate project at a Japanese underground research facility, facilitating comparisons of the technologies and strain in two very different geologic settings.

**1. Assessment of Science Opportunities**

The goals of this project are to develop and carry out strain measurements in order to understand "the effect of spatial and temporal scale on the mechanical and hydrologic behavior of crystalline rock masses." Specifically, the project poses two primary scientific questions:

i. How do stress, strain and pore pressure vary in scale from borehole to tunnel to regional geology?
ii. How are stress state and strength related to geologic heterogeneity, fracture geometry, the presence of fluids, and rock anisotropy?

These are solid, important scientific questions with impacts on the understanding of rock mechanics and fractured systems. In particular, understanding how permeability depends on length scale is important. There is potential for transformative science if measurements of hydrologic character at different scales can be linked to geology and fracture networks, in order to develop physical scaling models that are capable of predicting generalized fluid flow in fractured systems. In addition, significant breakthroughs are possible if the strain sensor network can be designed to detect displacements localized on (perhaps a few) faults and relate these to strains measured over larger scales.

This project focuses on development of fiber-optic strain technology and deployment of these technologies. A network of measurements throughout the mine will provide a 3D view of strain. Because DUSEL is located in a tectonically quiet region, the primary sources of strain are associated with the presence of the mine itself (most recently, the loading due to filling with water after the mine closed and the subsequent dewatering in preparation for establishing an underground science lab). Any theoretical framework that results from the measurements would be a separate effort (interpreting and modeling the observations.)

The main activities involve developing, installing, and operating new strain meter technologies for 3D measurement of strain. The scientific goals and the engineering development of strain meter technology are closely linked, and it is somewhat difficult to identify separately the advances in engineering and those in the geosciences. The experiment design is inherently based on being in a mine and requires working underground, therefore it requires an underground laboratory to make these measurements.

The experimental methods and technology for measuring 3D strains are carefully thought out and well conceived. Some significant effort may be required prior to installation of the strain network. For example, strain meters may exhibit drift with time; thus, instrument behavior needs to be characterized to enable meaningful interpretation of the measurements. As the design phase proceeds, it will be most cost effective to do testing of instruments at the surface before installing instruments below ground.

This project has strong broader impacts, in particular the international component and the K-12 component. The project will involve international partners and could potentially involve closer collaborations with the petroleum and mining industries.

The project will be cost-effective if the DUSEL lab is constructed as proposed. The strain measurements take advantage of the existence of the mine lab infrastructure and the forcing imposed by pumping water out of the mine. Specifically, the project takes the opportunity to develop and install these strain meters during a post-dewatering time interval when (small) strain rates will be at a maximum. If DUSEL is not developed, it may still be important to install some portion of the strain network, given that these measurements are time-sensitive; strain rates are maximum now and will decay with time.

## 2. Suitability of a Deep Mine for these Experiments

If a deep science lab is established in a mine in DUSEL or anywhere else, it is essential to measure strain. Indeed, it is impossible to imagine not making measurements of this sort if the decision is made to establish a deep underground science laboratory. Strain measurements will be required for safety, and these measurements should be made in a way that advances scientific knowledge. The strain meters must be sensitive enough (with data collected continuously at a suitable rate) to capture tidal variations; these can be used to test measurement quality but also constitute useful signals as well. More generally, opportunities for measurements of strain over long periods of time are rare, and the ability to make such measurements on the scale of years or a decade represents an opportunity for new observations that may be relevant to tectonics of the Earth's lithosphere, and to other geologic sources of distortion.

Because the techniques to be used depend on the strain rates in the mine, the Homestake location provides a unique platform, and the technology to be developed is intended to respond to the conditions at Homestake, which is located in a (presumably) slow strain rate environment. In a different, large strain rate location, this type of strain meter might not be useful or appropriate. The measurements are also intended to take the opportunity to measure strain during a window of time (post-de-watering) when the strain rates are the largest. If the Homestake location is kept open (dewatered) but the DUSEL lab is delayed for many years, the strain rate will drop and eventually the measurements will become more challenging or the strain rate may fall below the threshold of detection.

A concern at this site (and probably many other geologic sites) is the geologic heterogeneity. The concept of a 3D FEM-like network of sensors is compelling and a deep underground lab provides a unique platform for doing this. However, the 3D strain network should be linked to 3D mapping of the geology and fractures and faults, in particular.

## 3. Other Potentially Transformative Geoscience Opportunities

The strain measurements need to be combined with other observations to enhance the scientific return. It will be important to document spatial and orientation distributions of fractures of the mine (potentially drawing on mine records) and to measure in-situ stresses. Borehole logging of fractures should be done if the geologic data are not already available from the mining operation. These additional measurements are required to understand the implications of the observations over multiple scales within a given stress state. It is already known that effective permeabilities are greater at larger system scales; if permeability measurements and fracture mapping can be used to predict how permeability scales with the system dimension based on the fracture network, the results would be potentially transformative for hydrological models. The experiment as currently described does not directly address this; other efforts would have to be undertaken to make this link.

Other examples of transformative scientific opportunities include making this set of strain measurements in conjunction with stress measurements. In this case, it will be important to determine which fractures are responsible for more slip and/or enhanced fluid flow as a function of orientation relative to in-situ stress states (including both the geological and superposed mine-related loading) in various locations within DUSEL.

Some potentially transformative opportunities will result from strong coordination among the experiments. The strain rate measurements require coordination with other activities going on in the mine that could affect the strain rate. The strain rate measurements may also provide useful input into some of the other experiments; for example, coordination with studies of nutrients in pore fluids (to be studied as part of the ecohydrology experiments), which may be controlled by stress and fracture locations. There may be useful tracers (such as quantum dots planned for the transparent earth experiment) that can be used as markers for both the ecohydrology and strain measurement experiments that offer constraints to hydrogeologic scaling models.

## 4. Assessment of the Proposed Selection Process

The strain meters should be left in place as long as possible, to capture any changes in the long-term strain and to maximize the return on investment. Thus, longer periods of funding may be required to maintain the network and maximize its scientific value. Data management and archiving are essential to maximizing the return from these observations. Moreover, monitoring of the strain network should be carried out at a rate that can be used as a long term, long-period to tidal-period seismometer, and integrated with the subsurface imaging and monitoring experiments at DUSEL.

It would be useful to consider taking advantage of existing data infrastructure such as UNAVCO or other data management centers. These will support wide access to the data. At the same time, DUSEL itself would need to have a 'data identity' and coordination among the different observations is required with a DUSEL-wide website and data management plan. This should include documented coordination among all the science activities in the underground lab, overviews of data, and access to metadata and detailed datasets (perhaps after the PIs of each experiment have had a suitable time to analyze them).

**National Science Foundation**

**Deep Underground Science & Engineering Laboratory (DUSEL)**

**AC-GEO Subcommittee Science Review**

**Lead PI Name:** **Steven Glaser**

**Institution:** **University of California, Berkeley**

**Title:** **Subsurface Imaging and Sensing Experiments at the DUSEL**

### Experiment Overview

This experimental facility is designed principally to monitor natural and artificial seismic signals. The seismic waves will be used to image the Earth in the area of the mine, detect and analyze small earthquakes in the vicinity of the mine, and record natural earthquakes far from the mine. The array of instruments will record ambient noise, which allows passive imaging methods that create a virtual source at each station. The experimental facility is based on 22 high-frequency instruments within the Homestake mine. Active sources will be used to monitor stress changes. Vibrators will generate additional controlled seismic signals. Electro-magnetic measurements will monitor water-level changes and attempt to detect crack-tip processes. Several other geophysical imaging and monitoring techniques are also envisioned in Tier 2 of the facility.

Measuring seismic waves at very high frequencies facilitates recognition of rupture-tip processes analogous to those in natural earthquakes. The natural and artificial seismic sources will be analyzed to provide images of the subsurface in the area of the mine. The Homestake mine is situated in steeply dipping folded metasedimentary rocks. Given its complexity, an improved image beyond that obtained from drilling and exposures in the mine is useful but not a major advance. Cross borehole tomography is already well developed in the petroleum industry. Importantly, subtle seismic signals due to velocity changes are associated with known stress changes associated with tides, passage of strong surface waves, dewatering of the mine, and mine excavation. Triggering of earthquakes by the same processes should also be observable. Studies of seismic events at this facility will be relevant to the triggering of natural large earthquakes. The seismic array will image large distant earthquakes. The transmission of high-frequency waves through the mantle and rupture tip processes of nearby and distant earthquakes may be observable. Installation of a subset of these instruments may be justified well before the large-scale facilities at DUSEL are funded, on the basis of coordination with the deployment of transportable array stations of US Array (EarthScope). Moreover, experience with instruments deployed in the near future may allow better planning of the ultimate DUSEL imaging and sensing network, as described and reviewed here.

## 1. Assessment of Science Opportunities

The seismic array of this experimental facility will image high frequency seismic signals that are generated at the start of rupture. High frequency seismic measurements in the quiet subsurface environment of a deep mine in hard crystalline rocks may be regarded as a new class of data. Thus, there is significant potential for new geophysical observations and transformative science, defined by the National Science Board as "research that has the capacity to revolutionize existing fields, create new subfields, cause paradigm shifts, support discovery, and lead to radically new technologies." In addition, the seismic array deployed in Homestake mine is intrinsically a 3D array, which will offer observational opportunities that are unique.

The frequency content of seismic signals from large earthquakes has never been investigated to high frequencies, and the mantle of the Earth has never been imaged at high frequencies. It may be possible to detect the immediate precursor processes of large earthquakes at depth, which cannot be detected at the Earth's surface. High frequency seismic measurements can be used to calibrate the relationship between stress and seismic velocity for use in seismically active regions. Stress-dependent data may be applicable to detecting stress changes in seismic regions. High-frequency data may be used to check rupture-tip theory of large events, assuming that high frequency seismic waves are able to transit the Earth. The array may also be used to observe small, triggered earthquakes. In addition, observations of deep-focus earthquakes will facilitate analyses of the anelastic properties of the mantle. Lastly, there are potential new observations that this facility may enable, that cannot strictly be forecast. For example, underground seismometers have previously detected unexpected phenomena such as non-volcanic tremor in subduction zones.

The 3D array of seismometers will offer excellent opportunities to image and monitor excavation and experimental operations at DUSEL, providing scientific opportunities and contributing to mine safety. To fully realize these opportunities, coordination will be required with strain monitoring facilities, experimental fracture experiments, investigations of pore fluid flow and other experiments that alter thermal and mechanical states.

In the role of imaging, seismometers at DUSEL may be used to observe resonances associated with mine cavities. Resonant frequencies can be monitored by passive methods. Thus, vibrators may not be necessary. If high quality factor resonances exist, small shifts in their frequencies may allow small changes in seismic velocity to be measured that are due to changes in ambient stress. In addition, the resonances associated with the mine are effectively antennas for incident waves. There will be trade-off between having incident signals obscured by directional site resonances and the ability to use resonances as a signal.

In the role of seismological monitoring of excavation and operation of DUSEL, deployment of the seismic array is essential for mine safety. Deployment of some seismometers at depth may also be justified before DUSEL is fully funded, provided that the mine remains dewatered and safe access continues to be maintained. Overall, seismic imaging and monitoring of Tier 1 of this geophysical facility is cost effective.

It will be important to coordinate the seismic array with other DUSEL operations, and seismic data must be archived and made readily available. The high frequency data needs to acquired and stored in full form, and in filtered form decimated to about 250 per second for those interested in more distant earthquakes. It would help to archive data at an existing facility. It will also be essential to have at least one broad-band instrument in the mine to determine when teleseismic waves and hence stress perturbations occur. An additional broad-band instrument should be deployed at surface. There should not be a gap seismic data obtained, between high and broad-band frequencies. It would also help if some surrounding EarthScope stations were left in place to monitor surface waves from distant large earthquakes for some time. Improved techniques for analyzing seismic waves and imagining can then be applied as they become available. Data archiving needs to include logs of mine activities at depth and at the surface, which may generate seismic waves.

It is not clear how the EM measurements will contribute to underground imaging that cannot be obtained from seismology. Seismological imaging will be of higher resolution than EM imaging. Moreover, the rocks of the Homestake mine contain sulfides, concentrated locally, and in both bedded and foliated rocks. So it may be difficult to obtain better images than the geological maps that are already available. The strong anisotropy may aid in studying stress dependent processes.

There may be some applicability of EM methods to crack-tip monitoring. The idea that crack tips generate strong electric fields is supported by lab studies, but it is unclear whether the process is important in natural rock that is already cracked. An experiment in a mine at near-seismogenic depths could be useful to determine whether continued EM studies of seismogenic faults is warranted. In this application, EM monitoring needs to be coordinated with other mine activities and experimental operations, and a log of electrical activities is needed to interpret passive EM monitoring.

In contrast to seismic and EM monitoring of this facility, which are part of Tier 1 measurements, facilities and experiments for Tier 2 measurements are not well described, their scientific value are difficult to forecast, and they are likely to be expensive. It is not clear, for example, what the microgravity experiments will provide, or whether they will be better at detecting water movement or other processes than other methods. X-ray tomography is not applicable to large-scale imaging at DUSEL, and the quantum dots experiment is out of place. Fluid flow tracking could be facilitated with quantum dots, but they would need to be incorporated into hydrology experiments at other facilities. Their introduction in other projects will need future evaluation.

## 2. Suitability of a Deep Mine for these Experiments

The installation of a seismic monitoring and imaging network is clearly justified at a deep scientific facility such as DUSEL, on the basis of scientific opportunities and to insure mine safety during dewatering, excavation and operational phases. High frequency seismology can only be done in a mine in hard rock. High frequency measurements at the Earth's surface will always be too noisy, and weathered rocks and soils at the surface attenuate high frequency waves. Thus, instrument installations at DUSEL can test whether high frequency seismic waves in fact transit the Earth. If so, they will provide the unique opportunity to test rupture-tip theory of large fault seismic events. In addition, geophysical experiments and measurements with a three-dimensional array clearly require the underground mine environment.

Seismic monitoring is essential for safety of all phases of operation at DUSEL. An array consisting of 22 stations is appropriate. For comparison, early petroleum company multi-channel reflection work used 24 detectors, which allowed serviceable imaging. Any active-source seismic experiments will need to be planned in coordination with other DUSEL lab facilities and experiments.

Assuming the EM imaging is justifiable, these experiments may need to begin before other experiments of DUSEL, to insure a quiet environmental, and that active sources of the EM experiments do not interfere with sensitive physics experiments.

## 3. Other Potentially Transformative Geoscience Opportunities

Additional information can be obtained that will enhance the high frequency seismic measurements if one or two broad-band stations are installed in the Homestake mine and nearby at the Earth's surface. The objective is to detect when large surface waves pass. It will also be useful to monitor tidal stresses though high-tech methods are not needed. Seismic data should be collected continuously and archived so that they are available to a wide range of users.

## 4. Assessment of the Proposed Selection Process

This geophysical monitoring and imaging facility can be reviewed and assessed on a normal schedule, but deployment, maintenance and data collection and archiving must be seen as a long-term requirement of establishing DUSEL. This is required to obtain incoming seismic data from remote sources and to insure safe operation throughout the life of DUSEL. It is also possible to initiate installation of seismometers in the Homestake mine before the full development of DUSEL, with the advantage that subsurface measurements can be coordinated with US Array of EarthScope.

**National Science Foundation**

**Deep Underground Science & Engineering Laboratory (DUSEL)**

**AC-GEO Subcommittee Science Review**

**Lead PI Name:** **Leonid Germanovich**

**Institution:** **Georgia Institute of Technology**

**Title:** **Development of a Fracture Processes Facility at DUSEL Homestake**

### Experiment Overview

This geoscience facility is designed to initiate and induce slip on shear fractures at scales of 1-100 m using thermal loading, and to initiate slip on the Homestake fault at the Deep Underground Science and Engineering Laboratory (DUSEL) proposed for the Homestake mine, South Dakota. The scientific objectives are to study shear fracture and slip processes in controlled experiments on crystalline rocks at larger scales than can be investigated in laboratory experiments, and thereby understand scaling of fracture mechanics in the Earth. This scaling is important to evaluate fracture strength and fracture energy, and processes of fracture nucleation and propagation.

A number of configurations are evaluated to induce critical stress conditions for fracture initiation and frictional slip, by altering in situ stresses thermally by cooling and heating hydraulic fractures and boreholes. To initiate shear fracture in a rock mass, the facility will feature "thermal walls" adjacent to an existing mine drift, consisting of hydraulic fractures cooled by liquid nitrogen. When cooled, the minimum principal stress in the volume between the thermal walls is decreased by thermal contraction. Given an initial differential stress in the subsurface and sufficient cooling, critical failure conditions can be reached. Later injection of hot fluids is envisioned to reverse slip, and enable study of cyclic, multiple slip events and introduce slip damage and gouge along shear fractures. Fracture facilities are planned for several depths in the mine to investigate a number of in situ stress states. Each of these fracture facilities will be designed to monitor shear propagation by seismic monitoring. Following experimentation, the fractures are to be described and mapped in three dimensions by excavating the rock mass.

Slip on the Homestake fault is planned by reaching critical frictional conditions along a limited fault area by thermal loading, introducing liquid nitrogen into strategically located boreholes, and increasing pore fluid pressure in the fault zone between cooled boreholes. Monitoring of fault rupture and propagation will be monitored much as for newly initiated shear fractures.

In addition to its use in studies of fracture and frictional slip, the facility is to allow studies of fault permeability and evolution of subsurface fluid flow, and studies of microbial communities in active fractures, as influenced by hydrogen release from fresh fracture surfaces.

Given that the design of this facility is successful in meeting its objectives, important scientific questions can be addressed and there are opportunities for transformative science. However, there appear to be a number of significant design challenges and safety issues that must be resolved. Coordination with other DUSEL experimental facilities will be important to avoid conflicts and insure that fracture experiments at this facility are not disruptive to experiments at other DUSEL facilities.

## 1. Assessment of Science Opportunities

### *Opportunities*

The primary scientific questions addressed by this experimental facility involve scaling of fracture initiation, propagation, and fault rupture. Fracture strengths of rocks are known to be smaller at larger length scales, and fracture energies are disproportionately larger for larger fractures. This facility is designed to address a number of hypotheses:

i. Faulting processes change with scale
ii. Slip on faults at scale of tens of meters is a frictional process
iii. Secondary fractures associated with faulting can be predicted by fracture mechanics
iv. Fluid flow along a fault is a function of shape, slip distribution, and normal stress on the fault
v. Faulting at every scale has a characteristic length scale
vi. Faulting releases $H_2$, which is an important energy source for deep microbial life

Given that the experimental facility design provides measurements and observations to address these hypotheses, this facility will offer the opportunity to study fracture at large scales not addressed in conventional laboratory experiments. The current paradigm may need to be changed if fracture processes are different at large scales than investigated in small laboratory specimens (hypothesis i). At present, faulting processes are considered to be the same at different scales, though larger rock volumes may contain larger cracks and flaws, which influence fracture strength and energy. It is less clear that the remaining hypotheses offer transformative science opportunities. Slip on a fault, as described by a relationship between shear and normal stresses required for displacement, is frictional by definition, whatever the details of microscopic processes. It is also widely expected that fracture mechanics is well suited to predicting the mechanical behavior of secondary fractures, and that fluid flow in faults depends on geometry, damage, and stress state. It is also expected that newly formed fracture surfaces will release $H_2$. However, it is not clear that these emissions will be large, compared with background $H_2$ levels in pore fluids due to radiolysis, serpentinization, and other processes. Other experimental facilities planned at DUSEL sites probably offer greater potential of studying microbial life in fractures in the deep subsurface.

***Remaining Design Challenges***

The success of these experimental fracture facilities will depend on solutions to a number of significant design challenges. To insure that thermal loading achieves critical failure conditions, access to the Homestake mine is essential well before locations of the experimental facilities can be finalized. In situ stress measurements and fracture envelopes of rocks at the experimental facilities are required to be certain that the superposition of thermal stresses successfully leads to shear fracture. Local alignments of foliation and fractures must be evaluated to determine if the thermally perturbed stress state meets the shear failure criterion of planes of weakness (defined either by foliation or initial fractures). Foliation and fracture alignments may thus dictate the orientations of hydraulic fractures used to cool the rock volume. This is compounded by the possibility that hydraulic fracture orientations may be influenced by pre-existing fractures.

The generation of tensile fractures by hydraulic fracture should be relatively straight forward, but cooling large-scale hydraulic fractures by injecting liquid $N_2$ will involve significant technical challenges. Volumes and rates of injection of liquid $N_2$ need to be evaluated, in addition to venting of the large volumes of $N_2$ gas that will be generated as initially warm rock surfaces of injection boreholes and hydraulic fractures are cooled. Without very large volume liquid $N_2$ tanks and large aperture valves in each facility, cooling rates may be slow and impact the ability to cool hydraulic fractures sufficiently quickly to generate the desired thermal stresses. The distribution of temperature and thermal stresses may be affected by leakage of liquid $N_2$ from the hydraulic fracture into the surrounding rock. In addition, reductions in the minimum principal stress by cooling may be compromised by the formation of ice by freezing of pore fluids, leading to volumetric expansion in intervals of the Homestake mine where rock pore space is saturated.

These experimental facilities will enable transformative science if large-scale fracture propagation can be monitored and fracture networks can be mapped following mechanical experiments. Such results could then be compared with results of smaller scale experimental studies, field observations of large-scale natural fractures, and predictions of numerical fracture models. However, monitoring fracture propagation and mapping fracture networks will require significant methods development. Coordination with geophysicists designing the seismic imaging and monitoring facilities of DUSEL will be required to ensure that fracture propagation can be resolved spatially and events recorded rapidly. If fracture propagation becomes dynamic, it is not clear that cascading acoustic events, during propagation, can be detected or distinguished by geophysical instruments. In this case, the experiments would not offer key observations to test or validate numerical models of shear fracture propagation. The experimental breakthrough in small-scale fracture experiments in which fracture propagation was observed involved the ability to unload the system in response to acoustic emissions. Significant developments in control of thermal loading will be needed to maintain quasi-static shear fracture growth.

Three-dimensional maps of large-scale fractures following experimentation may be compared with natural fracture systems. These maps may reveal the flaws in the rock mass that serve as fracture nuclei, which cannot be done in field studies, and they may reveal processes of fracture linkage, given that newly formed fractures may utilize pre-existing fractures and flaws. Newly formed fracture surfaces can probably be distinguished readily from older, potentially weathered and mineralized fractures. However, excavation procedures need to be developed so that fresh fracture surfaces generated during the fracture experiments can be distinguished from fractures developed during excavation.

These fracture facilities may or may not allow multiple slip experiments on large-scale fractures. If thermal heating and cooling are sufficient for cyclic critical loading, damage and gouge formation can be studied and their effects on frictional slip determined. However, much remains to be tested to learn if thermal loading will successfully lead to shear fracture, before cyclic loading methods can be tested to generate multiple slip events. Fractures may alter the local stress or become locked up after their initial formation.

The fracture facilities at DUSEL may provide unique opportunities to study fracture initiation, propagation, and slip at larger scales than can be examined in small samples loaded by deformation apparatus. However, these facilities and experiments will be expensive, justified by major breakthroughs but not if measurements/observations are unable to answer transformative scientific questions. A cost-effective way of evaluating thermal loading methods could involve intermediate-scale experiments on samples 0.1 - 1 m scales using thermal loading to explore rock fracture, and the monitoring and observational methods at much lower expense than at DUSEL. These can be seen as scoping tests of the methods under development at DUSEL. These intermediate scale tests can be used to determine the scale of thermally induced cracking (grain scale versus transgranular macroscopic failure) and can ultimately be included in a data set spanning smaller lab tests and the larger fracture experiments at DUSEL. Methods of thermal loading to large-scale failure at DUSEL can also be evaluated from experiences reported for thermal loading of mine pillars in nuclear waste isolation applications (e.g., Andersson and Kärnbränslehantering, 2007, Technical Report TR-07-01, which can be downloaded at www.skb.se).

The large-scale fracture facilities are not well developed at this time for studies of deep microbial communities in fractures. More development will be needed to evaluate sampling and methods of study. It is not clear, for example, that hydrogen generated at propagating fractures will be large enough, over background levels associated with radiolysis or other processes to detect microbial colonization or changes in microbial communities. Collaboration with dedicated geobiologists or coordination with other experimental groups at DUSEL is needed.

In addition to laboratory facilities to initiate shear fracture thermally, facilities are planned to initiate slip on the Homestake fault by thermal loading and pumping fluids into the fault plane. It is not clear why thermal loading is required in this case, given that reducing effective normal stress on the fault by injecting fluid over a given area is likely to be sufficient to initiate fault slip. Coordination with other DUSEL laboratory facilities will be extremely important as a slip event on this fault has the potential to disturb other facilities and experiments. Safety considerations are also paramount for this experimental design, as addressed in the following section.

In summary, the science opportunities of this facility could be transformative to the field of rock mechanics if the observations contribute to theory and prediction of fracture scaling. However, this will be challenging. If results only confirm that fracture strength is smaller at larger scales and fracture energy is larger at larger scales, they will only confirm what is now known. The experimental design needs further work to allow large-scale fracture propagation to be monitored and fracture networks to be mapped. Constraints to fracture mechanics theory and model assumptions will require characterization of initial fractures (size distribution, spatial distribution, orientation distribution) in the rock mass prior to experiments, and detailed study of fracture networks and how they have developed from the initial fractures of the rock mass.

## 2. Suitability of a Deep Mine for these Experiments

The large rock volumes that are required for these experiments can be located and accessed from drifts in an underground mine more readily than they can from the surface by drilling. This is important to allow operations that lead to rock loading, nearby geophysical monitoring, and excavation of the rock mass. A deep mine is required for the large-scale fracture laboratory developed here, given that large deviatoric stresses are required for thermal loading to achieve critical conditions. However, there are a number of drawbacks to the rocks of the Homestake mine for fracture tests, and it is unclear that DUSEL is the best location for the thermal fracture and fault slip experiments, given that these operations may be disruptive to other DUSEL facilities and experiments.

Rocks of the Homestake mine present a number of complexities for experiments designed to initiate fracture. Rock types are inhomogeneous, and many of the metamorphic rocks are anisotropic with strong metamorphic foliations and aligned fractures. Moreover, rock properties and orientations of foliation and initial fractures are likely to vary in the Homestake mine due to complex geologic structures. These problems can be overcome, but they mean that each fracture experiment site requires substantial characterization, and that fracture propagation needs to be analyzed in terms of an aligned set of initial fractures, and growth of new large-scale shear fractures that link these aligned flaws.

Homestake mine is also not ideal for the thermal loading experiments given that the pore and fracture space of the host rocks is saturated with pore fluid that will freeze when liquid $N_2$ is injected into hydrofractures. Then the bulk rock will expand rather than contract upon cooling. This means that siting of the experimental fracture facilities must include characterization of horizons that are unusually dry.

Once other experimental facilities of DUSEL are operational, coordination with those facilities will be necessary to insure that sudden displacements and associated acoustic events during fracture do not damage other facilities, and are not disruptive to other experiments and measurements. These include neutrino detection facilities in the very large, deep cavity, which will be an engineering challenge without the potential for seismic events triggered nearby. Coordination will also be important for timing of the fracture experiments so that the objectives of other installations such as sensitive strain networks, seismometers, and tiltmeters are realized.

More significant siting questions are raised by safety issues. As liquid $N_2$ is injected into boreholes and hydrofractures, large volumes of nitrogen gas are likely to displace breathable air in nearby (and potentially more remote) drifts and shafts. How will staff and scientists be protected against suffocation? Safety plans are needed for rapid ventilation of nitrogen gas and/or evacuation of personnel during the thermal loading phase of these experiments. In addition to personnel associated directly with the fracture laboratory, personnel at neighboring DUSEL facilities may need to be evacuated, requiring coordination between different experimental facilities of DUSEL.

Safety problems associated with initiating slip on the Homestake fault must be investigated thoroughly. The risk posed by this experiment may prove unacceptable. While the chance of setting off events greater than M=2-3 may be relatively small, any significant seismic events triggered by slip on this large-scale fault may be highly disruptive to other experiments and may compromise the integrity of the mine and its larger cavities. The regional stress state should be examined in case shear stress is elevated on the fault, such that a larger event might be triggered, which would be damaging to surrounding communities.

## 3. Other Potentially Transformative Geoscience Opportunities

One of the key steps in preparing the fracture facilities for thermal loading is the hydraulic fracture of rocks by pumping fluids into a borehole until fluid pressure reaches or exceeds the minimum principal stress in the rock mass. Some of the same procedures of this facility designed to investigate shear fracture may be useful to study the opening-mode fracture process, hydraulic fracture propagation, and extent of hydraulic fracture. Hydrofracting is a widely used method to enhance fluid flow near wellbores of low-permeability rocks in energy applications, including oil and gas extraction, and geothermal energy. However, it is difficult to know the extent of hydrofracture in rocks or the surface areas generated. Studies of hydrofracture from surface-drilled wells do not allow high resolution seismic monitoring of the fracture process or three-dimensional mapping of fractures.

Monitoring of hydraulic fracture propagation can be studied by seismic monitoring, and unlike shear fractures that may exhibit run-away growth due to thermal loading, rates of hydraulic fracture propagation can be limited by controlling fluid injection rates. Three-dimensional mapping of the fracture network due to hydrofracting poses similar challenges to those of mapping fracture networks of shear fractures, but resin-injection methods may be developed that facilitate this. Thus, the prinicipal investigators of this experimental facility may test methods of studying fracture networks and gain important information about the initial hydrofractures before extending their study to shear fracture propagation. With the energy applications of understanding hydraulic fracture better, research funding may be possible from both NSF and DOE.

## 4. Assessment of the Proposed Selection Process

As for all NSF-funded projects, new research proposals that make use of the fracture experimental facilities at DUSEL should be evaluated in terms of scientific excellence, impact on fundamental understanding, PI productivity and ability to carry out the research. Evaluation of proposals should be carried out through external reviews and panel reviews, as practiced by NSF EAR divisions. Until thermal loading methods are demonstrated to bring large rock masses to failure, normal funding periods are appropriate, but once methods are proven, longer time periods may be necessary to study large-scale fracture.

## National Science Foundation

## Deep Underground Science & Engineering Laboratory (DUSEL)

## AC-GEO Subcommittee Science Review

**Lead PI Name:** **David Boutt**

**Institution:** **University of Massachusetts Amherst**

**Title:** **Ecohydrology of Deep Crystalline Rocks at DUSEL Homestake**

### Experiment Overview

The goal of this project is to investigate the ecohydrology of the deep subsurface. Ecohydrology is defined by the PI as the integrated fields of ecosystem science, geology, hydrology, and biogeochemistry. The main hypothesis is that hydromechanical characteristics of crustal rocks will control nutrient and energy fluxes of importance for microbial activity and abundance. To fulfill the experimental goals of this project, the PIs propose to drill up to 30 km of boreholes and establish underground laboratories at up to ten different sites ranging from surface and a shallow level at 300 ft down to the 7400 ft level. A surface laboratory will also be installed where sample preparation and analysis can be performed. The outcome of the project is expected to increase our understanding on how microbial diversity and activity vary with depth, and hydrological and geological conditions. It is also anticipated that new knowledge will be generated on how microbial activity can influence the biogeochemistry and flow conditions in the aquifers of deep hard rock. Finally, the project specifically aims to establish the upper temperature limit for life (currently at ~120 ºC) by drilling below 5 km depth.

The planned experiments have the potential to generate new knowledge on how deep microbial ecosystems are involved in complex interactions with environmental processes such as precipitation, dissolution, reduction and oxidation of inorganic and organic compounds. A very important opportunity is the possibility of setting up long-term experiments and observations under *in-situ*, oxygen-free geochemical conditions in combination with high pressure. The education and outreach potential is great owing to the fact that the scientific community and the general public recently have shown an increased interest in subsurface life. The main drivers behind this interest are the proposed subsurface origin of life hypothesis; the idea that deep subsurface life may be independent of photosynthetic processes on the surface; the understanding that extraterrestrial life most probably should be searched for underground, and the suggestion that subsurface ecosystems may harbor a biomass that equals the biomass in surface ecosystems including the sea. The project has a significant chance to increase our knowledge about the validity of these ideas.

## 1. Assessment of Science Opportunities

The proposed Deep Ecohydrology experiment at DUSEL Homestake seeks to address the question: *"What controls the distribution and activities of subsurface life?"* The hypothesis-driven science plan integrates these aspects through a coordinated multi-disciplinary program of coring, sampling, analysis, and in-situ experimentation of continental crustal depths ranging from less than 10 m to the deepest drilling platform at 2.3 km. This fundamental question can be broken down into several parts as recognized by the project collaborators:

i. Geochemistry (i.e., salinity, pH, oxidation-reduction potential, dissolved gases), the available electron acceptors for microbial life (e.g., $O_2$, $NO_3^-$, Fe(III), Mn(IV) $SO_4^{2-}$, $CO_2$), and trace elements will influence the diversity of microbial populations. This is because different microorganisms are adapted to different conditions. Consequently, geochemical characterization is important.

ii. The availability of renewable energy for metabolic processes is crucial. Such energy can be organic or inorganic. Organic compounds and dissolved inorganic, reduced compounds can be transported with groundwater. Gases such as hydrogen and methane can be found both in the rock matrix and in the groundwater. Understanding migration and transport of molecules that can drive metabolic processes is crucial because it controls microbial activity.

iii. Detailed understanding of hydrology, flow of groundwater and mixing of different types of groundwater is required. Of particular importance is the modeling of how the mine and its history influenced and presently influences these hydrological processes.

iv. The geology (i.e. rock types) must be studied. Some rocks may contain metal sulfides, ferrous iron and manganese(II), which all may serve as electron donors for microbial life. If new fractures are open, dissolution of minerals may add more components that control life.

These research foci are all relevant and they have a good chance to be successfully explored at DUSEL by the design team. Their successful exploration will, however, depend on the availability of the Homestake mine for *in situ* long-term observations and research. A key advantage for using DUSEL is the direct and immediate access to aquifers in the rock where life is expected to thrive. It is also a strong advantage that the investigations can continue for long periods of time, which requires that DUSEL stays in operation long term (suggested to be 20-30 years for the physics experiments). This access is suggested to occur via boreholes with packers that isolate the fractures connected to underground laboratories, at different so called facies. Once these systems have been set up, they will constitute unique opportunities only matched by facilities in Äspö Hard Rock Laboratory in Sweden and Onkalo in Finland. However, several of the

DUSEL facies will be situated at greater depths (>450 m) and in different geological settings than those in Scandinavia.

The suggested program is very extensive, including 30 km of new drill holes and the set up and instrumentation of 10 facies, and the establishment of so-called MULEs (Mobile Underground Laboratories for Experimentation). In addition, up to three very deep boreholes will be produced from the 7400' level. The time line is set to 2011-2016 (i.e. 5-6 years). The subcommittee felt this is too little time for such an extensive program and recommends a longer time line for the large-scale project, with a more focused set of experiments planned in the first several years. Step-wise testing and selection of the facies would ensure that different environments are covered. An alternative approach could be to select 4-5 facies and drill in several directions (up, down, and horizontal in several directions). This would ensure that a large rock mass is reached (250 $km^3$ suggested) with fewer MULEs and drill sites. The present budget and planning reports do not describe, in detail, how the selection of facies will be done. In the present design drill sites are selected based on various accessible depth locations. The subcommittee recommends considering a more dynamic selection process to ensure that facies are different enough to motivate drilling and instrumentation. The design plan suggests that 100 m is the maximum fracture zone dimension; however, this can be confirmed with a less expensive selection procedure.

The interest from the scientific community and the general public is high. The DUSEL opportunity to study and investigate the deep biosphere has attracted interest from the International Continental Drilling Program (ICDP) community and a workshop has been funded to evaluate the opportunity to drill from the 7400' level. In a broader perspective, the deep biosphere continues to attract attention from funding agencies and organizations. For example, the Center for Dark Energy Biosphere Investigations (C-DEBI, http://www.darkenergybiosphere.org/) and the Alfred P. Sloan Foundation's Deep Carbon Observatory (DCO, https://dco.gl.ciw.edu/) fund deep biosphere related research. The International Symposium for Subsurface Microbiology (ISSM, http://www.issm2011.com/index.php?id=9322) highlights this area of research. The interest for the continental deep biosphere is matched by a strong interest in the sub-seafloor biosphere, as exemplified by the EU DS$^3$F program (http://www.deep-sea-frontier.eu/). These are a few obvious examples of the wide interest in deep biosphere research. It should perhaps be noted in this regard that major technique development could and should be complementary with these other large-scale projects on the subsurface biosphere. This involves sampling operations, in situ monitoring, in situ experimentation, sample storage/archiving, and data collection/management.

The science proposed has a high chance to be transformative, defined by the National Science Board as "research that has the capacity to revolutionize existing fields, create new subfields, cause paradigm shifts, support discovery, and lead to radically new technologies." The ecohydrology program will support the discovery of new microbial ecosystems, and the work may result in new technologies on how to explore subsurface life. The deep biosphere is well recognized by a growing community of scientists, as reflected by the funding programs and meeting mentioned above. Within this community, a paradigm shift is presently occurring. However, from a larger perspective, the majority of the scientific and public communities are still unaware of the deep biosphere and the paradigm shift is yet to come. The biosphere on Earth is today understood by most people as life on the continents, in lakes, rivers and the seas. The ecohydrology program has a great chance to take a central part causing a paradigm shift, where the general understanding of the biosphere of Earth is extended deep into the continents and under the seafloor.

## 2. Suitability of a Deep Mine for these Experiments

There are numerous advantages to a deep mine location for detailed investigations in geobiology. These advantages include access to rocks and fluids of a wide range of compositions, as well as direct access (or facilitated access through additional drilling) to regions of elevated temperatures and pressures. This variability in physico-chemical properties increases the chances to characterize the full extent of the biosphere on Earth. It should be noted that our understanding of the deep subsurface biosphere - both continental and marine - comes from a very select few boreholes in mines and deep-sea sediments. The experiments planned here require very high quality samples (e.g., minimal contamination), continuous access to new samples, the ability to carry out in-situ experiments, and long-term study (years to decades). A deep mine best fulfills these requirements. Further drilling, extending that which was carried out as part of the mining operations, is necessary to accomplish many of the stated research goals, and there are numerous advantages to drilling and coring from an underground location. These include a substantial reduction in drilling costs, much greater sample quantity and quality, and the ability to drill with less contaminated drilling fluids and lower water pressures. While the Homestake mine is probably not the only location on Earth where these criteria are met, it is arguably the best site in the USA. The rocks range from felsic to mafic, clastic and carbonate, and they are divided into three units of varying ages, up to two billion years in age. The rocks are highly folded and therefore, mining tunnels and boreholes (and perhaps fractures) can transect multiple rock types and formations. While the local geology is very complex, detailed core sampling and available records from mining geologists permit an accurate characterization of any sample or drill hole to be used in geobiology studies here. It is also noteworthy that the general rock type at Homestake, heavily fractured metamorphic rocks, is exposed over ~20% of the land surface, making this a study site that goes far beyond a case study.

## 3. Other Potentially Transformative Geoscience Opportunities

The research project, as outlined, is extensive and broad, but parts of it are a bit vague in their description. Consequently, the opportunities identified here as "overlooked" may very well be on the minds of the PIs and their potential collaborators, but not expressed in sufficient detail for the subcommittee to recognize. Several possible opportunities discussed by the subcommittee are listed here:

a. Bacteriophages, viruses that infect bacteria, have recently been identified as important for the control of bacterial numbers and activity in deep groundwater. The detailed exploration of how phage-microbe interactions operate in the deep subsurface is a good opportunity for this program. It may be that phages are one of the most important factors "controlling the distribution and activities of subsurface life" when energy is available for life. In addition, phages may induce extensive genetic exchange between microorganisms via transformation and transduction, which in turn will drive diversification of deep biosphere life.

b. The main question "*What controls the distribution and activities of subsurface life"* should be expanded to include microbial diversity, in particular metabolic diversity. Subsurface microbial ecosystems may comprise microorganisms with unknown metabolisms. The study of metabolic diversity will require some classic microbiology including cultivation. Extraction and sequencing of DNA from the studied environments can be helpful, but culturing approaches are needed for successful metabolic research. The development and application of carefully controlled culturing methods (e.g., under pressure, anaerobic conditions, nutrient gradients) may be fruitful.

c. While the temperature limit of life received significant attention in the proposed research project, other limits of life were largely ignored. We refer, in particular, to limits of metabolic energy, nutrient availability, fluid flow (or 'openness' of the system), and/or overburden pressure. With the geologic complexity of the Homestake mine, the DUSEL offers excellent sites to investigate these other potential limits of microbial life.

## 4. Assessment of the Proposed Selection Process

This subcommittee recommends that the selection process for geobiology projects at DUSEL Homestake be considered under three potential situations. First, if DUSEL is ultimately funded as a high-priority, major research facility, geobiology projects using these facilities should be solicited and considered for funding, though planned more flexibly than presented in the review materials. Rather than initiate extensive drilling at all mine levels in the short time period specified, smaller, more constrained projects may be funded in early stages of DUSEL, over normal NSF funding periods. Sites of drilling and geobiological sampling can be evaluated, with refinements made in sampling strategies and desired facies selected on the basis of prior experience and results. Second, if DUSEL is not built in the near future, smaller scale research projects than outlined here can be initiated that are exciting and important. Standard NSF selection procedures for \$200-700K projects of 3-5 year duration funded by core and temporary programs are appropriate for many deep subsurface biology experiments at DUSEL Homestake. We note, however, that some activities will ultimately require longer timeframes and substantially greater financial investments, especially for drilling operations and infrastructure. Third, should the NSF develop a funding program for mid-size infrastructure - on the order of ~\$20M funding levels - geobiology research at this

DUSEL site will likely be highly competitive. This level of funding could be used to drill several high-priority holes and outfit them for microbiological studies, including appropriate sampling and monitoring technology. In addition, funds could be used to establish a mobile lab, not unlike that employed aboard research vessels for subsurface biology research in deep-sea systems. Given the investments that will be required for geobiological sampling, protocols for proper handling and archiving of sensitive and unique samples will need to be developed and executed to make them available for future geobiology investigations.

**National Science Foundation**

**Deep Underground Science & Engineering Laboratory (DUSEL)**

**AC-GEO Subcommittee Science Review**

**Lead PI Name:** **Eric Sonnenthal**

**Institution:** **University of California, Berkeley**

**Title:** **Coupled Thermal-Hydrological-Mechanical-Chemical-Biological Experimental Facility at DUSEL Homestake**

**Experiment Overview**

The focus of this project is the development of a large-scale subsurface experimental facility to investigate coupled thermal, hydrological, mechanical, chemical and biological processes in fractured rocks in deep formations. The facility involves excavation of a mine drift that is to be heated, with monitoring of surrounding rock by way of instrumented boreholes, bringing signals to an observation drift. The fractured rock volume that will be heated has dimensions of 50 x 40 x 40m and heating facilities are designed to reach temperatures of 150-300C. The facility is planned for a location at the 4850 ft level of the Homestake mine. Long-term experiments will be performed to monitor conditions and properties of the heated rocks as temperatures evolve, hydrothermal fluid transport is initiated, and reactions occur between the rocks and pore fluids. The goal is to make observations and collect data on fluid-rock interaction rates, multi-phase system behavior and spatial and temporal evolution of permeability in the fracture network. The boreholes will be instrumented with sensors (mechanical, thermal, hydraulic) and ports for collecting fluid samples (chemical, biological) as a function of space, time and temperature. The size of the facility and its sensor distributions will allow experimentation at length scales of ~1-10 m.

**1. Review and Assess Science Opportunities**

The scientific questions that are posed involve the coupling of the processes that occur in fractured rock systems subjected to heating. The first science question is related to the reactions between the minerals of the rock and the flowing fluids, and how the reaction rates themselves are controlled by the evolving fluid interfaces within fractures. The second question is related to the mechanical behavior of the rock-fluid system, and how this affects the permeability (and transmissivity) of the fractured rock system.

Reactions between the minerals and fluids of the system involve dissolution and precipitation and potential development of chemical seals of fractures. Thus, permeability and fluid flow will be affected, and in turn affect stress and reaction processes in the rock. The third question is related to quantification of the rates of mobilization and transport of chemical components of the rock-fluid system. A fourth question focuses on microbiological activity in the fracture as temperatures and geochemistry change. The final question is related to the challenging issue of how the mineralogy and permeability that changes at small scales can be used to predict system properties at larger scales.

This facility is designed to investigate coupling in hydrothermal rock-water systems where fluids such as water, $CO_2$, hydrocarbons, and magmas flow through hot rocks under stress in deep formations. Many natural geological processes involve coupling of processes where thermodynamic conditions vary spatially over a wide range of scales. Despite the importance of these complex processes in the Earth, we know relatively little about coupling in natural systems.

In addition to coupling, this facility is intended to address questions of scaling, including scaling of hydrological fluid flow, as well as fluid-rock reactions, solute transport, and dissolution and precipitation driven by gradients in temperature, chemical potentials, stress state of the rock, and pore fluid pressure. These processes are clearly important in fractured rock systems. They will alter the pathways for fluid flow in fractures that experience increases and decreases in aperture and tortuosity. They will also be important over extended time periods, so the facility is designed to operate over extended time periods.

The facility and experiments, as described by review materials provided for this report, suffer from two drawbacks. The complex coupling of this large scale experiment will be very difficult to analyze, particularly in the complex geological setting of the Homestake mine, and the relevance to geologic systems is not well developed.

The results of the large-scale experiment will likely be complex, with system measurements that will depend on multiple, concurrent interactions and complex coupling. Thus, the experimental results may not readily lend themselves to separation of variables or determining which coupling processes are most important. The scope of this project is very wide covering stress and deformation of the rock mass, fluid flow, conductive and convective heat transfer, solute transport and fluid-rock reactions, and biological-chemical processes. It is not clear how any one of the interactions between processes will be investigated, leading to fundamental understanding. The research on microbial communities is not developed to a stage that can be evaluated. Experiments at this facility could use further thought and development to allow some coupled processes to be studies while other processes are minimized. In general, a reduction in scope of study would be beneficial. This might involve parallel efforts on smaller scale experiments that involve fewer processes than in the full-scale facility designed for DUSEL. The smaller scale experiments will also have the advantage that they will add to our understanding of scaling. Modeling will also be very important, for the purpose of analyzing multiple processes identified in the experiments, understanding the complex coupling of processes, and to examine scaling.

The subcommittee recognizes the importance of developing up-scaling methods to simulate the behavior of large systems based on knowledge generated at smaller observation scales. The PIs recognize that fluid-rock reaction rates in large, natural systems are commonly 2 to 5 orders of magnitude slower than rates measured in small-scale experimental studies. However, for the proposed large-scale experiments to be useful and predictive, theory must be developed in parallel with the experiments at different scales. While heat flow modeling is well developed for this facility, little information is provided for the model development to analyze fluid transport in a changing fracture network, or to incorporate rock-water reactions, or solute transport. Modeling and well developed theory will assist in designing data collection strategies. Modeling and model assumptions are not addressed adequately in the current plan.

While coupling of physical, chemical, and biological processes are undoubtedly important in natural geologic settings, the design of this facility does not appear to be a clear physical-chemical analogue to natural geothermal systems. Thus, the geological relevance of the facility is not apparent. The facility bears greater resemblance to engineering projects such as Yucca Mountain, NV, and other nuclear repository designs. The heat source in large underground cavities of these applications will be low- to high-level radioactive waste that generates heat over time scales similar to those of the facility designed for DUSEL. Clearly, such applications will require large scale simulations with appropriate quality assurance to allow prediction of the waste isolation facility performance. However, it is unclear that the Homestake mine and its geology, with high permeability fluid-saturated fractures, would bear much resemblance to optimal geologic repository sites.

In addition to physical and geochemical processes, this facility is intended to study the response of microbial communities to the thermal and other perturbations imposed in the large-scale heating experiment. However, the biological hypotheses, sampling, and measurements are not well developed. Some portion of the heated rock volume will reach high temperatures and biological activity will likely be restricted to the periphery of the rock volume under investigation. This component of the experimental plan could be strengthened through coordination with other DUSEL geoscience experimental groups and development of sampling protocols and analysis by geobiologists.

The cost of establishing this facility will be high. It can be justified if other means of studying natural geothermal systems are not feasible or if it contributes to engineering practice of nuclear waste isolation facilities. If DUSEL is not established as a major research facility, it is difficult to conceive of a means of continuing this project development.

## 2. Assess Suitability of a Deep Mine for these Experiments

The large-scale heating experiment reviewed here requires the setting of an underground mine. However, it is not clear that the mine must be particularly deep. The Yucca Mountain, NV high-level nuclear wasted site is situated at a depth of ~250m. At the same time, the depth of the Homestake is not a disadvantage. The Homestake mine offers appropriate sites to investigate the response of fractured rock systems to thermal perturbation, and the many hydrological, mechanical, and biological processes anticipated in this experimental facility. However, the rock types of the Homestake mine are not optimal to study chemical fluid-rock interactions. The metamorphic rocks of this mine have been subject to temperatures larger than the experimental conditions. Thus, most fluid-rock reactions within fractures will involve traces of retrograde minerals rather than the crystalline rocks themselves. As a result, significant study will be required to identify and characterize trace mineralizations in fractures to learn whether they are stable or unstable at the experimental conditions. Reaction rates might be low, compared with those of reactions between fluids and low-temperature sedimentary rocks with phases that are not at equilibrium at the experimental conditions. This would necessitate long experimental times to evaluate the success of this facility in investigating changes in permeability resulting from dissolution and precipitation processes. Finally, there is a possibility that thermal stresses could trigger minor seismic events, which would interfere with other experiments. It will be important to investigate this possibility by measuring the in situ stress state and modeling thermal stress perturbations that might lead to critical conditions for rock failure.

## 3. Recommend other potentially transformative geoscience opportunities not yet identified

There is an opportunity to fully integrate large-scale experiments and modeling that capture multiple thermal, hydrological, mechanical, chemical, and biological processes, and their interactions. In addition, there may be opportunities at this facility to test and apply wireless sensor technologies for environmental monitoring and real-time data collection.

## 4. Review and Assess the Proposed Selection Process

Given the large scale of the hydrothermal experiments planned at this facility, the anticipated heating times, and times required to observe changes in hydrogeology at slow, natural reaction rates, funding periods of 10+ years must be envisioned. As a result, full funding of DUSEL will be a requirement for these experiments. Modeling and smaller, laboratory experiments, as recommended by the subcommittee, could contribute to improvements in the large-scale experiment, and these studies could be completed in normal 2-3 year periods typical of NSF research projects. The PIs are well qualified to carry out this research, but the addition of a geobiologist(s) would strengthen plans to investigate microbial responses and coupling to hydrological and geochemical processes.

## National Science Foundation

## Deep Underground Science & Engineering Laboratory (DUSEL)

## AC-GEO Subcommittee Science Review

**Lead PI Names:** **Catherine Peters**
**George Scherer**

**Institution:** **Princeton University**

**Title:** **DUSEL $CO_2$ - A Deep Underground Laboratory for Geologic $CO_2$ Sequestration Studies: Design of the Facility and Experiments**

### Experiment Overview

If we are to develop $CO_2$ sequestration in geologic environments as a viable tool for moderating greenhouse gas emissions, more research is needed. Experiments are needed at a variety of scales from small-scale laboratory experiments, to intermediate- and large-scale trials, as described for this facility at DUSEL, to field tests, all supplemented by modeling studies to evaluate those geological conditions that are necessary for long-term $CO_2$ storage. The PIs of this project propose to use the DUSEL site to construct large-scale sedimentary pipelines to study how $CO_2$ interacts with sediments, migrates as a function of pressure and temperature, changes its physical and chemical state in underground settings, and reacts with caprocks and cemented boreholes. In particular, this experimental facility is designed to investigate processes that influence $CO_2$ storage and migration as a result of the transition from supercritical fluid to subcritical gas.

Originally, the PIs planned to construct sediment-filled columns underground using existing "sandlines" of the Homestake mine, which would provide significant vertical pathways for buoyant interstitial $CO_2$ and allow studies of fluid transport and trapping. In their interim report of 08/01/2010, the research team changed their experimental plan from the original proposal, to one requiring the construction of three 500m stainless steel columns (1m in diameter), filled with sand and brine, installed within three new, large-diameter (3m) boreholes. The primary experiment entails examining how $CO_2$ will pass through a 500m sedimentary column in a "leaking" situation. Particular problems include potential transitions in phase, from supercritical fluid to a subcritical gas (and potentially liquid) phase, interactions with the primary brine pore fluid, multiphase flow, and reaction. Three experiments are planned: $CO_2$ transport and leakage, corrosion of a cap cement, and microbial activity affected by enhanced $CO_2$.

## 1. Assessment of Science Opportunities

### *Opportunities*

While this project is largely motivated by the practical challenge of storing $CO_2$ in sedimentary geologic settings, a number of fundamental scientific questions are posed as part of this engineering challenge. How does $CO_2$ flow through a sedimentary column? When, where, and how do the buoyancy and solubility of $CO_2$ determine whether this gas rises, sinks, or remains in place? The PIs have termed the revised experimental facility LUCI: Laboratory for Underground $CO_2$ Investigations. LUCI is presented as a facility that is crucial to bridge the gap between bench-scale measurements of $CO_2$ transport and trapping, numerical model simulations, and field-scale demonstrations. The PIs note that LUCI would be the only deep underground laboratory for controlled study of geologic carbon sequestration in the world. The findings from this unique experimental facility will advance carbon management technology worldwide and help remediate global climate change driven by greenhouse gas emissions. Clearly this research has high societal value, not only for the United States but for the climate and biosphere of the planet and sustainability of energy and land use.

The questions that the PIs address are high profile and strategic. The subcommittee is largely in agreement that large-scale experiments must be done to investigate many of the questions and problems that are to be addressed by the LUCI facility. However, the experimental plans, as described and analyzed in the materials reviewed illustrate some significant design challenges, and disappointments, such that further modeling and experimental design are needed before the significant financial investment in LUCI (or a similar large-scale facility) is made.

### *Remaining Design Challenges*

The team of PIs of this experimental facility carried out numerical modeling that predicted the type and timing of $CO_2$ transport in their proposed leakage experiment (in the 01/06/2011 Report). These results showed that $CO_2$, introduced as a pulse at the base of a 500m column, would take only 6 days to transit from the bottom to the top of the sand-brine column (where it might either be sealed against a caprock or leak to the atmosphere). Clearly, the effective permeability of the sand column for $CO_2$ transport must be large for such a short transit time. Even if the numerical model is accurate only to an order of magnitude, this result much be a disappointment to the PIs and to anyone's expectation to contain $CO_2$ at LUCI-model conditions. Rather than proceed to build a high-expense physical model, such as LUCI, further modeling experiments and/or small-scale physical models would appear to be called for, which might lead to more suitable subsurface geologic conditions for $CO_2$ sequestration. Large-scale physical experiments may ultimately be justified, but only after modeling experiments hone in on better sequestration/repository conditions.

The scale and expense of the experimental facilities, as presented, raise many challenging practical questions that are not addressed in the materials reviewed. How will the sands be filled into the large stainless steel columns and characterized? Will sand packing be promoted by a ultrasonic tool or other means? If so, how will this be accomplished along the entire column length? Packing of sands may be very heterogeneous, whether filled during the building phase of the 500m columns or introduced after assembling the columns, and they may be much more porous than natural sandstones and fine-grained sedimentary lithologies that are more prevalent in sedimentary basins than are sandstones. It is difficult to believe that porosity in these materials will replicate the pore space of sedimentary rocks, which have been subject to loading over geologic times, and chemical processes of diagenesis that decrease porosity and permeability.

Fluid sampling is probably relatively straightforward along the large-scale stainless steel columns with sufficient access to many different levels of the mine. However, how sediments are to be sampled to test effects of $CO_2$ (or carbonic acid) corrosion and etching is not well specified. It is not clear that these large facilities are needed to study corrosion or reactivity of $CO_2$ or resulting acidic fluids with cement. Experiments designed to investigate reactions between acidic brines and cement could be done in small-scale, low-cost laboratory experiments.

Given that modeling results suggest that the $CO_2$ transit time is only 6 days, will the sand columns continue to be useful experimental facilities for extended times or multiple experiments? If so, how will the sand packs be removed from the stainless steel columns? Or will the sand remain in the columns and the pore fluids flushed to initiate another experiment? If so, how will multi-phase fluids trapped in small-aperture pore throats be removed? If the PIs have a plan for repeat use of the columns (e.g. after the first $CO_2$ leakage experiment), it is not evident from the review materials.

The subcommittee acknowledges the value of making measurements of the sand columns by way of physical properties (using resistivity and other Schlumberger tools), which correlate with sediment pore space and fluids. However, sand packs even in smaller, more controlled experiments can be heterogeneous, and these heterogeneities can be extremely important to the transit of $CO_2$ and other interstitial fluids. It may be useful to do smaller scale laboratory experiments before initiating the large-scale, expensive experiments at LUCI. These experiments could provide scaling information in addition to testing of sand-packing methods and physical property imaging. Further numerical modeling runs are needed, in order to examine those sediment properties that would lead to longer transit times (so that the value of expensive, large-scale experiments can be optimized), and to evaluate effects of sediment heterogeneity and the processes of multiple-phase flow, which will also be important in the large-scale experiments.

The microbial experiments are not well described in the review materials, lacking hypotheses, sufficient controls, or predicted outcomes. Some specifications for the microbial experiments may include typographical errors. For example, the microbial inoculation chamber is specified to be $10^3$ $m^3$. It is unclear how such a vessel would constructed, and then used to inoculate a sediment column. Alternatively, if this is not a simple error in the review materials, the scale of this inoculation chamber may illustrate the enormous challenge of including biological processes in these experiments.

This facility will need a well-developed safety plan. Continuous monitoring of $CO_2$ will be required along the length of the three 500m columns, as well as nearby drifts and shafts to detect any leaks of $CO_2$ into the confined spaces of the mine at any stage of these experiments. Evacuation protocols will need to be established and special procedures developed to vent columns at the end of each experiment.

***Specific Experiments***

***Experiment #1 at LUCI*** addresses $CO_2$ leakage. More specifically, will buoyancy increase flow of $CO_2$ upward? Will Joule Thompson cooling mitigate flow rates? These are important problems but the current experimental plans suffer from lack of detail on how sands will be introduced into the columns, packed homogeneously (or heterogeneity characterized). Given that sedimentary basins are dominated by shales and mudstones, why has sand been chosen for these columns other than the fact that it can be added to the columns more easily than other lithologies? Sandstone reservoirs may have larger storage capacities than do finer-grained siltstones or interlayered sediments, but their high permeabilities do not promise long-term storage without appropriate stratigraphic and structural seals involving other lithologies. Heterogeneity of sediment in the columns will be difficult to resolve, and may render the data qualitative rather than quantitative. It is difficult to conceive how the results can be compared to some reference or control column, as is possible in smaller scale laboratory experiments.

The recent calculation of $CO_2$ transport (Interim Report for period 08/2010 - 01/2011, submitted 01/06/2011) indicates that the full-scale leakage experiment will be completed in just 6 days. This is an important result and suggests that further modeling and adjustment of experimental parameters are needed to seek geological rock types and conditions that may lead to longer term $CO_2$ storage. It is unlikely that many of the processes described in the proposal (and reports), such as reactions between $CO_2$ and minerals of the sediments, will be important in the short experimental times predicted. Yet, these processes are likely to be very important in successful geologic sequestration environments, in which fluid transport is slow.

The subcommittee suggests that model and experimental tests may be more promising on sand/clay/brine mixtures with lower effective permeabilities to $CO_2$ and longer transit times. Larger gradients in fluid pressure can be maintained in lower permeability columns consisting of sand/clay mixtures so that shorter columns in normal laboratory facilities can achieve many of the same results of the large columns of LUCI. For example, combined with modest pressure capabilities of a laboratory pressure vessel, the transition from supercritical to subcritical $CO_2$ can be achieved without siting in a mine.

***Experiment #2 at LUCI*** addresses corrosion. More specifically, will acidic fluids cause new escape pathways in caprocks or lead to solute transport and precipitation?

Will these fluids corrode cement? These experiments do not seem to require facilities of the scale developed as part of LUCI for the Homestake mine. Once the nature of the corrosive fluids is determined from Experiment #1 or similar tests, small-scale laboratory experiments can be done to answer these questions. It is not clear how the cement caps are to be included in the large-scale columns or how they will be recovered if they are included in the sand packs of a column. Will these be placed at the top of large-scale columns or at intervals along their length?

***Experiment #3 at LUCI*** addresses microbial processes in potential geologic $CO_2$ sequestration storage facilities. More specifically, will $CO_2$ be converted to $CH_4$ by anaerobic microbes? Separate chambers will be designed to test this. This microbiology experiment appears to be added to the $CO_2$ sequestration study, with little or no specific details of the experimental procedures or design described. If $CO_2$ were to be contained in a test column for a period of time, perhaps a microbial population might develop, but there are no hypotheses stated to test when conditions will lead to microbially generated $CH_4$. How will the microbial flora in the columns or side experiments be generated? Or will they be introduced once the columns are filled with sand and brine? An important consideration that is not stated in the materials reviewed concerns the stoichiometry of the geobiology experiment. If microbes were to consume and convert considerable amounts of sequestered $CO_2$, a suitable reductant would need to be available. What are the likely reductants of the sand packs, and will they be important in sedimentary rocks that are geologic candidates for $CO_2$ sequestration?

***Significance and Cost-Effectiveness***

The high cost of this experimental facility is not justified by fundamental scientific objectives, but can readily be justified on the basis of engineering applications and societal impact, given that the experiments may lead to practical and effective $CO_2$ sequestration. Investment into $CO_2$ sequestration by the United State is one of the highest priorities, and the PIs are noted experts in this field. Research funding may be more appropriate under the auspices of the Department of Energy.

As presented in the review materials, these one-shot experiments do not seem to be cost effective. They come at high cost (projections of $40-$60M), and it is unclear that the particular design or siting at DUSEL is required to accomplish the stated goals. It is also not clear that the large-scale experiments can be optimized before relevant, small scale experiments and modeling are done.

This subcommittee was not assembled to evaluate construction or maintenance plans, but it is difficult to evaluate whether the facilities are cost-effective without knowing that the cost estimates of building 900 ton columns (summing the weight of the stainless steel pressure vessels and sand-brine mixture) are realistic or accurate.

## 2. Suitability of a Deep Mine for these Experiments

As originally presented in the proposal for this facility, the Homestake mine may have seemed an appropriate and cost-effective site for these experiments, given the existence of sandlines that traversed significant vertical distances. However, given the deficiencies of the sandlines, and the development of the LUCI design, the need to site this experimental facility at DUSEL is unclear. The principal argument for a location in a deep mine appears to be the access a mine affords to intermediate positions along the length of the stainless steel columns. The PIs state that elevation gain along the column length is required to study density-driven fluid flow. However, this can be accomplished without the need of vertical columns.

Potential leaks of $CO_2$ in the confined space of a mine present significant safety hazards to scientists and personnel of this facility, and to other personnel of DUSEL if/once its experimental facilities are funded. As a result, the Homestake mine is probably not an appropriate location for the LUCI facility, and it would be preferable to isolate this experiment, siting it away from other DUSEL facilities.

An alternative design to LUCI, which does not require a mine and does not require drilling might consist of stainless steel pressure vessels placed along the slope of a mountain. It is not clear to the subcommittee that 500m of elevation gain is required, but similar elevation differences are possible as at DUSEL. Access could be better than in the mine and safety concerns related to $CO_2$ leakage would be far less serious than in the confined spaces of a mine. Moreover, the weight of the column would be distributed without the bracing that would be required for vertical columns in a mine. Intermediate parts of the column could be refilled with different geological materials without having to empty the column in its entirety.

## 3. Other Potentially Transformative Geoscience Opportunities

The objectives of this experimental facility, to study the transport, leakage, and corrosion in sediment/brine systems that are injected with $CO_2$ are important to develop long-term geologic $CO_2$ storage facilities and help remediate increases in atmospheric greenhouse gases. Given the early and disappointing results of modeling reported by the PIs for $CO_2$ transport through sand/brine, other types of sediments and rock types should probably be investigated. There may be a need for facilities such as LUCI once lab-scale experiments and models suggest promising large-scale tests. Ultimately, field/reservoir-scale tests will probably be needed.

## 4. Assessment of the Proposed Selection Process

Because this project could be constructed in another location, and because it is primarily a facility development with practical energy implications, its funding should be shifted to DOE funding. This particular team should review its current experimental design, consider dropping the microbial studies, and give greater consideration to wall effects, heterogeneity, filling the columns with different sediment matrices, and examine geologic materials and conditions that would lead to longer term transport and storage.

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