DUSEL Working Group: Underground Construction and Mining

C. Fairhurst & J.F. Labuz

Fundamental research in rock mechanics has focused on testing elements of the rock mass and simulating the interaction between the elements using numerical models. Advances in computational power allow the models to consider realistic in situ conditions and overcome the limitations of empirical rules, allowing prediction beyond current experience. However, a major obstacle is the inability to test the validity of the models against in situ behavior.

The establishment of a Deep Underground Science and Engineering Laboratory (DUSEL) in the US offers the exciting possibility to overcome this obstacle. Motivated initially by the need of the US physics community for underground facilities to conduct neutrino and related elementary particle research, the scope of DUSEL includes research in geo-engineering, where, for the first time, the community will have access to underground facilities dedicated to fundamental research on completing engineered structures—preventing failure of the rock mass—and on controlling underground operations for production of resources—promoting failure of the rock.

Leaders of the geo-engineering community gathered in Lead, SD, April 20 – 22, 2008 to discuss collaborative research for DUSEL. The two areas of focus were identified:

1. Cavern Design & Characterization, which include modeling, monitoring, risk assessment, and scale effects from the rock mass.
2. Fracture & Fragmentation, which include ground conditioning, blast design and modeling, hydraulic fracturing, and related fracture phenomena (e.g. crack interactions, fracture scaling, process zone effects).

Collaboration was discussed with Induced Rock Deformation and Geophysical Imaging working groups. Researchers (28) associated with the UCM working group include (by alphabetical order of the universities):

P.H.S.W. Kulatilake: *Arizona*
S. Glaser: *California, Berkeley*
M. Kuchta, U. Ozbay: *Colorado School of Mines*
C. Laughton: *FERMI Lab*
L. Germanovich, H. Huang: *Georgia Tech*
R. Ballarini, P.A. Cundall, (UMN & Itasca) E. Detournay, B. Guzina, J.F. Labuz, *Minnesota*, w/ R. Jeffrey (CSIRO), J. Furtney (Itasca)
H.H. Einstein: *MIT*, w/ Ribeiro e Sousa (Lachel, Felice), G. Callahan (RESPEC)
E. Asa: *North Dakota State*
D. Elsworth, M. Ge, J. Rostami: *Penn State*
A. Bobet, L. Pyrak-Nolte: *Purdue*
Z. Hladysz: *South Dakota School of Mines*
F. Tonon: *Texas, Austin*
J. Donovan, W. Pariseau: *Utah*
M. Mauldon: *Virginia Tech*

CAVERN DESIGN & CHARACTERIZATION

The vision for the Cavern Design initiative is to *"transform cavern design from empirically-based to performance-based."* Much of the design of large caverns has not changed in decades. It is still based on empirical rules derived from the performance of past projects. Rock mass strength and deformability behavior depend on the discontinuities present and their engineering characteristics, in situ stress distribution, and the constitutive properties of intact rock and discontinuities. Advances in numerical modeling allow for a rational design of caverns, but numerical models need to be calibrated and verified with observations of the actual performance of the rock mass. The excavation of a 100-kton cavern challenges current design procedures and opens an opportunity to foster a transition from empirical to performance-based design. As an added challenge, more than twenty years of cooperative rock mechanics studies at the Homestake mine has shown that creep occurs at the walls in the Ross. Whether the same is true of large caverns is unknown.

The experiment proposed is to use the construction of the large cavern as a laboratory to observe and analyze rock mass behavior over a period of years, to verify and improve design procedures and models. At the core of the experiment is the deployment of an array of sensors and instruments around the cavern, and prior to its excavation, to monitor the response of the surrounding rock mass to the excavation method (short-time scale, i.e. days), changes induced in the water flow with the cavern (intermediate-time scale, i.e. months), and deformations due to creep and sub-critical crack growth (long-term scale, i.e. years). Excavation and monitoring of the caverns will provide an opportunity to explore new technologies, such as LIDAR, which has the potential to be deployed as an effective tool to quickly measure deformations, acoustic emissions (AE) and other geophysical methods, which can be employed as "early warning" indicators of damage.

The construction of the large cavern can be utilized as a "virtual laboratory" where construction progress and rock response can be observed in real time over the web. Telepresence, following the concept introduced by NSF for the NEES program, can be achieved with the deployment of webcams at the site, and will constitute an effective tool for education and outreach. Subtopics include risk assessment and scale effects.

Risk Assessment & Uncertainty

The DUSEL underground construction work, whether it involves the creation of new underground space, or use and rehabilitation of existing tunnels, will be subject to numerous uncertainties ranging from geology to choice of tunnel excavation and support systems, to effects on the environment, to ability to meet scientific research goals. These uncertainties result in uncertainties in the estimated cost/time/resources, i.e. they result in risk for the DUSEL facility. These risks, together with similar risks regarding facility operation and science/engineering experiments should be formally assessed to provide the sponsors, the proposers and others affected by the DUSEL with a clear picture of the likely range of final costs and time to completion of the various phases. It is especially important that an evaluation of cost and time and the related uncertainties be given to the sponsors in order to avoid unanticipated overruns.

Scale Effects

The stability of underground structures depends on rock mass strength and deformability, which in turn depend on (a) geology/lithology, (b) discontinuity network, (c) geomechanical properties of the discontinuities, (d) geomechanical properties of the intact rock, (e) in situ stresses, (f) groundwater conditions, and (g) loading-unloading stress paths associated with the anticipated excavations and environmental changes. Due to the complex nature of discontinuity patterns in rock, and variability and uncertainties associated in estimating the factors (a) through (g), the prediction of rock mass strength and deformability properties and hence the stability of underground excavations at various scales using the available stress analysis techniques and a limited field and laboratory investigations presents a great challenge for the rock engineering profession. This proposal aims at estimating rock mass strength and deformability at various scales for the Yates unit that exists between the Yates and Ross shafts at the 4850 feet level of the Sanford Laboratory and to use that information to investigate stability of the anticipated underground excavations under different scenarios.

FRACTURE & FRAGMENTATION

Use of the subsurface is quite diverse, ranging from isolation of nuclear and hazardous wastes, underground storage of petroleum and natural gas, CO_2 sequestration, urban transportation, and Homeland Security issues, to name a few. However, central to all of these issues is the need to develop and control fracture of rock. DUSEL will provide the opportunity to establish a better understanding of crack growth and interaction in a naturally fractured rock mass. For instance, during a hydraulic fracturing process, any residual crack opening will induce compressive stresses that can cause the next fracture to grow asymmetrically or turn away from the previous fracture. Furthermore, issues of fracture energy scaling are critical in fragmentation studies, yet it is not known how lab testing of fracture toughness relates to the field scale, for both modes I and II.

Preconditioning

A novel method to engineer fractures in a rock mass for ease of excavation and enhancement of conductivity called preconditioning is proposed. The technique involves the use of hydraulic fracture and the DUSEL site provides a unique opportunity to evaluate the method using a “mine-through” study. Preconditioning requires placing many hydraulic fractures into the rock mass with a close spacing (on the order of a few meters). Besides weakening the rock mass to enhance the excavation process and improve fragmentation, the other uses are softening the rock mass and modifying stress to reduce risk from rock bursting, and potentially modifying rock mass permeability as an aid to in situ leaching operations. Thus, preconditioning has the potential to have a major economic impact in civil, mining, and petroleum engineering. With many of the more easily produced petroleum reservoirs becoming exhausted, petroleum companies must develop techniques to extract hydrocarbons from tight (low porosity, low permeability) formations. Furthermore, in underground mining, companies seeking less labor intensive mining methods are turning increasingly to mass mining methods where the ore body is induced to collapse in a controlled fashion. Where the ore-body is not already fractured, some form of pre-conditioning (i.e. creation of fractures in the ore body) either by explosives or hydraulic fracturing must be used. Similarly, extraction of geothermal energy from hot, dry rock requires the creation of fracture surfaces to increase the effectiveness of extraction by circulating fluids. Thus, the potential impact of efficient preconditioning techniques is large.

Blast Design

It is proposed to model the blasting process with the objective to optimize the design. Numerical modeling will be performed prior to excavation and measurements of velocity and acceleration will be compared to the simulation. The DUSEL construction phase would allow for in-situ validation test blasts to be conducted. In addition, the blasting process can be studied in the context of operations engineering, where the entire sequence of drill, blast, support can be optimized. The duration of the various operations in the drill-blast cycle will be studied to develop relationships among cycle components and shift time usage. The construction phase of DUSEL will be an ideal environment for testing and validation of the proposed technology.

Pre-proposals submitted as of April 20, 2008

The various topics were grouped by the following categories, with the title of the proposal and investigators:

- **Cavern Design (A. Bobet, coordinator)**
  - Mechanical and Geophysical Characterization of Rock Damage: A. Bobet and L. Pyrak-Nolte (Purdue University)
  - Building a Better Cavern: C. Laughton (FERMI Lab)
  - Cavern Design and Monitoring: M. Kuchta (Colorado School of Mines)
  - Rock Mechanics of Large Water Cherenkov Detector Caverns: W. Pariseau and J. Donovan (University of Utah)
  - Fracture Network Characterization at Homestake: M. Mauldon (Virginia Tech) and H.H. Einstein (MIT)
  - Stability contour map for optimizing the locations of DUSEL excavations: U. Ozbay (Colorado School of Mines)
  - Use of LIDAR (LIght Detection And Ranging) and digital photogrammetry for digital-terrain-model reconstruction of tunnel walls: F. Tonon (University of Texas, Austin)

- **Risk Assessment & Uncertainty (H.H. Einstein, coordinator)**

  - Risk Assessment of Underground Space Development for the DUSEL: H.H. Einstein (MIT)
  - New Models for Geomechanical Characterization in Underground Engineering: Ribeiro e Sousa (Lachel, Felice and Assoc), G. Callahan (RESPEC), and H.H. Einstein (MIT),
  - Probabilistic, Statistical and Uncertainty Modeling on Anticipated DUSEL Initial Suite of Experiment Activities: P.H.S.W. Kulatilake (University of Arizona)

- **Scale Effects (P. Kulatilake, coordinate)**

  - Investigation of Scale Effects on Rock Mass Mechanical Properties of Yates Unit: P.H.S.W. Kulatilake, University of Arizona

- **Fracture & Fragmentation (J.F. Labuz, coordinator)**
  - Blast modeling of the pre-construction and construction phases: B. Guzina, (University of Minnesota), P.A. Cundall, (UMN/Itasca), and J. Furtney (Itasca)
  - Mechanics of engineered fractures in discontinuous rock: E. Detournay, B Guzina, J.F. Labuz, and R. Ballarini (University of Minnesota); R. Jeffrey (CSIRO)
  - Solid Particle Placement in Hydraulic Fracturing: H. Huang (Georgia Tech)
  - Rapid Tunnel Development: M. Kuchta (Colorado School of Mines)

CAVERN DESIGN & CHARACTERIZATION

Mechanical and Geophysical Characterization of Rock Damage

A. Bobet and L. Pyrak-Nolte (Purdue University)

The Deep Underground Science and Engineering Laboratory (DUSEL) requires the excavation of very deep large underground cavities. As the applied stresses on a rock are changed, damage is caused by the creation of new cracks in the intact rock, initiation of new cracks from pre-existing fractures, or slip along pre-existing discontinuities. Ultimately coalescence of pre-existing and/or newly created cracks may induce failure in the rock mass. Geophysical methods have the potential, if linked with the mechanics of the phenomenon of brittle failure, to provide information regarding the type of crack, open or closed, location and extent of the crack, engineering properties such as stiffness, and potentially can be used to detect precursors to crack initiation and propagation. Development of geophysical methods for detecting and characterizing induced damage phenomena at DUSEL would be of great significance to the safety and operation of the underground laboratory, as well as for other societal interactions with the subsurface. What is proposed is a combination of experiments in the laboratory and at DUSEL.

The objectives of the experiments are: (1) to determine the fracturing mechanisms associated with frictional fractures in brittle materials; (2) to determine the seismic attributes needs to characterize, geometrically and mechanically, fracturing mechanisms; and (3) upscale laboratory experiments to the scale of DUSEL.

Observations from the laboratory are up-scaled to DUSEL by conducting large-scale experiments. At the DUSEL, the rock damage produced by stress changes will be monitored with geophysical transducers. The damage will be induced during excavation of the large caverns, or by large-scale loading tests at selected locations (e.g. excavation of additional drifts), both in intact rock (without discontinuities) and at locations with pre-existing joints. The objective of the experiments is to locate and characterize the new fractures formed from an engineering perspective, which includes the type of fracture, tensile or shear, size and stiffness, open or closed, presence of water filling the fracture. Determination of the optimum location and number of sensors, as well as development of the framework to interpret the measurements will be based on the laboratory experiments. The link between mechanics and geophysics at DUSEL will be done by direct observations through excavation and borings.

Building a Better Cavern

C. Laughton (FERMI Lab)

Many physics experimental proposals for DUSEL rely heavily upon the ability of the reinforced rock mass to support the excavation of large-span excavations. In particular, Long Baseline proposals, based on the use of Water Cherenkov detector technology, specify rock caverns with excavated volumes in excess of half a million cubic meters, spans of over 50 m, sited at depths of approximately one to 1.5 kilometers. Long Baseline proposals based on the use of Liquid Argon detector technology not only call for the excavation of large caverns, but have an additional need for the safe management of large quantities (kilo-tonnes) of stored cryogenic liquid, including critical provisions for the fail-safe egress of underground personnel, the reliable exhaust of Argon gas and the prevention of structural damage in the event of a catastrophic release. The Long Baseline and other cavern-housed physics experiments planned for DUSEL will challenge the rock mechanics and engineers to deliver caverns that will meet stringent operational requirements for periods conservatively estimated to be well in excess of twenty years.

This brief presentation will highlight some key end-user requirements, design criteria and geo-constraints likely to figure prominently in determining the viability of the larger cavern-housed experimental proposals. Given the scale and duration of the DUSEL excavation works it will be argued that there will be opportunities to improve design and construction performance (safety, quality, duration, cost and risk) through the integration of research tasks into the conventional design and construction processes. The objective will be to stimulate discussions on ways in which DUSEL physicists, geoscientists, rock mechanics and engineers can interact to formulate a research plan/proposal to build a better cavern.

Cavern Design and Monitoring

M. Kuchta (Colorado School of Mines)

Worldwide, large underground caverns house various industrial facilities – crusher stations, warehouses, fuel storage depots, even sports facilities. Of particular interest to the DUSEL community is the proposed construction of a large multipurpose detector, which requires a cavity 200 ft wide, 200 ft high, and 600 ft long situated beneath 5000 ft of overburden. A number of moderately sized caverns at other depths are also planned. From the standpoint of safety and effective construction technique, the knowledge gained through careful study of the design, construction, and post construction behavior of these moderately sized caverns can be advantageously applied to cavern making in general, and to the proposed large multipurpose detector in particular. Our cavern design procedure will be closely integrated with related work, such as exploratory drilling, rock mass characterization and classification, fracture mapping, and in situ stress determination. The overall study will include cavern size, shape and orientation considerations, excavation sequence, blast design (incorporating precision blasting techniques), and ground support including cable bolt design, rock bolting, shotcrete, and other support membranes. Where appropriate, we will study and compare numerical modeling techniques and empirical design procedures. Additionally, to improve understanding of rock mass deformations, both initially and over longer periods of time, we will put instrumentation and monitoring programs in place before, during, and after construction. A vital component will be a microseismic monitoring system. A large array of carefully placed instrumentation will be used to monitor the displacement field of the chamber structure, and a tightly controlled microseismic array system will capture the structure's dynamic response. We will use monitoring data to calibrate numerical models.

Rock Mechanics of Large Water Cherenkov Detector Caverns

W.Pariseau and J. Donovan (University of Utah)

Activities proposed at the Homestake site include: (1) diamond drill sampling to supplement definition of site geology and structure, and collection of drill core samples for laboratory testing, including intact rock and discontinuities as they are encountered, (2) in situ stress, elastic modulus, and permeability measurements proceeding from near tunnel walls to a distance into the wall where measurements become steady, and proceeding across geologic contacts to define the change in stress across material discontinuities, (3) imaging of rock walls underground for discontinuity analysis and borehole tomographic imaging of a sizeable rock mass, and (4) retrospective stability analysis of several large existing rooms, forward analysis of proposed 100-kton caverns, and calibrated model analysis of alternative excavations design sequences for safety and economy. Over 20 years of cooperative rock mechanics study at the Homestake mine has provided much valuable data and experience relevant to this site. For example, creep of walls in the Ross shaft (about 5 x 6m, commissioned circa 1935) is known to occur, but poses no threat to stability. Whether the same is true of large caverns is unknown. There is little precedent for design and construction of these very large caverns. Hence, there is an unmet need for research that insures reliability of an extreme size cavern design at the Homestake site.

Scaling up engineering of ordinary size civil and mining excavations at depth to the long service life of these extraordinary size detector caverns indicates a need for geomechanical research that would aid the design, construction and operation of the megaton cavern array. Accordingly, a 3-yr investigation of rock properties, in situ stress, and cavern stability is proposed with the goal of clarifying the issue of scale effects which are ever-present in rock mechanics but only vaguely defined and poorly understood. An important intellectual benefit is improved understanding of "scaling" in rock mechanics that is associated with various sources of heterogeneity in nature and how calibration of numerical models using scale factors for elastic moduli and strengths can be based less on trial and error and more on scientifically sound engineering principles. Data would also aid future geoscience and geo-engineering research at the DUSEL.

In addition to the benefits of graduate student education and of experience gained by junior faculty, a broader impact is anticipated through dissemination of results through a network of colleagues at national laboratories and universities that nurture interest in rock mechanics. There is also a considerable outreach program planned for the DUSEL; results from this first targeted on-site study would be available to this program.

Fracture Network Characterization at Homestake

M. Mauldon (Virginia Tech) and H.H. Einstein (MIT)

Rock fractures (joints) govern rock mass behavior; specifically the deformation, stability and hydraulic properties of rock masses. Important characteristics of fracture patterns, particularly fracture extent and interconnectivity, must generally be inferred from limited one-or two dimensional exposures such as boreholes or rock outcrops, or from rock core. Such observations then serve as input for three dimensional models which are used to make predictions of rock mass behavior. The problem is that it is usually impossible to determine the actual 3d fracture pattern subsequent to making predictions; i.e. to verify whether the fracture pattern models are correct or not. DUSEL provides unique opportunities to access a large amount of information about the rock mass, and this in a number of ways; which are the objectives of this research:

- The rock mass at Homestake is exposed at multiple faces; e.g., rock pillars, parallel drifts, and multiple levels. This provides a wealth of opportunities for direct characterization of the 3D fracture network geometry.
- Creation of new underground space or enlargements and modifications of existing tunnels and chambers. Such excavation involves removal of rock mass slices, again allowing real time construction and verification of fracture geometry models.
- Fracture data from the vast collection of rock core will be utilized in the fracture network characterization.

Observations and measurements of water inflow and water characteristics. According to Campbell (http://homestake.sdsmt.edu/Resources.htm), brittle deformation during the Tertiary is responsible for the network of joints that transmits meteoric water into the mine workings. Information on connectivity and permeability is also provided by groundwater temperature and chemistry. Campbell reports that drifting, cross-cutting, and diamond drilling have locally intersected these "watercourses", as they are called by the miners, and encountered medium to high temperature (45 to 85ºC) water under low to high pressure . The fracture network studies will make use of infiltration studies already carried out, and of additional seepage data collected during the early stages of DUSEL. Tracer experiments on a number of scales will also be carried out in this context.

Ground-truthing and calibration of indirect or remotely sensed measurement methods such as seismic, radar, etc. Signals measured with such methods are in principle related to the fracture pattern. However, information obtained by geophysics requires "ground-truthing," which is best achieved by direct correlation with the observed fracture geometry and other rock mass properties.

The three-dimensional exposures mentioned above provide opportunities for such ground-truthing. Calibration of geophysical measurements against extensive exposures of rock surfaces in the DUSEL will potentially result in advances in geophysical imaging and interpretation, which will in turn be of benefit in numerous fields, including hydrocarbon extraction, underground construction and groundwater modeling.

Stability contour map for optimizing the locations of DUSEL excavations

U. Ozbay (Colorado School of Mines)

DUSEL project requires several new excavations to be constructed at the Homestake site ranging from 100m down to 2000 m below the surface. There will be decisions that will have to be made in locating these excavations based on safety, experiment requirements, logistics, and the relationships between the experiments performed in these excavations. The pivotal parameter in optimizing the spatial location of these excavations will be the ground conditions, which must meet the safety and stability needs over the duration of DUSEL projects.

It is proposed that a study be carried out to characterize the ground conditions at the Homestake site in terms of rock mass conditions and field stresses. The product of this study will be a three dimensional map of the site that delineates the ground conditions in units of stability contours. This map can then be used for optimizing the excavation locations. It is crucial that this study starts promptly as it stands in the critical path of planning DUSEL excavations.

The ground conditions will be defined in terms of three main parameters, namely the geotechnical characteristics of the rock mass, prevailing virgin stress conditions, and most importantly, field stresses. The geotechnical characterization work will involve reviewing the available rock-mass data from the mine's archives and the large core-bank at the site. There have been some stress measurements taken at the Ross Shaft pillar area; these and other available virgin stress data will be reviewed and interpreted for the site.

The field stresses are caused by mining excavations as they alter the virgin stress conditions. Around these excavations, the field stress may vary from being significantly de-stressed to highly stressed depending on the extent of mining, presences of pillars, and proximity to excavation abutments, which will have a significant effect on the stability of the DUSEL excavations. A detailed review of mine plans will have to be carried out and numerical modeling studies must be performed to obtain the field stress distribution at the site.

Finally, recommendations will be made for further stress measurements and site characterization work to improve the reliability of the stability contour map.

Use of LIDAR (LIght Detection And Ranging) and digital photogrammetry for digital-terrain-model reconstruction of tunnel walls

F. Tonon (University of Texas, Austin)

These techniques generally include the following steps:

1. Collecting information on a rock face (using high-resolution digital cameras or LIDAR);
2. Producing an (oriented) point cloud, and a digital 3D surface and rendering of the face, called Digital Terrain Model (DTM). DTM may be draped with a picture of the face; and
3. Analyzing the DTM to characterize the rock mass (e.g., take dip direction and dip measurements, joint spacing, etc.).

Advantages of these remote techniques include:

- The ability to quickly analyze large portions of rock masses (including inaccessible areas), and acquire large data sets;
- The possibility to zoom in and out of a face, which leads to a better understanding of large features;
- Quantification of fracture scale-dependency and invariants;
- Decreased impact on construction activities;
- Permanent documentation of the rock face condition and excavation stages for reporting and contractual-legal issues;
- Relative ease of use.

In 2006, an ARMA (American Rock Mechanics Association) workshop on these topics was organized in conjunction with the 40th US Rock Mechanics Symposium. The workshop highlighted the following topics as outstanding research items, which are proposed as objectives for this research:

- Identify petrology and mineralogy;
- Develop fracture statistical tools for three-dimensional imaging.
- Quantify: roughness (JRC), wall strength (JCS), weathering, humidity/seepage, and filling (required for ISRM quantitative description of fractures).

Sequences of excavation rounds will be carried out during the ISE for many purposes (e.g., developing underground space for experiments). It is proposed to use either LIDAR or digital photogrammetry to map all rock faces during construction. Because of the large amount of detailed fracture data collected on cutting surfaces very close one to the other, this database will enable rock engineers to quantify fracture areal extension (persistence) in three-dimensions by following each single fracture from one cutting surface to the next.

RISK ASSESSMENT

Risk Assessment of Underground Space Development for the DUSEL

H. H. Einstein (MIT)

The DUSEL underground construction work, whether it involves the creation of new underground space, or use and rehabilitation of existing tunnels, will be subject to numerous uncertainties ranging from geology to choice of tunnel excavation and support systems, to effects on the environment, to ability to meet scientific research goals. These uncertainties result in uncertainties in the estimated cost/time/resources, i.e. they result in risk for the DUSEL facility. These risks, together with similar risks regarding facility operation and science/engineering experiments should be formally assessed to provide the sponsors, the proposers and others affected by the DUSEL with a clear picture of the likely range of final costs and time to completion of the various phases. It is especially important that an evaluation of cost and time and the related uncertainties be given to the sponsors in order to avoid unanticipated overruns.

The Decision Aids for Tunneling (DAT), which were developed at MIT, allow one to determine the cost, time and resources and their uncertainties with regard to tunnel construction. They have been applied in a number of tunnels, particularly the Transalpine tunnels in Switzerland. The DAT allow one not only to assess the uncertainties in tunnel construction cost, time and resources but to update how uncertainties (and thus risk) change as construction proceeds. With some additional work, it is possible to expand the DAT to consider the uncertainty associated with using and refurbishing existing underground facilities. Very importantly, the DAT structure lends itself to develop a formal assessment procedure for operational and experimental uncertainties and their consequences. This will require additional research and development.

It is, therefore, proposed to use the DAT in the early phases of the DUSEL development to assess the construction risk and, following this, to further develop them to be able to assess the operational and experimental risks.

Specifically, the objectives are:

- Adapt the DAT for new excavation at Homestake. Requires formulation of geology and construction procedures with associated uncertainties in time, cost and resources.
- Expand the DAT to consider modification of existing underground openings at Homestake. Requires formulation of construction parameters and related uncertainties
- Discuss with leaders of different scientific experiments if an application of the DAT structure to estimate uncertainties of some/most experiments is desirable. If yes, develop the DAT such that this can consider cost, time and other uncertainties regarding installation/operation of these experiments.

New Models for Geomechanical Characterization in Underground Engineering

Ribeiro e Sousa (Lachel, Felice and Assoc), G. Callahan (RESPEC), and H.H. Einstein (MIT)

The determination of geomechanical parameters of rock masses for underground structures is still subject to high uncertainties. The uncertainties are related to geotechnical conditions and construction. Yet an accurate determination of the geomechanical parameters is key for an efficient and economic design of the support of the underground excavation and for the excavation itself. The methodologies used to obtain the parameters are based on laboratory and in situ tests and on the application of empirical methodologies, mainly RMR, Q and GSI systems. The methods are based on an overall description of the rock mass and on the determination of key parameters that can be related to strength and deformability of the ground medium.

At the DUSEL facility, there exists a large amount of geotechnical data available not duly analyzed, which can be linked to underground chambers that have been stable for a long period of time. This information can be used in a rational way to develop new and better models for future underground projects. The use of Data Mining techniques is instrumental in the discovery of new geotechnical models that are consistent with existent knowledge. The models are expected to have higher accuracy than existing ones, because the latter do not use all available information, are too simple, and do not take into consideration the complete behavior of the rock mass. The process of discovering new knowledge from databases consists of the following steps: Data selection; pre-processing, where irrelevant information is removed; data transformation in suitable forms for application of Data Mining algorithms; application of data mining intelligent methods consisting of search and inference patterns or models such as Bayesian Networks; and interpretation of results from previous steps. In order to improve the predictions and the models developed, we propose to use the Bayesians networks, which allow the introduction of uncertainties related to geotechnical and construction aspects, risk management and decision making during underground construction.

Bayesian networks are representations of knowledge for reasoning under uncertainty. They can be used at any stage of a risk analysis and may substitute both fault trees and event trees in logical tree analysis. Bayesian networks provide a powerful tool for decision analysis, including prior analysis, posterior analysis and pre-posterior analysis. Furthermore they can be extended to influence diagrams, including decision and utility nodes to explicitly model a decision problem. In addition, Bayesian networks facilitate learning of causal relationships between variables. This is a process needed to understand the problem domain, for instance, during exploratory data analysis and to make predictions based on the knowledge of causal relationships.

The scientific goals will be achieved by completion of the following activities:

- Collection of geological and geotechnical data existing at the DUSEL underground facility. Since there is a large amount of information, a methodology will be implemented where the mine will be divided in regions and levels and in different geological formations. The information will be collected in a limited number of sites randomly chosen.
- Mapping of rock mass surfaces and application of common empirical systems, with special emphasis on RMR, Q and GSI systems. Laboratory tests will be performed to apply the empirical systems.
- Creation of a database and data analysis using Data Mining techniques, with particular emphasis in Bayesian Networks.
- Development of new geomechanical models in terms of deformability and strength and evaluation of the new models using Knowledge Discoveries in Databases processes.
- Development of tools for risk management and decision making in underground construction using the obtained Bayesian networks.
- Performance of in situ large-scale tests to update and validate the new models. Large scale tests are proposed to obtain the overall deformability of the rock mass.

Probabilistic, Statistical and Uncertainty Modeling on Anticipated DUSEL Initial Suite of Experiment Activities

P.H.S.W. Kulatilake (University of Arizona)

Rock mass geology/lithology, discontinuity geometry systems and in situ stress need to be inferred under a high degree of uncertainty using only a limited number of data obtained from field investigations. Random field theory, geostatistics and Markov models can be used for rock mass geology/lithology modeling. Discontinuity geometry parameters are inherently statistical. Discontinuity geometry systems differ from one statistical homogeneous region to another statistical homogeneous region. Cluster and discriminate analyses should be used to separate between different statistical homogeneous regions. For each statistical homogeneous region, a separate discontinuity geometry system should be developed. Discontinuity geometry parameter values obtained for orientation, spacing, intensity and size from one-dimensional or two-dimensional sampling surveys do not represent the actual distributions of these parameters that exist in three dimensions. These parameter values are subject to sampling biases. These sampling biases should be corrected by applying geometrical probability techniques. Then the corrected values should be used in developing appropriate probability distributions for the discontinuity geometry parameters. The developed probability distributions then can be used in Monte-Carlo simulations in generating discontinuity networks in three dimensions. Discontinuity roughness and aperture inherently belong to fractals. They cannot be modeled using Euclidean geometry. Self affined fractal concepts should be used in modeling discontinuity roughness and aperture. Due to factors such as the inability to simulate field conditions in the testing apparatus, material spatial variability, simplified assumptions used in test interpretations, scale effects, instrument errors and human errors, intact rock and discontinuity physical, mechanical and hydraulic properties estimated using laboratory or field tests are subject to significant uncertainty. They are subject to systematic (bias), random and statistical errors. Statistical errors arise due to the scarcity of data. Systematic errors should be eliminated in inferring the property values. Random and statistical errors should be incorporated in making confidence interval estimations of the aforesaid intact rock and discontinuity property values. Bayesian updating technique can be applied to make new estimation of parameter and property values as new data become available. Groundwater conditions in a rock mass exhibit spatial variability. Random field theory and geostatistics can be used in quantifying the groundwater distribution in a rock mass. Stress and hydraulic boundary conditions resulting from geo activities are inherently statistical. Modeling techniques used in rock mass stress and deformation analysis, fluid flow and transport modeling are subject to modeling errors due to built-in simplified assumptions. In applying modeling techniques to perform aforementioned analyses for underground excavations, we are faced with irregular problem domains, heterogeneous lithology, different geo-materials with complicated constitutive behavior and complex boundary and initial loading conditions. In order to simulate these features, it is necessary to resort to stochastic or probabilistic numerical methods. Rock mass stress and deformation analyses can be performed using first order second moment distinct element analysis. Such analyses will allow us to evaluate the uncertainties resulting on stress and deformation due to the uncertainties associated with the lithology, discontinuity geometry parameters, discontinuity roughness, in situ stress, physical and mechanical properties of intact rock and discontinuities, groundwater conditions and stress and hydraulic boundary conditions. Stress and deformation results in turn will allow us to make predictions about stability of intended underground excavations. Rock mass fluid flow and transport analyses can be performed using first order second moment finite element or finite difference analysis. Such analyses will allow us to evaluate the uncertainties resulting on fluid flow and transport due to the uncertainties associated with the lithology, discontinuity geometry parameters, discontinuity aperture, in situ stress, physical and hydromechanical properties of intact rock, physical, hydromechanical and transport properties of discontinuities, groundwater conditions and stress and hydraulic boundary conditions. Significant monetary savings can result from probabilistic and numerical based designs; catastrophic failures and unsatisfactory designs may be reduced.

SCALE EFFECTS

Investigation of Scale Effects on Rock Mass Mechanical Properties of Yates Unit

P.H.S.W. Kulatilake, University of Arizona

It is proposed to investigate rock mass mechanical properties of the Yates unit that exists between the Ross and Yates shafts at the 4850ft level of Homestake mine at different scales as briefly described below.

Laboratory scale: A few rock block samples will be obtained from the Yates unit at the 4850 ft level to prepare two to three samples of cubic rock blocks of side dimension 0.5m. The rock discontinuity geometry network including the discontinuity roughness of these blocks will be mapped carefully. Each of these blocks, first will be subjected to the existing in situ stress conditions at the 4850 level. Then it will be subjected to a selected loading or unloading stress path with deformation monitoring on the block faces until block failure. Results of these physical tests provide block deformability and strength. Some of the obtained block samples will be used to prepare intact rock discontinuity samples and then to determine physical and mechanical properties of the intact rock and the mechanical properties of the typical discontinuities. Based on the mapped discontinuity geometry data of the aforementioned blocks, 0.5m cubic rock blocks having discontinuities will be numerically simulated. To discretize the block into polyhedra, fictitious joints will be introduced. The mechanical property values of the appropriate constitutive models for the intact rock, actual discontinuities and fictitious joints will be selected based on the results obtained for the mechanical property tests conducted on intact rock and discontinuities. Each of these blocks will be subjected to the same stress path numerically as used in the physical test performed at the laboratory with deformation monitoring. These stress path simulations will be done in three-dimensions using the distinct element method to investigate the block deformational and strength properties. Comparisons will be made between the laboratory test results and the numerical predictions to evaluate the capability of the numerical modeling procedures. If discrepancies are found, attempts will be made to evaluate the uncertainties associated with the discontinuity geometry network, discontinuity roughness, used constitutive models and used material property values in the numerical model and then to calibrate the numerical model to produce laboratory test results.

Field block scale: A rock block of 3-5 meters will be identified in the Yates unit. The rock discontinuity geometry network including the discontinuity roughness of this block will be mapped carefully. Based on the mapped discontinuity geometry data of the aforementioned block, a rock block of the same size having the aforementioned discontinuities will be numerically simulated. The calibrated numerical model obtained from the laboratory scale will be used to predict the block deformability under a selected stress path. The actual block in the field will be subjected to the same stress path physically. Comparisons will be made between the field block test results and the numerical predictions to evaluate the capability of the numerical modeling procedures. If discrepancies are found, attempts will be made to evaluate the uncertainties associated with the discontinuity geometry network, discontinuity roughness, used constitutive models and used material property values in the numerical model and then to calibrate the numerical model to produce field block test results.

Typical cavern scale (tens of meters): Available geology data and the rock discontinuity geometry data will be used to develop a three-dimensional rock mass structure model for the Yates unit. If the available discontinuity geometry data are insufficient, fracture geometry mapping will be performed in the existing shafts and galleries at the 4850 ft level to build the three-dimensional rock mass structure model for the Yates unit. The calibrated numerical model from the field block scale will be used to simulate a cavern excavation of size tens of meters in the developed three-dimensional rock mass structure model of the Yates unit. This cavern will be excavated in the field with displacement monitoring using multiple point borehole extensometers, and wire and tape extensometers. Comparisons will be made between the field cavern excavation test results and the numerical predictions to evaluate the capability of the numerical modeling procedures. If discrepancies are found, attempts will be made to evaluate the uncertainties associated with the discontinuity geometry network, discontinuity roughness, used constitutive models and used material property values in the numerical model and then to calibrate the numerical model to produce field cavern excavation test results.

Nutrino Detector cavern scale (hundreds of meters): Available geology data and the rock discontinuity geometry data will be used to develop a three-dimensional rock mass structure model for the Yates unit. If the available discontinuity geometry data are insufficient, fracture geometry mapping will be performed in the existing shafts and galleries at the 4850 ft level to build the three-dimensional rock mass structure model for the Yates unit. The calibrated numerical model from the typical cavern scale will be used to simulate a cavern excavation of size hundreds of meters in the developed three-dimensional rock mass structure model of the Yates unit. This cavern will be excavated in the field with displacement monitoring using multiple point borehole extensometers, and wire and tape extensometers. Comparisons will be made between the field cavern excavation test results and the numerical predictions to evaluate the capability of the numerical modeling procedures.

FRACTURE & FRAGMENTATION

Blast modeling of the pre-construction and construction phases

B. Guzina (University of Minnesota), P.A. Cundall (University of Minnesota/Itasca), J. Furtney (Itasca)

As part of the Hybrid Stress Blast Model (HSBM) project, Itasca has developed software to model the rock blasting process. The code, Blo-Up 2.0, uses a unique combination of continuous and discontinuous numerical methods to represent the key processes occurring in non-ideal detonation, rock fracturing, and muck pile formation. The objective of the HSBM project is to be able to make predictions of fragmentation for a given blast layout.

As of April 2008, code development is nearly complete and initial testing has been conducted. Validation of the code against physical experiments is currently in the planning phase. The construction phase of the DUSEL project would be an ideal environment for testing and validation of this new technology.

The primary objective is to conduct a full-scale validation of the code for a practical blast layout. This would take the form of defining a blast layout and determining the local rock and joint properties. Determination of the rock properties requires testing rock samples for dynamic properties. This information could be used to construct a numerical model to be run before the actual blast. During the blast, measurements of face velocity and acceleration will be taken. After the blast, fragmentation and back break will be estimated, with a direct comparison with the numerical results. The DUSEL construction phase would allow for in-situ validation test blasts to be conducted. The in-situ test blasts are more realistic and would allow for an assessment of the “quiet boundary” condition used to represent intact rock in the far-field.

Important questions to be answered in the validation phase of this study are:

1. Is the magnitude of the stress wave reaching the free surface predicted accurately?
2. Is the predicted face velocity accurate?
3. Is the predicted pattern of fracture accurate?
4. Is the fragmentation predicted accurate?
5. Does the numerical code predict the size of the near-borehole crushed zone?
6. Is the muck pile profile predicted by the code accurate?

Once validation is achieved, secondary research objectives can be addressed. Currently in the industry, blasts are designed using general rules of thumb and experience from previous blasts. Blo-Up 2.0 is an ideal numerical laboratory for conducting experiments to help understand the mechanisms behind the rules of thumb currently used. For example, the effect of the number, size and layout of blastholes on the resulting fragmentation could be explored. Electronic detonators, which allow for precise detonation timing, are coming into common use. Blo-Up 2.0 would be an ideal tool to learn how to take advantage of this high-resolution timing capability.

Several more advanced research topics would also be possible.

1. Direct numerical simulation of the detonation wave in non-ideal explosives
2. Decoupled charge modeling
3. Air blast coupling to ground support

The results from this work could serve to assist in the design of more effective blasting procedures to ensure minimum damage to the cavern walls.

Mechanics of engineered fractures in discontinuous rock

E. Detournay, B. Guzina, J.F. Labuz, and R. Ballarini (University of Minnesota); R. Jeffrey (CSIRO)

A novel method to engineer fractures in a rock mass for ease of excavation and enhancement of conductivity called preconditioning is proposed. The technique involves the use of hydraulic fracture and the DUSEL site provides a unique opportunity to evaluate the method using a "mine-through" study.

Preconditioning requires placing many hydraulic fractures into the rock mass with a close spacing (on the order of a few meters). Besides weakening the rock mass to enhance the excavation process and improve fragmentation, the other uses are softening the rock mass and modifying stress to reduce risk from rock bursting, and potentially modifying rock mass permeability as an aid to in situ leaching operations. Thus, preconditioning has the potential to have a major economic impact in civil, mining, and petroleum engineering. With many of the more easily produced petroleum reservoirs becoming exhausted, petroleum companies must develop techniques to extract hydrocarbons from tight (low porosity, low permeability) formations. Furthermore, in underground mining, companies seeking less labor intensive mining methods are turning increasingly to mass mining methods where the ore body is induced to collapse in a controlled fashion. Where the ore-body is not already fractured, some form of pre-conditioning (i.e. creation of fractures in the ore body) either by explosives or hydraulic fracturing must be used. Similarly, extraction of geothermal energy from hot, dry rock requires the creation of fracture surfaces to increase the effectiveness of extraction by circulating fluids. Thus, the potential impact of efficient preconditioning techniques is enormous.

The DUSEL experiment will provide the opportunity to establish a better understanding of crack growth and interaction in naturally fractured rock. For instance, during the hydraulic fracturing process, any residual crack opening will induce compressive stresses that can cause the next fracture to grow asymmetrically or turn away from the previous fracture. In addition, determining the effect of preconditioning on rock mass strength is critical. Placing a fracture in a rock mass every few meters may not cause a big enough change in caveability. Inducing shear stress by proper placement of hole may be part of the answer, but fatigue and weakening by microcrack growth might also be important.

The main thrust of the work would be to produce fairly continuous quasi-planar fractures extending tens of meters. The rock mass would be subjected to stress and pore pressure changes during each treatment, and the loading episodes would be repeated multiple times for any given representative sample of the rock mass as fractures are placed along a single borehole and, to some extent, along adjacent holes. Microseismic events would be monitored around the main hydraulic fracture. Together, the cycles of loading and unloading (mechanically and via fluid pressure) would produce a change in the in situ stress (reducing the deviatoric component) and in the rock mass strength. Both of these effects are poorly understood and both are critical for the caving and fragmentation process. Laboratory work would also be performed to investigate the effect of multiple load cycles on rock strength. Field work would consist of an instrumented site with microseismic, stress change, and pressure monitoring to obtain data on damage-induced phenomena.

Solid Particle Placement in Hydraulic Fracturing

H. Huang (Georgia Tech)

We propose to perform hydraulic fracturing experiments with solid transport in complex fluids in DUSEL to investigate the effect of fluid rheology on hydraulic fracture width creation and particle transport pattern.

Hydraulic fracturing has been widely used as a reservoir stimulation technique, where artificial fractures are created by injecting slurry into the rock mass. The placement of solid particles props the fracture open and creates passages for hydrocarbon flow. Fracture conductivity is therefore one of the most important factors that affect well productivity. Hydraulic fracture width and solid transport pattern are two of the most critical factors in achieving desired conductivity. However, in classical hydraulic fracturing models, fluid rheology and particle transport models have traditionally been kept simple (Newtonian or power law) in order to accommodate the difficulties arising from strong coupling between fluid flow and rock deformation. The final placement is assumed to be uniform in porosity. As hydraulic fracturing fluids evolve to complex polymers and viscoelastic surfactant (VES) based fluids, simply Newtonian or power law fluid rheology becomes inadequate. Strong elasticity and peculiar rheological characteristics such as a flat stress plateau across several orders of time scale or non-monotonic behavior (strain rate softening) in the shear stress vs. shear strain rate curve are not uncommon in those complex fluids. Particle transport pattern maybe also be strongly affected by the shear induced mesoscale structures often observed for such kinds of complex fluids.

Understanding the effect of rheology on hydraulic fracturing width creation and solid particle placement with complex fluids has been a great challenge. The need for field tests in a lab like DUSEL lies in the facts that 1) it is not yet possible to perform theoretical (analytical or numerical) analysis of the transport process in complex fluids with strong elasticity at the particle scale; 2) even large scale parallel plates experiments (meter scale) could be strongly affected by the entrance and exit effect and are unable to mimic many characteristics in hydraulic fracturing, e.g., the leak off process and roughness of the fracture faces; 3) it is also unclear whether those laboratory experiments can be scaled to describe flow in the field treatment with complex fluids.

It is therefore of great value to conduct field scale hydraulic fracturing experiments with particle transport in complex fluids to get a better understanding of how the complex rheology affects the process of width creation and how the transport patterns in a field scale hydraulic fracture differ from parallel plates experiments. Effect of fluid rheology on width creation and particle transport could be analyzed via downhole logging tools and the use of markers (e.g., radioactive tracers). The transport pattern can be examined during the mineback process. Results from such studies would benefit not only our fundamental knowledge of solid transport and behaviors of complex fluid flow in hydraulic fracturing but also the state of practice of the oil and gas industry.

Rapid Tunnel Development

M. Kuchta (Colorado School of Mines)

Drill and blast drifting is a cyclical operation requiring specialized equipment and highly trained crews. The basic cycle includes surveying, drilling, charging, blasting, ventilating, scaling, rock removal, and ground support. The latter typically involves rock bolts and shotcrete. The goal of this research is to optimize the overall efficiency of the drill and blast drift driving cycle in order to improve overall safety (both during construction and long term), to reduce the overall cycle time (thus increasing the drift advance rate), and to reduce drift driving costs. A systems approach will be taken that involves studying and attempting to optimize the interaction of all cycle components, and will include: (1) blast pattern design using state of the art blast design software being developed as part of the NIOSH-sponsored Optimum Rock Excavation Project, (2) precision-drilling techniques to insure accurate hole placement, (3) evaluation of electronic detonators as a means of improving blast performance, (4) application of the foregoing techniques to increase blast round length, (5) evaluation of advanced smooth wall blasting techniques to minimize damage to wall rock and reduce ground support requirements, (6) evaluation of water jet scaling with the objective of improving worker safety and the performance of shotcrete, and (7) evaluation of new ground support techniques such as Thin Spray-on Liners, alternative shotcrete designs, and self drilling roof bolts. Additionally, the duration of the various operations in the drill-blast cycle will be studied in order to develop a better understanding of the relationships among cycle components and for optimizing available shift time usage. This study will be conducted on non-critical path drift excavations.