Engineering Research Opportunities in the Subsurface: Geo-hydrology and Geo-mechanics

October 27, 2002

0. Executive Summary

The potential development of a national underground science laboratory offers significant opportunities to improve our understanding of the processes governing the mechanics of, and the transport of fluids in, fractured rocks. Importantly, these processes govern our ability to recover petroleum, mineral and geothermal resources, to restore contaminated sites to pristine conditions, to construct safe structures in rock, and to provide for the safe entombment of wastes. Despite significant advances over the past three decades, our understanding of the processes governing the transmission of stress and the motion of fluids in fractured rocks, the agents of complex thermal-hydraulic-mechanical-chemical-biological interactions, and our ability to both characterize material properties and to project system response remain limited. Lacking is access to a centralized underground laboratory, where the critical issue of scale effects may be rigorously examined with unusual spatial access to a large block of rock. The absence of rational procedures for the design of full-scale engineering structures in rock is a critical limitation compared to other branches of engineering. The potential NeSS site at the Homestake Mine represents but one opportunity for the constrained study of these process-interactions at relevant spatial scales of meters to hundreds of meters, at a broad range of stresses and temperatures, and at temporal scales of days to years to decades.

Important advances in geo-engineering and geo-hydrology are necessary/possible in the four areas of *complex coupled-process interactions*, *rock deformation and the state of stress* with application to *construction in rock*, the *profound effect that fractures may exert in conditioning behavior*, and the resulting *flow and transport of fluids.*

Complex coupled-process interactions control the *flow and transport of fluids*, and of energy and nutrient fluxes in the fractured subsurface - these are strongly stress, temperature, and scale dependent. Experiments conducted at an underground laboratory will contribute to our understanding of key process-interactions over the short- and long-term, catalyze interactions between scientists representing a broad array of disciplines, and spur the development, deployment, and testing of new sensors and sensing techniques.

Similar experiments will contribute to our understanding of *rock deformation and the state of stress,* accommodating the strong controls of fractures, spatial scale, and process-interactions on the performance of structures *constructed in rock.* An underground laboratory will allow the testing of rational methods of design and new construction systems that both reduce reliance on empirical methods, and minimize over-support. Uniquely, detailed measurements of system durability may be made over extended durations, and compared with predictions of process-interactions.

Fractures control the mechanical behavior, and the *flow and transport of fluids* in fractured rock. Observations and tests in an underground laboratory will advance understanding in the modes of fracture formation, and enable the constrained development of geophysical methods of fracture-detection, and fracture-characterization.

Experiments at an underground science laboratory encompass those that examine the existing conditions of the access drifts and chambers, those that predict mechanical and hydraulic response as new structures are excavated, and those that seek pristine conditions in remote portions of the laboratory for the conduct of in situ tests, or the examination of the performance of structures in rock. The potential for the forensic examination of structures, including the confirmatory exhumation of test blocks, is an important and unique attribute of an underground science laboratory.

Important parallel opportunities exist in education from elementary to graduate level. These include an important contribution to the training of a new generation of Earth scientists and engineers, through the provision of field school activities, participation in important research projects, and through economies of scale with other science and engineering communities in the U.S.. Specific opportunities exist with current or proposed seismic (Earthscope-USArray), and hydrologic (CUAHSI) initiatives.

1. Overview

The engineering accomplishments and advances in scientific understanding of outer space by the United States over the last half century are eloquent testimony to what can be achieved when the national government makes a commitment to a particular goal. The Neutrino and Subterranean Science (NeSS) project is an exciting development whereby study of elementary particles from *outer* space requires a link to the science and technology of subterranean or *inner* space. An underground site dedicated to geoscientific investigations on various scales, such as envisaged in the NeSS project, could result in major advances in subterranean science.

The proposed development of an underground science laboratory for neutrino experiments offers significant opportunities to improve our understanding of the processes governing the mechanics of, and the transport of fluids in, fractured media. Access to an extensive network of drifts to depths of 2500 meters, the attendant large range of in situ stresses and temperatures, and the potential long-duration of the experiments offer unique opportunities for geo-hydrological and geo-mechanical research. Importantly, the unusual spatial access to a regional-scale geologic block enables, through its dissection, the corroboration of processes not feasible by mere access through boreholes or geophysical methods. Specifically, proposed tests will examine the role of complex process interactions of temperature, stress, reactive chemistry and biology on the hydraulic and mechanical behavior of fractured rock masses, at spatial scales of meters to hundreds of meters, and at temporal scales of days to years. In addition, the facility offers important opportunities for the development and validation of new mechanical, hydraulic, geochemical tracer, and engineering geophysical methods for the characterization of mechanical and transport properties, and for the development and testing of new sensors and improved mathematical models to be applied to fractured rock masses, aquifers and reservoirs.

These scientific needs are addressed in a series of proposed experiments, identified following.

2. Scientific Rationale

The proposed underground research laboratory addresses a number of contemporary needs in geo-hydrology and geo-mechanics.

- The processes governing the transmission of momentum, fluid, mass, and energy fluxes, particularly in fractured media, remain inadequately understood.

- These processes govern our ability to recover petroleum, mineral and geothermal resources, to restore contaminated sites to pristine conditions, to construct safe structures in rock, and to provide for the safe entombment of wastes. Engineering applications of particular societal significance, and key technical uncertainties involved in their development are included in Table 1. These include:

Resource Recovery	Petroleum and Natural Gas Recovery from Conventional/Unconventional Reservoirs
	In Situ Mining
	Hot Dry Rock/ Enhanced Geothermal Systems (HDR/EGS)
	Potable Water Supply
	Mining Hydrology
Waste Containment/Disposal	Deep Waste Injection
	Nuclear Waste Disposal
	CO_2 Sequestration
	Cryogenic Storage/Petroleum/Gas
Site Restoration	Acid-Rock Drainage
	Aquifer Remediation
Underground Construction	Civil Infrastructure
	Underground Space
	Secure Structures

- Lacking is our ability to understand processes governing the transmission of stress and the motion of fluids (*viz.* fracture geometry, and connectivity, and transmission characteristics), processes governing their interaction with their environment (*viz.* coupled THMC(B)[1] feedbacks, involved in developing conduits and in modifying their properties), in effectively characterizing their mechanical and transport characteristics (*viz.* mechanical, hydraulic, tracer, and geophysical techniques), and in effectively projecting system response (*viz.* sensing and monitoring, data fusion and modeling).

- Although significant advances have been made in understanding these interactions in the past three decades, important questions remain. These relate both to the understanding of fundamental process interactions that control the response of the natural system, and how these systems may be harnessed for the recovery of minerals and energy, utilized for civil infrastructure and the safe disposal and containment of wastes, and with minimized impact on the natural environment.

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[1] Thermal-Hydraulic-Mechanical-Chemical-and-(Biological) processes influence the transport of fluids in fractured rocks. These processes may act against us, for example limiting the delivery of amendments for bioremediation by pore or fracture clogging; or may act for for us, in improving recovery from petroleum reservoirs by hydraulic fracturing.

2.1 Societal Needs

Important societal benefits will accrue from improved techniques and technologies to recover minerals and energy, to provide safe disposal and containment of wastes, to afford the effective restoration of contaminated sites, and to contribute to safe use of the subsurface for civil infrastructure.

Resource Recovery: The ready supply of fuels, energy, and minerals powers modern society. The availability of a secure, extensive, and distributed supply of potable water is a societal imperative.

Petroleum products supply modern society with inexpensive and convenient transportation fuels, and an endless array of plastics and petroleum products. Natural gas is an abundant fuel that generates the least CO_2 when burned compared to petroleum or coal, and provides one likely fuel-stock to power the widely-touted hydrogen economy[2]. Effective recovery of these fuels require their initial discovery, typically through surface geophysics and drilling, and their subsequent removal from reservoirs typically 2 to 5 km deep, via an array of vertical or horizontal branching boreholes. Endemic uncertainties relate to the hydraulic connections that may be developed by routine completion methods. Such methods include hydraulic fracturing of the wells, where the roles of structural features such as faults and fractures at a variety of length-scales control the depletion of the reserve. Ambiguity remains between features usefully observed from geophysical imaging, and what these features mean in developing the reservoir. A depleted reservoir may retain 80% of the original-oil-in-place and improved methods and understanding of the motion of fluids may increase this yield, with subsequent improvement in the reserve base and in energy security. The provision of an underground laboratory may address these issues, albeit in a non-reservoir rock, through an improved understanding of the crucial role of fractures and faults on the displacement of fluids, on the integrity of wells, and in controlled appraisal of geophysical methods in defining hydraulic performance.

Mined minerals are a fundamental need of modern society, encompassing copper recovered for use in power electronics, to gold and other precious metals whose use pervades electronic components and devices. As high-grade deposits are depleted, the lower grade and deeper deposits may only be recovered if mining methods are economically viable. In situ mining provides a potential solution where the desired mineral is recovered directly by a solvent that targets that mineral in particular. The solvent is injected in situ, into the ore, through boreholes drilled either from the surface or from the deep mine. In situ mining methods offer the environmental advantage of reducing the amount of waste rock produced per ton of recovered mineral, and thereby reducing production costs. However, it also poses significant challenges in the development of controlled fracturing in the remote ores, in adequately characterizing the transport characteristics of these pathways, and in predicting the recovery of minerals from the application of tailored solvents. More directly than in the case of petroleum recovery, an underground laboratory provides a unique opportunity to explore these recovery techniques under closely controlled conditions. This evaluation may include the effective exhumation of the test cell to corroborate estimates of transport behavior from time-lapse geophysics, and predictions of reactive transport.

The recovery of geothermal energy from hot dry rock (HDR) reservoirs offers the potential to drastically reduce the emissions of greenhouse gases associated with the recovery and utilization of fossil fuels. HDR reservoirs have the advantage that they are ubiquitously present beneath major population centers in the United States, and

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[2] Reliable, Affordable, and Environmentally Sound Energy for America's Future. Report of the National Energy Policy Development Group, to the President of the United States. http://www.whitehouse.gov/energy/ ISBN 0-16-050814-2.

the world, with an estimated reserve base one-hundred times larger[3] than that for fossil fuels. The further development of HDR geothermal reservoirs suffers from the disadvantage that access to the large resource is limited, both for want of an inexpensive methods of drilling, and by our understanding of processes for development and production of the reservoir. A deep underground laboratory offers the opportunity of testing and observing the effectiveness of drilling methods, at depth, and in developing geophysical and tracer methods to follow the evolution of the reservoir with time, with unusual access to the reservoir level.

The availability of a dependable, secure, and uninterrupted supply of potable water is a societal imperative, and so far within the US, has proved an inalienable right. As population-pressure reduces the excess of availability over demand, any and all potential sources of potable water will play an increasingly important role. Ground water will become an increasingly important resource that offers significant advantages over surface supply in its potential for protection against surface-borne pathogens, maliciously introduced agents of bioterrorism, and of routine evaporative losses to the atmosphere. Non-traditional aquifers, including those that are fracture-dominated, may become increasingly important. In the Northwest, for example, deep fractured basaltic aquifers may become important, if the recharging annual supply from the snowpack is reduced, as projections of global warming indicate. Groundwater resources may become an important secondary source of supply.

Waste Containment and Disposal: Modern society produces a vast array of wastes ranging from the massive and benign unregulated discharge of CO_2 from the burning of fossil fuels, to the scrupulously controlled inventory of long-lived fission products from nuclear power generation. For many of these products, deep geologic isolation is a potentially effective method of disposal, although many questions remain of its effectiveness.

Deep injection offers a convenient, environmentally safe, and economical method for the disposal of liquid and solid wastes in deep saline reservoirs, or in depleted petroleum reservoirs. An injection well is completed to depth, and the waste is pumped either as a liquid, a slurry, or as a grout that will solidify in place. Disposal is relatively inexpensive, and ostensibly secure – formations that once trapped hydrocarbons over geologic time may also provide adequate long-term containment of the injected fluids. Despite the relative surety of this logic, few means exist to track the migration of these fluids, and ensure their immobilization. Similarly, deep sequestration of CO_2 is one potential method to stem the release of anthropogenic greenhouse gases to the atmosphere. Again, saline aquifers may be used, or the CO_2 may be utilized as a stimulant to improve the recovery from otherwise depleted petroleum reservoirs. Current estimates of $100/ton-disposed must be reduced to $10/ton if geologic sequestration is to be economically viable. Significant unknowns remain in characterizing reservoir capacities, in certifying the integrity of caprocks, and in assuring containment over many decades. The development of an underground laboratory offers the potential to observe, in a controlled environment, the factors that influence the development of injection processes, albeit in an unlikely candidate rock, and confirm the efficacy of containment.

Deep geologic isolation is the preferred method for the interment of spent nuclear fuel for all 30 developed nations who face this issue. Despite $6B spent on site investigation and process characterization studies at the proposed repository for civilian and defense high-level nuclear waste at Yucca Mountain, significant uncertainty remains in the role of hydrologic processes controlled by the effects of the heated canisters. Importantly, the hot repository will alter the current hydrological regime, which in turn may modify the transport characteristics of the fractured rocks surrounding the repository. Migration pathways may seal or gape, with the coupling of subtle and of strong chemical, biological, and mechanical feedbacks alike, only marginally understood. The development of an underground laboratory offers the potential to observe such interactions at a variety of

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[3] Reserve base based on a drawdown in crustal temperature by 120°C from a crustal depth of 3 km to 6 km. A 1°C drop in temperature over the same interval yields 200, 000 Quads (Quadrillion BTU), comparable to the total fossil fuel reserve of 360,000 Quads [Armstead and Tester, Heat Mining, Spon, p 57., 1987].

length- and time-scales of relevance, where importantly, subsequent exhumation will not compromise the integrity of the containment structure.

Site Restoration: The mining of sulfide deposits has left a significant legacy of acid rock drainage from the resulting waste rock piles and tailings sediments. When removed from depth by mining, pulverized by the processing of the ores, and finally given free access to oxygen, water, and catalytic bacteria, sulfide waste products readily generate sulfuric acid that may be lethal to the ecosystems they encounter. The resulting problems are epitomized by the consequences of the bankruptcy at Summitville,[4] where restoration costs are estimated at $120M, and in the reclamation of the Berkeley pit[5] in Butte Montana where the recovery plan will cost $87M. Absent are effective and inexpensive methods to reduce or eliminate acid discharges, by either active or passive means. The provision of a facility where tailings have been pre-disposed underground, and of the extensive surface waste facilities that must be immobilized, provide an important natural laboratory for prototype testing of passive treatment, encapsulation, and immobilization technologies, and techniques for the value-added recovery of remnant ores.

Underground Construction: Increasing urbanization and the desire to maintain environmental quality in the face of increased demands for surface space are focusing more attention on the possibility of using the underground space *beneath* cities. The traditional underground road, rail, fresh water supply and sewage systems are being augmented by a variety of uses. In Stockholm, sewage treatment plants are underground; in Chicago, the Tunnel and Reservoir Plan (TARP) now under construction, is intended to capture combined storm and sewer water overflows during high flow periods and to store this contaminated water in an underground reservoir until it can be processed by a sewage treatment plant. This avoids the discharge of sewage into local waterways and, in some cases, into basements.

The ability of a solid rock cover, be it some meters, tens or hundreds of meters thick, to provide a robust isolation of an activity from the surface and the open atmosphere, is a valuable attribute that offers numerous opportunities, for the geologic isolation of high level nuclear waste, for the basing of underground reactor facilities, and hardened structures.

Atmospheric contamination is a particularly severe hazard because of the rapidity with which it can spread and the great difficulty of controlling the movement of air in the open atmosphere. A number of industrial operations pose significant hazard when located on the surface. In 1984, for example, an explosion at the Union Carbide chemical plant at Bhopal, India, released toxic gases into the air, resulting in almost 4,000 deaths and leaving 11,000 with disabilities. In April 1986, the Chernobyl (Ukraine) nuclear explosion projected a plume of dangerous concentrations of radionuclides into the atmosphere where winds carried it rapidly well beyond the boundaries of Russia and around the world. Nobel Laureate Andrei Sakharov recommended that nuclear plants be located underground. Several designs had, in fact, been proposed prior to Chernobyl.[6] The generator plant, 100m~150m underground, would be linked to the surface by a number of tunnels containing filters to trap any radionuclides released in the event of an explosion. Several underground nuclear power plants were constructed and operated in Siberia.

The decision to conduct all nuclear weapons testing underground in response to worldwide protests against atmospheric testing of nuclear explosives also indicates recognition of the isolation capability of rock.[7]. The

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[4] The Summitville Mine and its Downstream Effects. USGS Open File Report (update) 95-23 by Bigelow, R.C., and Plumlee, G.S. geology.cr.usgs.gov/pub/open-file-reports/ofr-95-0023/summit.htm

[5] See the Department of Justice settlement of March 25, 2002. www.usdoj.gov/opa/pr/2002/March/02_enrd_180.htm

[6] Watson, M.B, W.A.Kammer et al. (1972) ***Underground Nuclear Power Plant Siting***, EQL Report No. 6 Environmental Quality Laboratory, California Institute of Technology, Pasadena, Calif. 91109, September, 150p: Bernell L. and T. Lindbo (1965) ***Tests of Air Leakage in Rock for Underground Reactor Containment***, Nuclear Safety Vol.6 No.3 Spring, p.267.

same attribute of rock cover has also been used widely to protect people and sensitive military installations against aerial attack. How to deal with such *hardened facilities* is a continuing military challenge.

Underground structures are intrinsically more robust than surface structures to earthquake events. Ground deformations produced by seismic waves are intensified at the surface compared to the interior of the rock. Also, structures within a closed surface such as an excavation can be supported by the rock so as to undergo less differential movement than a freestanding surface structure. The Magnitude 6.8 Northridge earthquake (20 miles NW of Los Angeles) in January 1984, disrupted surface transportation systems. The Metro Red Line subway, then under construction, sustained no damage. This is consistent with experience in other earthquake-prone cities such as Mexico City and Tokyo. Transit systems can serve an invaluable emergency role after earthquakes when surface transportation systems are disrupted.

These are but some of the important societal benefits that may accrue from a proposed underground laboratory. The important scientific and technological advances that must precede this realization are included in the following.

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[7] Most of the radionuclides generated during an explosion were trapped by the shell of solidified rock melt produced around the underground explosion cavity. Although now banned as part of the Comprehensive Test Ban Treaty, scientific knowledge gained during underground testing led to a number of proposals, such as the Ploughshare program, for peaceful uses of this enormous energy source in major engineering projects.

2.2 Research Needs

The drive to improve the recovery and utilization of necessary resources, to complete this while providing appropriate stewardship to the environment, and furthermore to restore existing contaminated sites, requires that we address the crucial technological needs, identified previously. A ubiquitous issue that affects all activities of construction, of utilization, and of resource recovery in and on rock is that behavior changes, sometimes drastically, with the scale of the structure or applied disturbance. This scale effect is a fundamental motivation in our attempt to understand rock behavior at multiple scales, and provides a compelling incentive for the establishment of an underground science laboratory.

Scale Effects

The deep underground facility proposed by the U.S. physics research community focuses attention on the central fundamental issue of the effects of scale, both in size and in time, in rock mechanics. The facility would consist of several excavations of the order of 50 m in span, each 100 m or so in length, at a depth of the order of 2.5 km or more. Such an excavation would cause a substantial redistribution of both solid and fluid pressures within a region of the order of 100 m or more of each excavation. On such a scale, a rock mass typically contains joints and similar discontinuities of varying orientation, length and connectivity. These can have a dominant influence on the constitutive behavior of the rock mass. The excavations will need to remain open and stable for several tens of years. It is obviously not possible to determine rock mass properties directly on these scales.

Design procedures for large-scale excavations in civil and mining engineering rely currently on empirical *rock classification* systems developed over the past 30 or more years. Much of the data on which these systems are based have been obtained for shallow structures. As with all empirical methods, extrapolation, in this case to very large-scale problems at great depth, is of unknown validity.

Analytical and numerical modeling techniques are now available to predict the behavior of jointed rock from the constitutive behavior of the system components (i.e. intact rock and joints) but are seldom used because of the lack of information on the effects of scale. The absence of rational procedures for the design of full-scale engineering structures in rock is a critical limitation compared to other branches of engineering. Research to overcome this obstacle could yield major benefits.

Several avenues of research could be pursued, including:

1. Analytical and experimental studies of the influence of scale on the (effective) normal and shear stiffness and strength of joints. These properties appear to be governed largely by joint roughness, which varies with scale. Direct tests in the laboratory would need to be supplemented by field studies.
2. Comparison of model predictions with values indicated by the empirical systems. Such comparisons could serve to develop a more rational basis for extrapolation of these systems.
3. Instrumentation (including microseismic observation of slip on individual joints) to observe the response of jointed rock to excavation.

The interaction between the various joints in a rock mass when subject to stress (and stress changes induced by fluid pressure variation) is a topic of considerable theoretical and practical importance. Slip on joints may result in stable (aseismic) and/or unstable (seismic) energy releases, probably the principal mechanism for rock bursts and earthquakes.

The technological needs for research in geo-engineering and geo-hydrology are in the four areas ***of complex coupled-process interactions****,* ***rock deformation and the state of stress****, the profound effect that* ***fractures may***

***exert in conditioning behavior**, and the resulting **flow and transport of fluids.** We explore these issues, in turn, in the following:*

2.2.1 Complex Coupled-Process Interactions

Momentum, fluid, mass, energy and nutrient fluxes control the development of biota and fluids in the crustal environment. However, these processes are poorly understood under conditions of high pressure, temperature and stress in complex fractured rock. The opportunity for the multidisciplinary investigation of the important parameters controlling these processes is an important benefit of an underground science laboratory. A better understanding of the feedbacks between key processes will aid in development of innovative techniques for resource recovery, waste disposal, site restoration and remediation, and underground construction.

Important unknowns exist in our understanding of coupled processes. Our understanding of the feedbacks may be enhanced in an underground science laboratory through both the observation of coupled processes that operate at the site, and in the development of active experiments that test the modes of coupling.

In the evaluation of existing processes, distributed isotopic, geochemical, and biological markers may be used to indicate the large-scale upflow or downflow of fluids and nutrients, differentiate between distributed and localized transport pathways, determine the limits of deep circulation and constrain recharge rates. Similar surveys will quantify the switch between the stresses and other agents that enhance the development of fracture porosity, and those that result in the loss of porosity by mineral precipitation and dissolution. Likewise, the excavation of new caverns, or the review of existing openings in a refurbished facility, will naturally provide information on the effect of mining on coupled processes of heat, fluid, chemical, and biological transport.

Active coupled-process experiments may be used to stimulate and observe process interactions of relevance in understanding the response of the engineered or natural environment. All physical experiments may be preceded by predictions using numerical models that couple THMCB processes in fractured rock at various spatial scales. Their concurrence with the outcomes of the *in situ* experiments will provide insight into our understanding of process-feedbacks of varying complexity, and the scale-dependence of behavior at scales not possible in the laboratory. These experiments may examine, for example, microbial growth and colonization in newly developed fractures, inclusive of bio-stimulation for aquifer remediation, and the converse effects of bio-clogging and bio-mineralization.

An underground science laboratory has the potential to directly address the THMCB experiments at a variety of scales, including hydrothermal convection in anisotropic fractured media, the accommodation and observation of complex thermal-fracturing, microbial, and chemical effects, the attendant sealing and dissolution of fractures, and controlled development of hydro-fracturing techniques. Manifestations of these behaviors impact the transport of metals in ecosystems, the formation of ores, and the in-situ recovery of minerals, as complementary systems of interest to very different scientific communities.

Whereas numerical modeling of hydrothermal convection in fractured rock has been applied to the study of many natural systems (e.g., convection at sea-floor spreading centers, in geothermal systems, and in the formation of ore deposits around plutons) and man-made systems (injection in geothermal reservoirs and effects of heating by nuclear waste) no large-scale hydrothermal tests have ever been attempted in liquid-saturated ore-bearing rocks under elevated stress and temperature conditions. True breakthroughs in numerical modeling of such complex systems, and therefore of our predictive ability, can only take place through exercising the models on large-scale well-controlled in situ experiments where thermal, mechanical, hydrological, chemical, and biological processes can be examined over long periods of time.

The acceptable completion of the experimental work will require the development and application of new technologies, including inexpensive and miniaturized sensors capable of widespread deployment and distribution, and capable of reporting reliably at high sampling rates and for long durations. These signals will provide a glut of data, which if used appropriately, may provide important contributions to our understanding of coupled THMCB processes. These will be applicable for bioremediation, exploration and geologic engineering, and for other applications.

An underground science laboratory offers a unique opportunity for the three-dimensional access to large volumes of rock at depth, for the investigation of important THMCB interactions at a variety of scales of engineering and scientific significance.

2.2.2 Rock Deformation and State of Stress – Influences on Rock Engineering

Unlike most branches of engineering, where design loads are known and, in many cases, applied only after the structure is assembled, structures in rock are preloaded, by gravitational and tectonic forces whose magnitude in the vicinity of the structure are usually not well defined.

Techniques are available to determine the state of stress *in situ* and to measure deformations induced by the redistribution of stress, but these are costly procedures and often limited in scope. It is not uncommon to see stresses determined from one or two measurements, essentially at a point in the rock mass, extrapolated far beyond their region of validity. In some cases, for example, isolated point measurements are used to infer tectonic stress conditions on the scale of intraplate regions. Considerable research effort is needed to allow more realistic assessment of the state of deformation and stress in rock over the region of interest, whether in the vicinity of engineering excavations or representative of larger geological features such as that influenced by joints and faults. Is it true, for example, that the state of stress in rock is everywhere in a state of limiting equilibrium, dictated by the conditions for slip on critically oriented faults or other discontinuities in the region?

A better understanding of stress distribution within rock masses, the controls on it, and the associated deformational characteristics of the rock, would greatly enhance rock mechanics, prediction of the potential for unstable changes in deformation, and appreciation of the influence of geological heterogeneity, in general. Studies of such effects on the scale of engineering excavations could assist in verifying the predictions of analytical and numerical models allowing more confident application of the models to still larger scale problems. Implicit in this discussion is the need to develop improved experimental procedures for the in-situ observations.

Potential Impacts on Construction in Rock: A variety of rock construction issues are affected by the rock stress and deformation, together with the influence of other environmental factors of temperature and aggressive chemical environments. Stress state, and rock strength affect the effectiveness of mechanical rock breakage, for example by tunnel boring machines (TBM), and various environmental factors affect the long-term support provided by rock bolts, shotcrete, and tunnel liners.

Design improvements in rockcutters have historically followed from tunnel boring machine manufacturers and have proceeded in an unplanned evolutionary manner from button to cutters, to multi-disc cutters, to large (0.5 m diameter) single disc cutters. In this half-century-long process TBM advance rates have gone from a meter per day to (sometimes) a hundred meters per day. It appears, however, that development has hit a plateau due to lack of directed planning, lack of incentive, and lack of funds. A reasonable objective is to triple or quadruple advance rates by the use of innovative materials. Such materials could be derived from military armor, the use of higher capacity but smaller diameter cutters, and the development of smart cutterheads capable of sensing variations in the hardness of the rock face. Through sensed vibrations, these cutterheads would automatically adjust the thrust to individual cutters – concentrating the thrust where it is most productive. From this program, we could develop TBMs capable of advancing 100 to 150 meters per day in hard rock compared to the current 25 to 35 meters per day.[8]

The long-term behavior of rock mass support remains poorly understood, including the individual and combined use of rock bolts, a durable lining, and shotcrete. Rockbolts and shotcrete are commonly used as initial support for underground excavations in rock, but their behavior in the long term (100 yrs ±) is undefined. Therefore, their positive influence in providing ancillary support to the final reinforced concrete lining is commonly neglected in design. It is important to understand mechanisms contributing to loss of support over time. For example, due to the corrosion of rock bolts and steel fibers in reinforced concrete, the loss of keying in the blast-damaged zone, and the potential buildup of fluid overpressures as drainage conduits degrade over time. The development of an underground facility offers the potential to excavate new tunnels and caverns with TBMs, roadheaders, and by drill-and-blast, to provide initial and final support that includes bolts, anchors, cables, mesh and shotcrete in a range of configurations. An underground laboratory would allow the examination of very long-term behavior by measuring the build-up of loads with time. By testing and documenting these tests it could be shown, for example, that a given rock bolt system can safely be assumed to have a long-term load carrying capability to provide the support necessary for long-term stability.

2.2.3 The Influence of Fractures on Hydraulic and Mechanical Behavior

Modes of fracture formation control the development of connected pathways and disjointed rock blocks in jointed rock masses that impart the unique scale-dependent deformation and transport response. The detection of fractures, and the characterization of their properties, are crucial components in characterizing mechanical and hydraulic response to engineered structures.

Formation: Models of fracture patterns, connectivity, and other network characteristics at depth are conditioned on an understanding of fracturing processes. Fractures are mechanical breaks or discontinuities that form by brittle failure within the rock mass and act both as structural defects and as pathways for the transport of fluids, gases and particles. Nucleation and growth of fractures in rock depend on the local stress field, the shapes and sizes of pre-existing flaws and fractures, and material and environmental properties such as fracture toughness, strength and stress level. Stress changes that could lead to fracturing of rock can arise, for example, from changes in overburden pressure due to burial or erosion of overlying material, from fluid pressure within the rock mass, from tectonic forces arising from plate movement, from extension or flexure or other deformation of the Earth's crust, from thermal stresses, from geological processes such as volcanism, or from drilling, hydrofracturing, excavation for mining or the development of civil infrastructure, or other human activity.

Fractures can therefore form by any of several mechanisms that alter either the state of stress or the physical properties of the rock material. Particular modes of fracture formation lead to characteristic geometries; for example cooling of basaltic lava often leads to reticulated fracture patterns separating hexagonal prisms of basalt. On a more fundamental level, any of three fundamental modes of fracture mechanics can theoretically lead to fracturing of rock: mode I (opening), mode II (sliding) and mode III (tearing). Mode I fractures (i.e., fractures that formed by opening rather than sliding or tearing) are known as joints.

Detection: Fractures can often be observed on rock outcrops, tunnel walls and in excavations. For engineering applications involving fractures in near-surface environments, such exposures are a valuable source of information. However, great care must be taken when using surface exposures as the basis for inferring fracture characteristics at depth; fractures exposed at the ground surface may have been altered by weathering processes, stress changes and other near-surface effects. Access to fractures in the subsurface can be gained *via* oil and gas

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[8] Note that this is known to be possible because we have already advanced soft rock TBMs at more than 130 meters per day on the SSC.

wells, water wells, or geotechnical drilling. Rock core from such borings can be an extremely good source of fracture information; however, this again must be interpreted with care as core can be altered by drilling operations and by stress changes upon retrieval.

In recent years, optical borehole imaging tools such as the Digital Borehole Scanner (DBS) have been developed that provide high resolution optical images of the borehole wall. The resolution of the DBS is such that the observation of fracture wall alteration, mineral filling and fracture surface roughness is feasible. Images of borehole walls that display fractures are also routinely obtained using acoustic and electrical techniques.

Fracture detection in the future is likely to be increasingly dominated by indirect methods or remote sensing. All such methods depend on the characteristic shape of fractures, i.e., width and length much greater than thickness or aperture. A wide range of geophysical remote sensing techniques exists that are suited to fracture detection in an opaque rock mass over a range of scales. These include elastic methods (e.g., seismic reflection, vertical seismic profiling (VSP), cross-hole reflection and acoustic logs), electrical and electromagnetic methods (e.g., sounding, profiling and tomography), radar methods (e.g., ground-penetrating radar, borehole radar, radar tomography), conventional well logs (e.g., neutron logs, gamma ray logs, temperature logs) and flowmeters (Table 4.1, NRC Committee on Fracture Characterization and Fluid Flow, 1996). Several remote sensing techniques further exploit the tendency of rock fractures to occur in sets with preferred orientation. Fracture sets impart an anisotropy to the rock mass, which may be detectable by geophysical remote sensing. In this case fracture characteristics must be inferred from rock mass properties, which are themselves measured indirectly using geophysical techniques.

Characterization: In addition to detecting fractures, geophysical and hydraulic methods may be used to characterize the deformational and transport behavior of fractured rocks. These properties are particularly difficult to determine because of the important influence of scale effects – the representative elemental volume must be suitably large that the test is representative of behavior at the prototypical scale of the intended structure. In situ mechanical, and in particular seismic methods that also sample the deformational response albeit at a much higher frequency, show great promise in characterizing mechanical behavior. Importantly, seismic methods are able to sample large volumes of rock, at a resolution controlled by sensor coverage, and directly deliver mechanical characteristics of relevance in engineering and process-based investigations. The challenge remains in interpreting the recorded signal in terms of parameters of particular interest in engineering design. Similarly, alternate geophysical signals sample other parameters of engineering interest - electrical resistivity and electromagnetic (radar) measurements are sensitive to distributions of water content, and related fluid transport pathways. Transport properties may be indirectly inferred from geophysical signals, and may also be directly measured by fluid and tracer injection tests conducted at a variety of scales and for a variety of durations. Complementary results from natural tracers, and from forced-flow tests involving non-reactive and reactive tracers, thermal tracers, colloids and particulates yield important information about the current transport characteristics of the rock mass. Evaluating these parameters remains a difficult problem - predicting how these properties may change with modification of the stress regime remains an elusive goal.

2.2.4 Fluid Flow and Transport in the Deep Subsurface

Our ability to meet our increasing energy needs, develop and protect supplies of fresh water, provide raw materials to industry and reduce pollution in our environment require new technology and better understanding of fundamental scientific issues regarding flow and transport in the deep subsurface. In this environment, fluids move through pores and fractures in rock. Fractures often dominate flow and transport processes. Their ability to transmit fluids and particles is strongly stress-dependent, and to a lesser extent, temperature dependent. Petroleum reservoirs often lie at depths ranging from a kilometer to nearly six kilometers. Schemes to develop pumped hydro-electric storage with a combination of surface and deep underground reservoirs may help meet existing and future cyclical energy demands in regions where no additional hydroelectric projects are feasible. Deep injection of wastes is likely to play an increasing role in the future as well.

Our knowledge of flow systems at depth has been limited by the lack of large-scale access to fractured rock at the stress and temperature conditions that are typical of the deeper subsurface where we need to make advances in energy, water supply, mineral extraction and environmental enhancement. Currently, the only direct access to the deep subsurface is through wells. Wells and data inferred from wells or deep boreholes sample rock properties at a scale much smaller than most fractures and fracture networks. The inference of large-scale flow and transport properties of fracture networks, from well tests or other wellbore-scale logs or core, is challenged by fundamental uncertainties in how large-scale flow processes relate to flow and transport in individual fractures, and how knowledge of small-scale flow and transport can be used to reliably infer flow and transport at the scale of tens or hundreds of feet.

While many of these questions could be resolved in shallow underground facilities, such as those that exist in support of nuclear waste isolation, these facilities are on the order of 300 m in depth, where stresses are lower. The fractures may not be at the critical stress state, and so the flow and transport behavior may differ substantially from that at greater depths.

Likewise, there are many promising geophysical techniques that may indicate relative changes in fracture intensity and fracture network permeability. The resolution of these techniques is depth-dependent and acquisition of data for imaging the subsurface has a cost that escalates per acre as the target becomes shallower. Reduction in cost favors a deeper test site, as does the similarity in resolution between an experiment carried out in the deep subsurface and applications involving energy production. Only a deep underground facility where there is access to a large volume of rock will make it possible to understand how to interpret these new types of geophysical data, and the develop this technology to enhance its usefulness.

Therefore, the objectives of many fundamental scientific questions, as well as the development of new technology, critical to societal needs in many areas, requires access to a deep underground facility that contains natural fractures and allows direct testing and observation of volumes of rock on the scale of tens to hundreds of meters. Among the key processes that need to be investigated in such a facility are ways to quantify the connectivity, flow and transport properties of fracture networks at these scales; multiphase flow in fracture systems; and the transport of colloids or bacteria in these networks.

Approaches: A deep underground science laboratory offers an excellent opportunity to study these key scientific questions and to develop important new technology. Some of the attractive aspects of such a facility are the access to large volumes of rock at many different depths and in many different rock types, stress conditions and geological settings, and the high level of geological knowledge already available. In general, it will be possible to carry out experiments in many different stress settings, at scales ranging from borehole to hundreds of meters, and in rock with widely varying mechanical and hydrological properties. A hallmark to any experiment that could be carried out in this facility is that the wide range of stress, geology, and scales available will make it possible to study in detail how processes are influenced or not influenced by these factors. More importantly experiments could show how to predict the processes or fundamental behavior from one setting, scale or stress state to a different one that is of interest but for which data does not exist or cannot be obtained.

In general, there will be approaches in several categories:

- Development and validation of geophysical techniques for fracture network characterization;
- Development of a fundamental understanding of what well tests reveal about the large-scale flow and transport properties of fractured rock;

- Increased understanding of the fundamental processes that take place in multiphase flow in fracture systems, such as gas-oil-water, or water-air, with and without matrix involvement;
- Development of tools to model multiphase flow and reactive transport and the validation of these tools;
- Determination of the role of stress on flow and transport in fracture networks, as opposed to individual fractures;
- Examination of how colloids, such as gels, grouts and other materials move in fracture systems as a function of the fractures themselves, the stresses in the rock, and the properties of the colloids themselves; and
- Examination of how subsurface bacteria "circulate" through fracture systems in the deep subsurface.

Experiments, such as the studies involving geophysics or well testing, would be designed to determine what, in fact, these data do indicate about fracture networks and their flow and transport properties. Because the proposed facility will provide access to large volumes of rock in the subsurface, it will be possible to determine a great deal about the fracture networks through direct observation or boreholes at the scale and spatial resolution of the geophysical or well test data, and then to directly compare it to these observations.

Other experiments will be carried out in the subsurface. For example, it will be possible to introduce many multiphase systems into the rock mass, and then to measure how the phases behave under differing stress and temperature conditions, and also in different geological settings. Likewise, colloids could be introduced into the fracture systems, and their movement and composition tracked through large volumes of rock under varying conditions.

One of the exciting opportunities that a deep test facility offers is the opportunity to develop tools to alter the flow and transport properties of fracture networks. This could offer many benefits, from selectively enhancing or reducing the fracture permeability in oil reservoirs or geothermal fields; slowing the movement of contaminants or harmful biota released into the water supply as a biological weapon; or enhancing access to pockets of water in an aquifer without having to drill additional wells. In these experiments, researchers will be able to understand how stress impacts fracture network flow and transport, and then to develop tools or processes to alter the stress state in a way that alters the network properties in the manner desired.

Expected Outcomes: Outcomes will be of two types: resolution of fundamental scientific questions that currently limit how we interact with deep underground flow systems; and the development of new tools to quantify these flow systems and to alter them in desirable ways. Some specific outcomes should include:

- Utilization of existing geophysical tools to greatly improve the quantification of fracture intensity and permeability at depth;
- Enhancement of these tools to provide higher resolution and additional types of information;
- A greatly improved ability to quantify large-scale fracture network permeability and transport from existing well tests;
- Enhancement of well testing techniques to improve resolution and quantification;
- Fundamental physical understanding of how important multiphase systems work in fracture systems at depth;
- Development of modeling tools to predict these multiphase processes in fracture systems at depth;
- Improved knowledge about how colloids move through fracture systems;
- Improved ability to engineer colloids so that they move through fracture systems in ways that improve energy recovery, reduce pollution or enhance environmental remediation;
- Development of methods to control the movement of biota in fracture systems that could reduce the threat or spread of natural or introduced pathogens into groundwater supplies;
- Improved understanding of the way in which deep bacterial life thrives in the subsurface;

- Design of solution mining processes that significantly reduce costs, increase recovery efficiency, or lessen environmental impact; and
- Provide a teaching laboratory to train a new generation of geoscientists, hydrologists and engineers.

3. Approach

The desire to develop an underground science laboratory for engineering geo-hydrology and geo-mechanics is driven by three key observations:

1. **The mechanical and hydraulic response of fractured rocks, including aquifers and reservoirs, are strongly scale dependent.** The thoughtful use of in situ tests to exercise processes at a variety of length- and time-scales that honor the scale of the intended prototype has proven useful, for example in the development of designs of deep geologic repositories for nuclear waste. Investigations at the potential civilian waste repository site at Yucca Mountain have involved tests at small (the Large-Block-Test), intermediate (Alcove and Single-Heater-Tests), and large (Drift-Scale-Tests) scales, with the largest spanning almost a decade in duration.
2. **Interactions between physical, chemical, and biological processes are inadequately understood.** These interactions are strongly temperature and stress dependent, in addition to the important influences of length and time scales. Engineering designs, absent a critical process interaction, are likely more in error than those merely mis-evaluating physical parameters. The range of stresses and temperatures at the proposed site span a range of engineering significance, for resource recovery, waste isolation and site restoration projects, that enable relevant processes to be exercised, observed, and characterized.
3. **Advances in science and engineering are often driven by surprises and failures.** Progress in geo-hydrology also benefits from serendipity, and large-scale field tests are an important mechanism to witness such surprises under controlled and reproducible conditions. Notable advances in our understanding of relevant process interactions include: the surprise development of wet holes in the unsaturated rocks of the Yucca Mountain Single-Heater-Tests; the geyser-like expulsions resulting from the breakdown of cooling during the Yucca Mountain Large-Block-Test; surprising patterns of permeability change around alcove tests at Yucca Mountain; the inability to develop a single hydraulic connection at the Rosemanowes HDR reservoir; and the anomalous subsidence and evolution of the reservoir at the Ekofisk field in the North Sea.

These observations underscore the key potential contributions of an underground science laboratory. The extensive network of development drifts provides unusual access at spatial scales as large as a few kilometers, and the anticipated lifetime of the facility will allow test durations in excess of a decade. The extensive depth of the facility samples a broad range of in situ stresses and temperatures that in turn mediate important and poorly understood physical, chemical and biological interactions.

Potential test types include those that explore mass and energy transport phenomena, those that attempt to understand environmental interactions of stress and temperature that spur physical, chemical, and biological process interactions and their effect on material parameters, and those that explore tracer and geophysical techniques to define these process interactions and parameterizations at a variety of scales.

Potential tests are divided chronologically into three types. The earliest are those run-of-mine experiments that utilize existing mine drift structures, historical records of mine environmental conditions including temperatures and water inflow rates, and observations of rock structure. Next are tests that accompany the construction and monitoring of the caverns that will be purpose-built for the neutrino detectors. The final experiments would be of extended-duration, and conducted in existing or purposely-built drifts that are commissioned exclusively for Earth science investigations. Key uncertainties addressed by these experiments are included in Table 2.

3.1 Run-of-Mine Experiments (HCB)

Run–of-mine experiments will assess the natural scaling of fracture connectivity and transport parameters over the range of rock stresses and rock temperatures accessed by the mine.

Historical records of flow rates, rock and water temperatures, relative humidities, water chemistry, and in situ stresses will be used to develop a quantitative geo-hydrological model of the mine block. Drifts will be mapped for rock structure, with these data augmented by core recovered from boreholes that access the rock mass between drifts. Hydraulic, tracer, and geophysical tests will be used to characterize rock structure, fracture connectivity, and transport properties, and their variability with scale, with depth, and with distance across the excavation-disturbed zone.

Portions of the mine are backfilled with sulfide rich tailings, and provide a challenge to providing environmental containment. Monitored isolation of the tailings under aerobic and anaerobic conditions enables the effectiveness of a variety of passive remediation schemes to be evaluated.

3.2 Experiments Concurrent with Excavation of the Detector Caverns (THM)

Excavation for the detector caverns will produce local rock mass deformations that provide an important opportunity to observe the coupling between transport parameters and mechanical and thermal stresses.

The planned Neutrino facility is to be of the order of 60 m clear span and several hundreds of meters long. Underground excavations of this span have been constructed (e.g., the ice hockey stadium at Gjovik, Norway, constructed for the Lillehammer Olympic Games in 1994) but in high quality rock such as granite and at shallow depths (*c.* 50 m~100 m). Construction of a cavity of 60 m clear span at a depth of the order of 2500 m in jointed rock is unprecedented. While feasible, construction is likely to be costly and to require detailed preliminary field investigations. The strength of a rock mass in jointed rock decreases with the size of the cavity and with time. For any proposed facility, rock mechanics studies conducted during past mining operations would be useful, but it is unlikely that the question of size effect has been investigated on the scale considered for the neutrino cavity. The availability of mining excavations to the depth envisaged for the cavity would be very valuable in gathering the data required for the cavity design. Investigations needed for the cavity design, involving both classical and numerical analysis together with in situ experiments should provide valuable fundamental insights to advance the state of the art of rock mechanics.

Practical evaluations of the long-term behavior of underground caverns may also be determined from the development of cavities by varied methods of blast excavation, by the application of varied methods and levels of excavation support, and the careful monitoring of changes in support loads over time – as an indicator of the long-term durability of the support system. This program will include study of existing openings and (primarily) construction of new ones to improve our understanding of drill and blast openings in hard rock. Various controlled blasting methods/techniques will be used to excavate the openings. Instrumentation will be used along with exploratory cores to determine the degree, depth and properties of the blast damage zone. This will define variations in stress and modulus back from the opening, through the blast damage zone and into the "native rock". If possible, similar measurements will be made in existing openings to add to the available data. (This assumes the conditions at these existing openings can be determined and shown to be useable.)

For example, as part of other construction, various types of shotcrete linings can be installed and monitored. This would include "standard" reinforcement by rebar welded wire fabric, lattice girder and rebar mat, and for comparison, reinforcement by plastic and steel fibers. By instrumentation and observation the behavior of these systems can be compared in a known environment over decades. Of particular interest is the behavior over decades of shotcrete reinforced with fibers to determine whether support will deteriorate with the rusting of fibers or from the loss of bond. If so, is the magnitude of strength loss so large that the contribution it provides should be neglected?

The region surrounding the proposed caverns will be instrumented prior to enlargement. Instrumentation will be located in coreholes adjacent to the excavated block. Recovered core will provide information on structure, groundwater chronology and the physical, chemical, and biological properties of the rock and fluids. The coreholes will be variously instrumented to allow comprehensive monitoring of excavation-induced displacements, microseismic activity, temperatures, and fluid pressures, and to recover aqueous and particulate samples. Hydraulic, tracer, and geophysical characterizations of transport parameters, concurrent with cavern-enlargement will be used to define the form of the coupling between mechanical and thermal effects, and hydraulic transport parameters. After excavation, the instrumentation arrays will be used to monitor the long-term passive response in the stable zone surrounding the detectors.

3.3 Purpose-Built Experiments (THMCB)

Designed specifically to investigate processes of transport, fluid-environment interaction, and methods of characterizing material properties and modeling process interactions, these experiments fall into two categories. The first are those that seek pristine conditions, remote from the drift, to examine transport and fluid-environment interaction processes. The second are those that examine the influence of an engineered structure on the hydraulic response.

3.3.1 Large Block Tests

Large block tests involve the hydraulic and mechanical (and THMCB) characterization of a pristine block using mechanical, hydraulic, tracer, and geophysical methods. Sequential studies may involve the validation of hydraulic, tracer, or geophysical characterization methods themselves, and may involve short- or long-term environmental changes to the block itself (such as heater-tests, hydraulic fracturing, or forced fluid injection and heat recovery tests). Tests may terminate alternatively with post-test exhumation to confirm recovered structure, or may continue either as a mine-by and drift structure test, to define the evolving hydraulic characteristics of the excavation-disturbed zone, or as an extended experiment to observe the very-long-term evolution of transport parameters. Numerical models that predict the transport of metals and other species along with the localized crystallization of various mineral phases can therefore be directly validated by investigation of the exhumed fracture surfaces, and by collection of water and gas samples in space and time for analysis by a host of modern geochemical and isotopic methods.

The tests may be conducted at a variety of scales, involve characterization for single and multiphase flow, aqueous, particulate, thermal, and reactive transport, and be correlated with seismic, electrical, and electromagnetic methods of determining structure and correlating transport parameters. A unique aspect to such tests is that they aim to quantify the coupled effects between various processes; for example, the effect of changing mineral properties on fracture surfaces and the potential changes in the mechanical properties of the fractures, and vice-versa.

3.3.2 Mine-By and Drift-Structure Tests

Drift-structure tests examine the response of the rock mass to engineered structures, specifically the role of the drift in focusing or diffusing flow, as transport parameters are modified throughout the excavation-disturbed zone. Excavation of the drift (mine-by) within a pre-instrumented block allows changes in transport parameters to be monitored concurrent with mechanical deformations, giving key information regarding the evolution of the excavation-disturbed zone, and constraint on hydro-mechanical process coupling.

The broad range of in situ stresses and temperatures present at the underground laboratory site, together with the extended period of access, make it a unique location for extended-duration tests examining complex THMCB processes.

3.3.3 Educational Opportunities

Long-term access to the large-block and drift-structure tests will provide an important resource for the education of graduate students in geo-hydrology, combining important components of hydraulic, tracer and geophysical characterization methods, with other aspects of geochemistry, geobiology, and geomechanics. Specific opportunities include:

- The opportunity for the development of underground access to visitors to examine the range of activities conducted at the site. This would include access by elementary and secondary students, members of the public, and public officials, and would be limited only by the potential geographic remoteness of the site.
- The provision of instructional opportunities for undergraduate and graduate students to view and to use specialized hydrogeologic and geomechanical field characterization equipment in a dedicated underground laboratory. These activities could be run as a form of "field school" with students gathered from universities around the country to receive intensive training in field techniques – from the use of borehole jacks and methods of in situ stress measurement, to running packer tests, collecting and analyzing samples with analytic chemistry tools, and using a variety of borehole geophysics tests to infer large scale structure in the subsurface.

  Having an extensive array of equipment at a centralized location, with broad access by collaborating universities, offers a significant economy-of-scale. The educational activities at the seven FHWA/NSF-sponsored National Geotechnical Experimentation Sites could serve as a model.
- If instrumented as a research watershed, the potential site has a natural interface with the proposed Consortium of Universities for the Advancement of Hydrologic Science[9] (CUAHSI) initiative that is considering the establishment of a number of well-instrumented watersheds as part of its mandate. Activities at these instrumented watersheds would be broadly available to the scientific community, and indeed would be proposed and run by that same community. This potential function of CUAHSI has many parallels with the goals of a national underground science laboratory. Similarly, the site could provide one node in the proposed NSF-Earthscope-US Array[10] project, a proposal to provide broadband seismic coverage over the entire continental United States, to delineate the underlying deep crustal structure and processes.

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[9] See for example www.cuahsi.org

[10] See for example www.earthscope.org

4. Anticipated Benefits and Applications

The development of an underground science laboratory may present a variety of benefits that directly address societal needs. As described in the foregoing, improved techniques and technologies to recover minerals and energy, to provide safe disposal and containment of wastes, to afford the effective restoration of contaminated sites, and to contribute to safe use of the subsurface for civil infrastructure, are likely benefits from the underground science laboratory.

The unique attributes of such a facility would be long-term access to a three-dimensional block of rock at an unprecedented scale, enabling the development and testing of geophysical prospecting tools with the unusual prospect for the close verification of the results. The long-term occupation of the site will enable extended-duration testing and observation of a variety of rock construction prototypes, that offer prospects for improved safety, more efficient construction systems, and extended longevity. Monitoring of the facility, and the attendant spectrum of in situ tests, offers the potential for an improved understanding of the complex interaction and feedbacks of thermal, hydraulic, mechanical, chemical and biological processes that both shape the Earth, and affect the performance of a variety of engineered structures.

An improved understanding of the transmission of stress and the motion of fluids in fractured rock, together with the interaction of complex THMCB feedbacks, has widespread application to problems of societal relevance. These include improvements in the efficiency of recovery of energy and mineral resources, the restoration of contaminated sites, and in the development of underground structures for civil infrastructure and security. Advances in these sectors center on a need to improve methods for characterization in the subsurface at scales ranging from the meter- to the kilometer-scale, and to better understand the innate scale dependence of rock properties and behavior. The development of an underground science laboratory provides a unique opportunity for such an advance.

			Key Technical/Scientific Uncertainties												
			Process Uncertainties							Parameter Uncertainties					
			Transport			Interactions				Characterization			Information Technology		
			Fracture Connectivity	Multiphase Flow	Particulate Transport	Fracture Development	Coupled Processes - THM	- CB	- THMCB	Hydraulic Methods	Tracer Methods	Geophysical Methods	Sensing	Data Fusion	Modeling
Engineering Applications	Resource Recovery	Petroleum & Natural Gas	X	X		X	X	X		Y	Y	Y	Y	Y	Y
		In Situ Mining	X			X	X	X	X	Y	Y	Y	Y	Y	Y
		Geothermal Energy	X	X		X	X	X		Y	Y	Y	Y	Y	Y
		Mining Hydrology	X			X	X			Y		Y	Y	Y	Y
	Waste Containment and Disposal	Deep Injection	X		X	X	X			Y	Y	Y	Y	Y	Y
		Nuclear Waste Disposal	X	X	X		X	X	X	Y	Y	Y	Y	Y	Y
		CO_2 Sequestration	X	X			X	X	X	Y	Y	Y	Y	Y	Y
		Underground Storage	X	X		X	X			Y	Y	Y	Y	Y	Y
	Site Restoration	Acid-Rock Drainage						X	X		Y		Y	Y	Y
		Aquifer Restoration	X	X	X			X	X	Y	Y	Y	Y	Y	Y

Table 1 **Important scientific issues, relevant to engineering applications involving aspects of engineering-geo-hydrology. "X" notes an important process in understanding the engineering response. "Y" represents a key tool in defining the engineered response of the system.**

			Key Technical/Scientific Uncertainties												
			Process Uncertainties							Parameter Uncertainties					
			Transport			Interactions				Characterization			Information Technology		
			Fracture Connectivity	Multiphase Flow	Particulate Transport	Fracture Development	Coupled Processes - THM	- CB	- THMCB	Hydraulic Methods	Tracer Methods	Geophysical Methods	Sensing	Data Fusion	Modeling
Potential Underground Science Laboratory Experiments	Sensing & Data Fusion	Existing Data Fusion	X				X			X					
		Sensor Deployment	X							X					
	Process Exercising Tests	Run-of-Mine Tests	X				X			X					
		Detector Excavation Tests	X	X	X	X	X								
		Large Block Tests	X	X	X	X	X	X	X				X	X	X
		Mine–by and Drift Structure Tests	X	X	X	X	X	X	X				X	X	X
	Property Characterizing Tests	Run-of-Mine Tests	X				X			X					
		Detector Excavation Tests	X	X	X	X	X								
		Large Block Tests	X	X	X	X	X	X	X	X	X	X	X	X	X
		Mine–by and Drift Structure Tests	X	X	X	X	X	X	X	X	X	X	X	X	X

Table 2 **A description of how key technical uncertainties would be addressed by potential science experiments conducted within an underground laboratory. “X” denotes that the test would address the uncertainty.**