An NSF-Sponsored Workshop
on
Deep Underground Science and Engineering Laboratories (DUSELs)

In Conjunction with
10th Congress of the International Society for Rock Mechanics
Johannesburg, South Africa
14.00-17.00, Thursday, September 11, 2003.

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Final Report

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Executive Summary

This report presents the findings of a Workshop on Deep Underground Science and Engineering Laboratories (DUSELs), held at the 10th Congress of the International Society for Rock Mechanics in Johannesburg, South Africa. The workshop was organized by the American Rock Mechanics Association and sponsored by the U.S. National Science Foundation. Thirty-nine geo-engineering practitioners participated in the workshop, representing 14 countries.

The workshop was convened to refine the scope of activities proposed at EarthLab[1], an underground research laboratory that may be developed in conjunction with a deep neutrino detector. The development of EarthLab will involve the construction of unusually large caverns at unprecedented depths, and presents both unique challenges and particular opportunities for research in Earth science and engineering at depth. Particular attributes for such a laboratory are long-term (~100 yr) access to an unusually large (~20 km^3) and well-characterized block of rock. This access, over the 2500m depth of the site, includes varied *in situ* stress, fluid pressure, temperature, and chemical fields, as well as the ability to measure and modify these environmental conditions.

The workshop summarized the current status of activities in underground research laboratories worldwide and examined critical complementary questions that may be addressed at a future DUSEL. The EarthLab plan calls for the development of a series of science and engineering laboratories at depth. The current science plan was developed to provide an adequate framework for the proposed science and engineering studies. An extensive body of knowledge has already resulted from the worldwide network of underground research laboratories (URLs) that have been developed over the past 25 years. The cataloguing of capabilities at these laboratories, and of principal scientific lessons already learnt, would provide a rational basis for the further development of the EarthLab plan. In addition, the development of an infrastructure for communication between active laboratories to facilitate the broad interaction of researchers is worthwhile. This would both provide focus to activities worldwide and also help prevent duplication of effort. These goals may be met by the convening of a task force involving representatives from the various research laboratories, worldwide.

In addition to the science plan for geo-mechanics and geo-hydrology, there are considerable benefits in incorporating a broad range of research activities of interest to the extractive and construction industries. These may include elements of occupational health and safety, materials handling, mechanical excavation, and environmental control, among others, and may be best defined in consultation with stakeholders from those industries. This goal is best met by involving the industrial community in consultation over the proposed EarthLab project. This community has been largely absent in organizational activities so far, and may provide an important focus for government-industry-university partnerships in support of this endeavor. This proposed involvement could be via individuals or professional or trade organizations, representing the constituencies of mining, petroleum, and construction engineering.

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[1] McPherson, B.J., Elsworth, D., Fairhurst, C., Kessler, S., Onstott, T.C., Roggenthen, W., and Wang, H. EarthLab: A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation, Geosciences Professional Services, Inc., June 2003, 64 pp.

Introduction and Overview

The United States still lacks access to a comprehensive long-term deep underground laboratory to complement the successful activities of the National Geotechnical Experimentation Sites.[2] In the fields of geo-hydrology and geo-mechanics, significant gains have resulted from *in situ* research, largely conducted in underground facilities, in support of the high-level radioactive waste disposal and defense programs. These gains have been realized despite the limited longevity of these facilities and in the absence of broad access across the research community.

To address this perceived need, a group of Earth scientists and engineers is pursuing the opportunity of developing an underground research laboratory. This effort is in conjunction with a proposal to create an underground neutrino observatory. An Earth Science Workshop was held in October 2001 to discuss earth science studies that could be conducted at a proposed underground laboratory and the technical requirements for such studies. These concepts were broadly endorsed by the National Research Council's Committee on Geological and Geotechnical Engineering (COGGE), and the NSF's Geoscience and Geo-Engineering Programs sponsored the refinement of concepts in support of an underground laboratory at a series of workshops in September 2002. This successful collaboration between the science and engineering communities resulted in a research blueprint for such an underground facility[3], and a detailed review[4] of construction, engineering, and science needs for any laboratory.

Following the completion of these reports, this workshop[5] was convened at the 10th Congress of the International Society for Rock Mechanics, in Johannesburg, South Africa, on September 11, 2003. The purpose of this workshop was to refine the scope of activities proposed at a deep underground science and engineering laboratory (DUSEL). The workshop featured plenary presentations[6] summarizing past and current activities at existing underground research laboratories, worldwide, and was attended by thirty-nine practitioner experts[7] in geo-hydrology and geo-mechanics, representing 14 countries. This report summarizes the findings of this workshop.

Summary Presentations

Following introductions and background information, a total of four formal presentations were made at the meeting. The first was an introduction of the current status of the EarthLab Project, followed by perspectives of research in geo-hydrology and geo-mechanics being conducted worldwide. These presentations are summarized here.

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[2] The National Geotechnical Experimentation Sites program comprises seven characterized research sites that are available for outside research initiatives. It was established by the Federal Highway Administration and the National Science Foundation and is currently managed by the National Council for Geo-Engineering and Construction. See: www.geocouncil.org

[3] McPherson, B.J., Elsworth, D., Fairhurst, C., Kessler, S., Onstott, T.C., Roggenthen, W., and Wang, H. EarthLab: A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation, Geosciences Professional Services, Inc., June 2003, 64 pp.

[4] ARMA Panel (2003) Engineering Research Opportunities in the Subsurface: Geo-hydrology and Geo-mechanics. Report of an ARMA Workshop on the National Underground Science and Engineering Laboratory (NUSEL), Washington, D.C., September 18, 2002.

[5] Appendix A.

[6] Appendix C.

[7] Appendix B.

1. ***Workshop on Deep Underground Science and Engineering Laboratories - Introduction and Background.*** *By Derek Elsworth.*

   The desire of the physics community to develop a large, deep, and hence very high resolution, neutrino observatory is driving the potential development of an underground research laboratory for Earth science and engineering. Existing neutrino detectors at the Soudan, Minnesota, and Homestake, South Dakota, mines, and at the Waste Isolation Pilot Plant (WIPP) site in New Mexico, have insufficient resolution, and a deeper facility is sought. Three sites recently proposed for potential development are the existing Soudan and Homestake mine sites, and a new facility at San Jacinto, California. A recent peer review of proposals to NSF for these three sites has favored the Homestake mine, and encouraged the (re)submission of a combined and revised proposal based on facilities at Homestake.

   The development of any DUSEL will involve the construction of large caverns at unusual depths (spans ~50m, heights ~60m, and depths ~2500m). This will present both unusual challenges in their construction and particular opportunities for research in Earth science and engineering at depth. Particular attributes for such a laboratory are long-term (~100 yr) access to an unusually large (~20 km^3) and well-characterized block of rock. This access over the ~2500m depth of the site includes varied *in situ* stress, fluid pressure, temperature, and chemical fields, and the ability to measure and modify these environmental conditions.

   There exists a high potential for scientific and engineering innovation at such a facility. New genetic strains with novel capabilities may result from microorganisms recovered from the deep crust. New instruments for the mapping and monitoring of extreme environments may result, accelerating the current trends in the miniaturization of existing sensors and their distributed deployment. The DUSEL may spur improvements in the current efficacy of environmental remediation of aquifers, of waste disposal in, and resource recovery from, reservoirs, and in the development of rock and construction engineering.

   The proposed DUSEL addresses these major challenges via a series of experiments that would be conducted in five deep laboratories. These projects include: a deep flow and palaeoclimate laboratory and observatory; an induced fracture processes laboratory; a deep coupled-processes laboratory; an ultra-deep observatory for biogeochemical research; and a deep seismic observatory.

2. ***The Value of Underground Laboratories.*** *By Charles Fairhurst.*

   The principal attribute of an underground research laboratory is the ability to examine complex rock mass behavior at large scale, and over periods of relevance to engineering structures. Critical issues in rock mechanics include the ability to define rock mass strength at a variety of scales, both beyond post-peak, and at time-scales from tens to hundreds-of-thousands of years. This need remains, despite 40 years of activity in geo-mechanics, and is reinforced by societal needs for the safe interment of radioactive wastes in geologic repositories.

The development of large-span caverns at depth presents its own challenges, and innovative methods will be required to construct the desired structures at both reasonable cost and with a suitable guarantee of safety. Other critical needs in mining, petroleum, and waste disposal engineering include the importance of developing more efficient methods of mechanical excavation, and in remote methods of site characterization, emphasizing whole-body coverage via geophysics. All of these endeavors, with important benefits to the competitiveness of the basic resource and disposal industries, emphasize the critical contribution of underground research laboratories.

3. ***Underground Test Facilities.*** *By Thomas Doe (presented by Derek Elsworth).*

Underground laboratories were first developed a quarter-century ago to provide the scientific basis to support decisions in the deep underground disposal of radioactive wastes. Host rocks have included salt, tuff, and basalt in the United States, and primarily granites and clay rocks elsewhere. These facilities have been both in mines and in dedicated facilities, and have examined a wide-range of basic problems in geo-hydrology and geo-mechanics, including the projected performance of prototype repositories.

Among other locations, laboratories in granite have been commissioned at Pinawa (Canada), Äspö (Sweden), and Grimsel (Switzerland), with a new site being developed at Mizunami (Japan). These laboratories have contributed significantly to our contemporary understanding of flow and mass transport in naturally fractured media, and of the retardation and attenuation of both solutes and particulate contaminants. Implicit in this has been improvements in our understanding of factors that affect transport properties over the long-term, and at length-scales of relevance to the repository. These factors include the roles of thermal and mechanical loads, and the influences of chemical and biological effects on the likely integrity of the repository.

Important observations at the Pinawa URL in Canada were the strong scale-dependence of transport properties in moderately fractured rock, and the surprisingly large horizontal stresses present in the shallow subsurface. These large stresses were manifest as asymmetric over-break in shallow tunnels and in the development of a time-dependent enlargement of the excavation damage zone with time.

Important observations at the Grimsel URL in Switzerland are related to the understanding of gas migration in complex shear-zones and to the low attenuation of colloids when transported in natural fractured systems. Additional experiments examined the role of a hyperalkaline plume, resulting from the deterioration of introduced materials (cements) on the evolution (plugging) of fracture porosity with time.

A broad series of experiments on natural barriers and on the performance of a prototype repository are being conducted in the complex faulted rock at the Äspö URL in Sweden. Current experiments include the detailed examination of the transport of solutes and colloids in complex fractured, chemical, and biological environments including the long-term performance of the repository structure.

Various international laboratories in mudstones examine suites of material behavior that are significantly different to those in granites. Clay rock plays roles in many of the most serious geo-engineering problems both underground at on the surface including geo-hazards from landslides. Many of the fundamental processes of clay rock behavior remain poorly understood. Clay rock laboratories have been developed at Mol in Belgium and Mont Terri in Switzerland. The Meuse/Haute Marne underground laboratory is under construction in eastern France at Bure and shaft sinking preparations for a facility in mudstone are underway at Horonobe in Japan.

The Mont Terri laboratory had played host to experiments in excavation damage development, groundwater transport processes, microbiology, coupled processes (chemical, thermal, and mechanical), and multiphase flow. The following presentation highlights the activities at the Meuse/Haute-Marne URL.

4. ***Overview of the Experimental Programme in the Meuse/Haute-Marne Underground Research Laboratory.*** *By Jack-Pierre Piguet.*

ANDRA, the French radioactive waste disposal agency, is responsible for the Meuse/Haute-Marne URL, which is located in the eastern Paris basin in low-permeability shales. The current sinking of a shaft will evolve into the excavation of drifts and the development of niches for experiments at a depth of ~450m. Following site selection investigations from 1994 to 1995, detailed laboratory-site characterization activities began with surface-based drilling in 1999. Using data from this laboratory and from Mont Terri a report on the suitability of the geologic host for waste disposal will be issued to the French government in 2005. Major scientific questions relate to the potential for containment of interred wastes, the related potential of the shales to retain low permeabilities following excavation and disturbance, and the ability to upscale the mechanical and transport properties of the rock to repository and regional scales.

To date, the program has involved the completion of 2-D and 3-D seismic reflection surveys, confirmation of the structure by the completion of exploration boreholes, and the utilization of these boreholes to determine *in situ* stresses and initial permeabilities. Additional boreholes are underway for establishing the hydrology of the over- and under-lying units as well as checking for the presence of fracturing in the shale itself in 2003-2004. New boreholes in 2003 and 2004 are planned to investigate possible structures inferred from the 3D seismic survey in the Dogger formation immediately below the URL location. This access will enable the evaluation of transport properties at the scale of many tens of meters. These experiments will provide new data to constrain the regional hydrogeologic model, at regional scale, and reduce uncertainties in the potential transport of solutes in the underlying aquifers.

Identification of Research Needs in Geo-Hydrology and Geo-Mechanics for a DUSEL

Informal comments were received from URL directors and practitioners present at the workshop.

1. ***What critical questions in geo-mechanics and geo-hydrology may be addressed by a DUSEL that are not currently addressed?***

   The current plan addresses a broad array of critical contemporary issues in science and engineering, including those identified as focus areas for research in the European Union (EU), such as CO_2 sequestration in deep formations. It is possible that a deep laboratory may provide dual-use research on microgravity in the available shafts.

   The availability of a dedicated underground research laboratory would also enable mining research that is not currently feasible, due to the significant constraints of scheduling in an active mine. A deep laboratory would complement the capabilities of the shallow Lake Lynn facility operated by the National Institute of Occupational Science and Health (NIOSH), and enable deep mining research to be conducted (~3-5km depth). Research in deep mining has been particularly relevant in South Africa where $10 million has been invested over four years to examine problems in mining at depth, and in Canada where a research program has been recently initiated. In both instances, geo-mechanics has represented only a portion (~15%) of the focus, with work on occupational health and safety, ventilation, and mechanization comprising the remainder. These developments are driven by industrial needs as mines go deeper, and they offer the potential for significant government/industry partnerships in the development of EarthLab.

   Recommendation: Integrate activities beyond geo-mechanics and geo-hydrology, and foster industry/government/university partnerships that address the defined issues of industry.

2. ***How do these prospective areas influence the competitiveness of the extractive (mining and petroleum) and construction industries?***

   Research issues of critical importance to industry are best addressed in direct consultation with the stakeholders. Critical issues in the mining and construction industries must address their collective vision to provide revolutionary advances in productivity.

   Recommendation: Develop a workshop or consultation to define the needs of the extractive and construction industries.

3. ***How do these goals fit with other proposed deep URLs?***

   With over 25 years of activities recorded in URLs around the world, there are clear benefits in both cataloguing the current state of practice at these facilities, and in summarizing their contribution to contemporary advances in science and engineering. For those facilities that are currently active, there is considerable merit in encouraging worldwide networking among URL researchers.

Recommendation: Catalog the current state of practice at URLs worldwide and summarize their contribution to scientific and engineering innovation. Identify critical and unmet needs of a DUSEL, including a rational plan for international collaborations and communication.

Summary Recommendations

The current EarthLab proposal to pursue a deep underground science and engineering laboratory provides an adequate framework for the proposed science and engineering studies. An extensive body of knowledge has already resulted from the worldwide network of URLs that have been developed over the past 25 years. The cataloging of capabilities at these laboratories and of principal scientific lessons already learnt would provide a rational basis for the further development of the EarthLab plan. In addition, the development of an infrastructure for communication among active laboratories, to facilitate the broad interaction of researchers is worthwhile. This would both provide focus to activities worldwide and prevent duplication of effort. These goals may be met by the convening of a task force involving representatives from the various research laboratories worldwide.

In addition to the science plan for geo-mechanics and geo-hydrology, there are considerable benefits in incorporating a broad range of research activities of interest to the extractive and construction industries. These may include elements of occupational health and safety, materials handling, mechanical excavation, and environmental control, among others, and may be best defined in consultation with stakeholders from those industries. This goal is best met by involving the industrial community in consultation over the proposed EarthLab project. This community has been largely absent in organizational activities so far and may provide an important focus for government-industry-university partnerships in support of this endeavor. This proposed involvement could be via individuals or professional or trade organizations representing the constituencies of mining, petroleum, and construction engineering.

Appendix A

Workshop on Deep Underground Science and Engineering Laboratories
Agenda
September 11, 2003.

1. Introduction
    a. Welcome and Introductions (10 min)
       Prof. J N Van Der Merwe, President ISRM
       Francois Heuze, President, ARMA

    b. US DUSEL Concept (20 min)
       Rick Fragaszy, National Science Foundation
       Derek Elsworth, Workshop Chairman

2. Review of Related International Laboratories and Needs (1hr)
    a. Derek Elsworth (in collaboration with Tom Doe)
       URLs - An International Perspective
    b. Charles Fairhurst - Rock Mechanics and Radioactive Waste Isolation; One Small Step for Geology, One Giant Leap for Rock Mechanics
    c. Jack-Pierre Piguet – The Meuse/Haute-Marne URL
    d. Informal comments from the floor from URL directors/experimenters

3. Identification of Research Needs in Geo-Hydrology and Geo-Mechanics for a DUSEL - Ideas for International Cooperation (1 hr)
    - What are critical questions to be addressed by a DUSEL that are not currently addressed?
        - Geo-mechanics
        - Geo-hydrology
    - How do these prospective areas influence the competitiveness of the extractive (mining and petroleum) and construction industries?
    - How does the current suite of geological host environments address the needs of these industries?
    - How may the science and engineering plans mutually complement?
    - How do these goals fit with other proposed deep URLs?

4. Summary Discussion (10 min)
       Derek Elsworth

Workshop on Deep Underground Science and Engineering Laboratories
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