A U.S. DEEP UNDERGROUND SCIENCE AND ENGINEERING LABORATORY
SCIENTIFIC OPPORTUNITIES AND TECHNICAL REQUIREMENTS

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INTRODUCTION

This proposal is in response to the site-independent solicitation issued by the National Science Foundation ("Solicitation 1") for an integrated study of a Deep Underground Science and Engineering Laboratory (DUSEL) at one or multiple sites. This is a community-wide and cross-disciplinary effort, independent of specific sites, to develop deep underground science and engineering program planning and technical requirements, as requested by NSF. The proposal is supported by all the eight potential sites, currently known to us (there might be more), and involves physics (nuclear physics, particle physics and astrophysics), earth sciences, biology, and engineering communities. If designed properly, DUSEL will not only offer exciting opportunities for physics but also for earth and biosciences and engineering communities with significant impact on resource development and environmental management.

The PI and co-PIs have taken the initiative to gather the community-wide support for the idea of writing a single, site-independent document that would represent the community viewpoints, map the scientific and engineering program enabled by DUSEL, and provide broadly accepted criteria for site and experiment selection. In the past few months, we have developed a framework, which includes all relevant scientific and engineering fields, involves scientists from broad institutional and geographical backgrounds, and ensures that the process is site independent and driven by rigorous scientific criteria. Before submitting the final proposal, a community-wide workshop was organized in August in Berkeley with three goals:

- To finalize the DUSEL proposal in a way that is fully representative of the community;
- To identify the missing pieces of the scientific arguments for a deep underground laboratory;
- To get a head start on technical requirements that will be useful for all site-specific proposals in the second NSF solicitation expected later this year (Solicitation 2).

The supplementary materials herewith include the workshop's program, a list of participants, and the preliminary conclusions of the working groups specially organized for the workshop.

The outcome of the proposed six-month's study will be a report of 50–60 pages, which will

- summarize the scientific, engineering and education opportunities offered by a U.S. DUSEL within the broader international context and over a 20-year life time;
- outline roadmaps toward the corresponding objectives, grouping generic experiments with similar infrastructure needs in cross-disciplinary modules; and
- describe the technical infrastructure requirements for the broad spectrum of deep underground science and engineering.

The report—similar in style to the "Quantum Universe" report [HEPAP 2004]—will be written for nonspecialists, program officers at the various federal funding agencies, and staffers in Congress, the Office of Management and Budget (OMB), and the Office of Science and Technology Policy (OSTP). It will be complemented by 600 pages of detailed technical background documents, which will be available on the Web. This study will consolidate the diverse perspectives of the scientific and engineering communities. As already partially demonstrated at the Berkeley workshop, this process will provide a synergistic link between the various scientific fields involved, build a consensus on roadmaps and priorities, and prepare grounds for the whole community involvement in the site, or combination of sites, chosen at the end of the selection process.

We will describe the methods that we plan to use to explore the science and engineering opportunities, and to define the technical requirements and evaluate the demand for a deep underground laboratory as a function of time and the management structure. We will finish by comments on broader impacts of the proposed activity. Note that for conciseness, we do not always add "engineering" after "science." In this proposal, engineering is considered to be an integral part of physics, earth sciences, and biology.

1. EXPLORATION OF SCIENCE AND ENGINEERING OPPORTUNITIES

Although a large amount of material on scientific justification for DUSEL exists (see References), there is still a lot of work to be done on mapping the medium- and long-range programs of underground science and specifying the infrastructure requirements.

1.1. Scientific focus

A deep underground laboratory gives us an exceptional opportunity to find answers to fundamental questions about the dark side of the earth and the cosmos; for instance,

- What is the nature of dark matter and, possibly, of dark energy?
- What are the properties of neutrinos (νs)?
- What causes matter/antimatter asymmetry and the instability of matter?
- What are the characteristics of dark life and early cellular evolution?
- How are fluid, heat, chemical and biological transport and biogeochemical processes coupled to tectonic processes?
- How can we image the underground world to have total mastery of the rock?

These questions fall in at least four broad scientific and engineering fields

1.1.1. Physics and Astrophysics

Important discoveries can be made in experiments that aim to understand the nature of the nonluminous matter—the matter that dominates the universe, in experiments that measure the fundamental properties of neutrinos, or in an experiment that tries to determine whether stable matter actually decays very slowly, beyond the lifetime of the universe. Other experiments will equally impact astrophysics and, possibly, geophysics. Among those are experiments that determineneutrinoluminosity of the sun; constrain the model of the earth's core through measurement of geoneutrinos; measure the relic supernova ns to constrain the history of star formation in the universe; or detect neutrinos from any future supernovae to understand the dynamics of the gravitational collapse of a stellar core. A small particle accelerator in the underground laboratory will address important questions in nuclear astrophysics. We also envision a facility for prototyping advanced instrumentation for use in the underground laboratory and for measuring the trace radioactivity in detector materials.

1.1.2. Molecular, Evolutionary and Geo-microbiology

Dark life, microorganisms that live sheltered beneath the planet's surface, may be the most abundant form of life on Earth and quite possibly the universe. Experiments performed underground will be able to determine how these microorganisms alter their rock environment to survive, how they are able to migrate great distances through rock, and how they are able to evolve or adapt to slowly changing conditions. Because the biogeochemical processes in the deep subsurface have remained the same for billions of years, the key to understanding ancient cellular evolution may reside in the genetic expression of subsurface microbial ecosystems. The interactions of microorganisms with the geological environment also have practical applications, including the long-term sequestration of CO_2, containment of radioactive wastes and immobilization of toxic metal contaminants.

1.1.3. Earth Sciences

Understanding the mechanical, thermal, hydrological, chemical and biological processes operative in the deep subsurface, and the complex interactions between them, is the key to a better understanding of the evolution of the planet and how to live in harmony with it. The forces induced by tectonic plate motion, heat, and by gravity, carried in part by the solid skeletal structure of the rock and in part by the interstitial pore fluids, are distributed nonuniformly due to the heterogeneous structure of the rock mass. Changes in the solid/fluid force distribution can promote or inhibit earthquake slip. Fluids circulating through fractures in the rock and associated dissolution/precipitation processes can produce mineral deposits or trasport groundwater contaminants.

The paucity of in situ experimental facilities to test the validity of numerical models severely limits the ability to predict the long-term isolation of hazardous materials. DUSEL would overcome this obstacle. DUSEL models and technical developments can then be tested through shorter-range studies in subsurface industrial or government sites, where access for research is more restricted. It is no exaggeration to say that development of the DUSEL will permit a quantum jump forward for earth sciences and engineering research, development, and technology transfer. Regardless of the site(s) selected for DUSEL, access to a large, 3D exposure of the crust will provide important opportunities to study geological history of tectonic, sedimentary, or igneous processes. DUSEL will be unprecedented, however, in that geological models based upon observations can be tested by further underground exploration. DUSEL will therefore be an interactive geological experiment, much like an active mine, but with very sophisticated scientific observations.

1.1.4. Engineering and Rock Mechanics

Traditionally associated with the extractive mineral industries, underground engineering is being applied increasingly to novel uses, (mitigation of adverse environmental consequences of surface-based industrial activities (e.g., underground location of sewage treatment plants; geological isolation of nuclear and hazardous waste; carbon sequestration; geothermal energy; etc).

Virtually all of the research envisaged for DUSEL requires access to the subsurface via underground excavations. The stability of these excavations depends on how the strength of the rock mass deteriorates over time as it is exposed to the chemical environment in the excavation. Lack of research on this central question forces current excavation support design procedures to rely heavily on empirical rules of dubious validity. The influence on the deformability and strength of the rock mass of systems of joints and other scale-dependent weakening elements, often water bearing, is the major unknown, The long-term availability at DUSEL of a dedicated research site and excavation of various sizes of cavities will provide an unprecedented opportunity to undertake the research needed to resolve this major issue.

Geophysical techniques that effectively render the rock mass “transparent” would be a major advance in observing directly the heterogeneous and discontinuous manner in which jointed and fractured rock masses deform and how fluids move through them. Novel imaging procedures offer considerable promise but further development is possible and needed. DUSEL would greatly accelerate progress towards this goal. Depending on the setting and layout of the underground infrastructure, DUSEL may be able to accommodate seismological arrays to monitor earthquakes or electromagnetic arrays for whole earth signals. Studies of the interaction between the rheological properties of different rock formations and tectonic strain rates at depth can provide important insights into the distribution of stresses in rock, how underground observations compare with GPS surface data and how to accurately model large scale deformation.

Innovative proposals for research at DUSEL are being suggested and more are likely. It has been proposed, for instance, to conduct large-scale studies of cloud droplet and ice particle formation, growth, and interaction, in long vertical shafts at DUSEL.

1.2. Working groups

We have identified fourteen working groups and chosen two coordinators for each. All coordinators are well-known specialists in the considered disciplines:

1) Low-Energy Neutrinos: Tom Bowles (LANL) and Bruce Vogelaar (Virginia Tech)
   The principal experiment in this area will be a measurement of the low energy pp νs emitted by the Sun to measure the ν luminosity of the Sun. The group will also study measurements of geoneutrinos from the Earth's interior, of relic supernova νs as a constraint on the history of star formation in the universe, and of contemporary supernovae to understand the dynamics of gravitational collapse of a stellar core.
2) Neutrinoless Double Beta Decay: John Wilkerson (U. of Washington) and Charles Prescott (SLAC)
   Observation of neutrinoless double β decay would show that lepton number conservation is violated and that a matter particle, the ν, is its own antiparticle. If double beta decay occurs in nature, it is sensitive to a linear combination of neutrino masses, and can provide an important constraint on the absolute scale of neutrino masses.
3) Long-Baseline Neutrino Experiments: Milind Diwan (BNL) and Gina Rameika (Fermilab)
   A long baseline ν experiment in the DUSEL era will measure the "small" mixing in the ν sector and could determine whether matter/antimatter symmetry is violated in the ν sector. A detector for this experiment could be made suitable for studying nucleon stability.
4) Nucleon Decay/Atmospheric Neutrinos: Hank Sobel (UC Irvine) and Chang-Kee Jung (Stony Brook)
   Observation of nucleon decay would be an indication of important physics at energies well above those attainable with accelerators. A nucleon decay detector that is multipurpose would have sensitivity to some of the low energy neutrino physics studied by Working Group 1.
5) Dark Matter: Dan Akerib (Case Western Reserve U.) and Elena Aprile (Columbia U.)
   This group will not only focus on the searches for dark matter but will attempt to identify other uses of underground space for cosmology and gravitational physics
6) Nuclear Astrophysics and Underground Accelerators: Michael Wiesher and Joachim Goerres (U. Notre Dame)
   This group will study the potential for making important measurements for nuclear astrophysics that require a small particle accelerator and very low backgrounds. The measurements made will be applied to the understanding of nuclear reactions and other processes in stars.
7) Coupled Processes: Brian McPherson (New Mexico Tech), and Eric Sonnenthal (LBNL)
   Building on our current understanding of petrology, hydrology, geochemistry and geomicrobiology, this group will focus on understanding the interactions that must be considered to explain many of the phenomena observed in geological processes.

8) Rock Mechanics/Seismology: Larry Costin (SNL), Paul Young (U. of Toronto)
   This group will study how to integrate studies of rock deformation and stability and whole earth geophysical studies with the development of the DUSEL.
9) Applications: Francois Heuzé (LLNL), Jean-Claude Roegiers (U. Oklahoma)
   Use of the subsurface includes many traditional (e.g. mineral extraction) and an increasing number of novel applications. This working group will examine opportunities for research in DUSEL to advance these uses.
10) Geomicrobiology: Tommy Phelps (ORNL), Tom Kieft (New Mexico Tech)
   This group will investigate microbial community composition and dynamics, microbial physiologies and abiotic-biotic interactions, as well as pioneer the sampling strategies and insure contamination control.
11) Microbial Biology and Evolution: Jim Fredrickson (PNNL) and Nancy Moran (U. Arizona)
   This group will focus on the fundamental questions involving molecular evolution, cellular and molecular biology, systems biology, and ancient molecules.
12) Low-Background Counting Facilities and Prototyping: Prisca Cushman (U. Minnesota) and Harry Miley (PNNL)
   Many experiments that will be performed at DUSEL require materials with very low trace radioactivity. Assays of these materials and construction of prototype detectors can only performed in an underground facility. The group will also explore other applications, such as earth sciences and national security.
13) Infrastructure requirements and management: Lee Petersen (CNA Engineers), Derek Ellsworth (Penn State U.), and David Berley (U. Maryland)
   This group will define and analyze the infrastructure requirement matrices, paying attention to the commonality and differences between physics, earth science, biology and engineering and extract from these data the generic requirements for laboratory layouts underground and common infrastructure. A subgroup will deal with generic principles of management of the laboratory.
14) Education and Outreach: Willi Chinowski, (LBL) Susan Pfiffner (U. of Tennessee).
   We have specifically chosen scientists to coordinate this working group, as we believe it important to involve scientists in the E&O effort from the beginning. The group will also enlist help of professional educators.

The charge of these working groups is to

- Summarize the scientific opportunities: What are the big questions that can be addressed by DUSEL in a unique way?
- Develop roadmaps establishing the likely evolution of the subfields and the succession of generic experiments or experimental/observational facilities. The working groups will obviously look into the results of previous workshops and reports and focus on missing components—important aspects not yet studied, points of disagreements, etc. Very likely, these will be the medium- and long-range projections.
- Participate in the definition of the infrastructure requirement matrices and fill them for each discipline.
- Work with other working groups to identify "modules" (set of generic experiments with similar or compatible infrastructure requirements).
- Identify within each discipline the most significant education and outreach opportunities.

It is clear that the work and needs of many working groups strongly overlap and that the groups will benefit from common meetings. For instance, the dark matter and neutrinoless double beta decay searches face very similar low radioactivity and neutron background issues, and their infrastructure needs are substantially the same as those of some solar neutrino experiments studied by Group 1. It is likely that the long baseline neutrino program and the nucleon decay will share the same sets of very large detectors (megaton water Cherenkov and/or hundred-kiloton liquid argon). The design of these large detectors will most certainly attempt to allow their use for solar neutrino and neutrino from supernovae collapse. In the earth sciences arena, substantial overlap exists between coupled processes, rock mechanics and geomicrobiology. This list of working groups may be extended or modified according to needs, and a number of sub-groups will undoubtedly be spawn during the process.

1.3. Workshops

In order to bring together this large and cross-disciplinary community, we are proposing a series of workshops, in addition to the one held in Berkeley, August 11–14, 2004 (see Supplementary Material):

1.3.1. Earth science workshop in November 2004.

A consensus emerging at and after the Berkeley workshop has been that earth scientists need a workshop by themselves (to be financed in part by the use of the 90-day pre-award expenditure clause) as soon as this fall. The purpose of this workshop would be to start constructing scientific roadmaps for the deep underground earth science research and identify a series of generic experiments and experimental or observational facilities. Because of the DUSEL history, there has been less time for these discussions among scientists in the geology, biology, and engineering fields than in the physics/astrophysics community. Having a specialized workshop before the general meeting described below will help the earth science communities to find a common voice and better define their infrastructure needs.

1.3.2. General workshop in January 2005

Preliminary conclusions of the working groups will be presented at a workshop to be held at a central location, possibly Denver. We envision five focal points:

- Engaging a broad cross-section of biologists specialized in evolution, cellular and molecular biology, genomics, proteomics, and system biology;
- Aligning the conclusions of the working groups and amplifying common themes and synergies;
- Identifying cross-disciplinary modules, based on the roadmaps elaborated by the working groups and the corresponding infrastructure-requirement matrices
- Discussing generic laboratory infrastructure needs
- First look at the likely evolution of the demand for underground facilities

1.3.3. Conclusion workshop in March 2005, in the Washington DC area

This workshop will focus on the overall conclusions of the study and streamline the overall message—big questions, broad modules, priorities, generic needs for common infrastructure, and organization. We are considering organizing this workshop in College Park, MD, to allow the program officers from NSF and other federal agencies potentially involved easy access.

2. Infrastructure Needs, Modules, and Generic Laboratory Characteristics

Determination of infrastructure requirements, modules, and generic laboratory characteristics follows naturally from the science and engineering research program. The principal steps in the process are:

- Collect technical requirements for the various scientific and engineering research to be conducted at DUSEL
- Identify primary technical requirements
- Identify technical requirement relationships
- Develop the relationship matrix
- Develop relationship diagrams indicating modules

The middle three steps are the linkages between the technical requirement of the first step and the module development of the last step. Additional details may be found in Section 2.1 below.

In order to provide a strong evaluation of needs and requirements, we are proposing to involve as collaborators, engineers familiar with the technical details of underground laboratories, even though we will have to pay for their services. The engineering team, selected with the approval of the Site Consultation Group (see 4.2. below), will be led by Lee Petersen. As a member of Charles Nelson & Associates (CNA) Consulting Engineers, a well-known underground engineering firm, Mr. Petersen has a unique experience in the engineering of underground research laboratories. The consortium he has set up with Dale Holland of Dunham Associates Consulting Engineering and Greg Hulne of Miller Dunwiddie, Architects brings together a full range of expertise in civil engineering, mechanical/electrical engineering, and architecture needed to map the technical requirements for a deep underground science and engineering laboratory. Members of this team have a long history of collaboration with scientists. They have been active in the design of the presently operating laboratories at the Soudan and Sudbury mines and are contributing to the studies of the infrastructure for prospective underground sites—Icicle Creek, San Jacinto, and Kimballton. We believe that their personality and involvement in multiple studies guarantee their objectivity.

2.1. Infrastructure requirement matrix

The infrastructure requirements and other design criteria for the various science and engineering components of the research program must be collected from the working groups and experiment developers. Following is a partial list of these requirements and design criteria:

- Occupancy
- Access from surface & from/to adjacent areas underground
- Depth/shielding and size/volume/shape of caverns
- Environment control; power, communications, lighting
- Special systems
- Containment
- Common / storing / staging / assembly / prototyping
- Rock environment

Experiment	Category	Depth / Shielding (mwe)	Space, area or volume (m^2 or m^3) l*w*h unless specified	Radon Background (mBq/m^3)	Hazardous Materials	Ventilation	Stable Temp. (A/C Reqd.)	Electrical Power (kW)	"Clean" Areas (class)	Special/Additional Facilities
MOON	Solar neutrino	>2500	11x8x6	10	Toxic, flammable liquids/cryogens			80	Yes	
LENS	Solar neutrino	>3800	16x16x16	1	Fammable scintillation			250	Yes	
HYBRID	Solar neutrino	7000	80x18x19	None	None			Modest	No	
HERON	Solar neutrino	4500	m radius, 20m high cyl	None	Large volume cryogens			600 Peak, 125 Avg.	Yes	
CLEAN	Solar neutrino	4500	5m radius, 20m high c	None	Large volume			100 Avg.	Yes	
TPC	Solar neutrino	~2500	30x21x21	1	High pressure gas/cryogens			70 Avg.	No	
Majorana	Double beta decay		5x4x3 m^3 4x4x3 m^3	<1000000	Rn, acids & plating baths from Cu electroforming		Yes	10 to 25	Yes	UG Cu electroforming facility, UG Ge crystal growth & detector, machine shop, low level counting, Rn-free matl. Storage, DI water system
EXO	Double beta decay		5x5x5 m^3 5x4x3 m^3 4x4x3 m^3	<1000000	Large volume liquid xenon/cryogens, Rn		Yes	10 to 25	Yes	Xenon containment, cryogenic purification system, machine shop, low level counting, Rn-free matl. Storage, DI water system
MOON	Double beta decay		5x8x5 m^3 8x11x6 m^3	<1000000	Rn		Yes	10 to 25	Yes	Machine shop, low level counting, Rn-free matl. Storage, DI water system

Some potential research areas have well-developed descriptions of specific experiments, while others are still in the concept phase. The infrastructure requirements and design criteria will be collected in a so-called infrastructure requirement matrix. A preliminary infrastructure requirement matrix is shown above.

This matrix contains information about six possible solar neutrino experiments and three double beta decay experiments (all information extracted from the Lead-workshop white paper [Lead, SD, 2001]). While a single row and column matrix is probably inadequate to represent information about all research areas and all requirements, the example matrix illustrates the kind of information that needs to be collected.

An important outcome of the Berkeley workshop was a clear understanding of the need to verify information. Previous experiences have shown that much of the information received must be independently verified. The CNA team will have a primary role in this verification.

2.2. The building of modules

In this context, modules are groupings of experimental functions with common, or at least compatible, infrastructure requirements and design criteria. Some physics experiment commonalities are obvious (e.g., amount of shielding, radon control and clean conditions), but determining commonalities and incompatibilities across all science and engineering disciplines requires a structured approach. We envision four steps:

- Identify primary technical requirements. We anticipate that the infrastructure-requirement matrices may contain more than 100 requirements and criteria. Hence, we must identify, for each research discipline, a short list (say, ten items) of primary technical requirements. Such primary requirements, essential to the experiment, would be difficult, costly or impossible to satisfy unless provided at the module level.
- Identify technical requirement relationships. In this step, we must integrate the individual experiment top-ten lists into a list of more than ten and less than twenty DUSEL-wide requirements. This integration will require close cooperation between the scientific working groups, PIs, and engineering team.
- Develop the relationship matrix. The relationship matrix is a graphical representation of the compatibilities and incompatibilities between experiments. Each experiment or other research endeavor is both a row and a column in the triangular relationship matrix, where each matrix entry indicates whether the experiments have a strong commonality, weak commonality, strong incompatibility, weak incompatibility or are indifferent.
- Develop relationship diagrams indicating modules. Once the relationship matrix is created, relationship diagrams indicating modules will be created.

2.3. Generic laboratory characteristics

An important aspect of a site-independent study is the recognition that there is more than one optimal solution. Obvious differences in approaches include: vertical vs. horizontal access, a single site vs. several sites, small experiments only vs. small and large, construction as you go vs. generic halls. The choice is not within the scope of solicitation 1, but the study will list a few generic scenarios with a number of self-consistent design criteria; for example, access dimensions and weight-carrying capabilities, number of people to move in and out, access hours, control of electric noise, vibrations, dust, generic cost of maintenance, etc. We will look into existing facilities in the world for guidance on requirements for administrative and technical support, for example, or scientists attached to the site.

We will also define the precautions that need to be taken during the exploration and construction phases to guarantee that at least some parts of the laboratory remain virgin for biology studies. We will also identify the instrumentation required to maximize the scientific return of the excavation itself for rock mechanics and engineering.

2.4. Need for R&D, low background counting facilities and underground construction and prototyping space

The low background counting facility should be one of the first facilities established in DUSEL so that it can contribute to the development and instrumentation of the experiments that are limited by backgrounds from trace radioactivity. A plan must be developed that will allow an early commissioning of this facility and a growth path to respond to the needs of experiments that will develop as DUSEL matures. The working group and construction experts will study the special requirements of this laboratory such as cleanliness, cryogenic capability, and chemical handling issues. It will also identify the facilities needed before DUSEL may be available, so that experiments can be ready when DUSEL starts.

2.5. Laboratory management

Finally, we propose to list a few characteristics of a management structure that are essential to ensure the optimal scientific output of the facilities, the handling of the multidisciplinary and international aspects, and the inclusion of education and outreach from the start of the program.

3. Uniqueness and International Context

We believe that this study must establish the need for a U.S. national underground facility (or set of facilities) in the international context. We are planning to approach this complex issue in three different ways, providing data necessary to frame the decision of the funding agencies.

3.1. Unique Characteristics

What characteristics would make a U.S. national underground facility, or set of facilities, unique? A preliminary list compiled at the Berkeley workshop include:

- The greatest depth in the world (if indeed available) for ultra-low high-energy neutron background experiments and for long-duration biological studies of microorganisms at large depth
- An underground site combining a very large detector and a neutrino superbeam
- An unprecedented long-term access for deep-site earth science observations, experimentation, including the possibility of "mining back" to check *in situ* the information provided by imaging and other remote-sensing methods.
- The strategic advantage of a U.S. national site in terms of leadership in frontier science, scientist training in frontier fields, engineering innovations (particularly in underground engineering), and involvement of U.S. industry and homeland security.

This preliminary list will have to be critically reviewed and expanded during the course of the study.

3.2. Evolution of the demand

Our current study will establish a catalog of possible experiments and their likely time scale. We will ask the working groups to include financial, manpower, and timeline information in the generic infrastructure matrix—the projected cost, likely number of U.S. and foreign scientists involved, anticipated start-up date, duration.

Obviously, summing these requests will lead to an overestimate of the likely demand for an underground space, as a number of experiments currently considered will not be funded within a reasonable extrapolation of the funding and the number of scientists available, or the currently envisioned timescale may be overly optimistic. However, with the collected estimates of cost and people, we can recalculate the numbers to bring them within the bounds of the possible. We will also have to make provisions for unforseeable future experiments in the long-term planning. In sum, this exercise will give us a handle of the likely evolution, with no doubt large error bars.

We will consult with the Particle Physics and Astrophysics Research Council (PPARC), which is conducting a similar study in the UK, and the directors of the National Gran Sasso (Italy) and Modane (France) laboratories.

3.3. International context

Once we know the likely demand, we will be able to estimate how this demand can be split between the various facilities worldwide. The first step is to summarize the capabilities of the existing facilities worldwide and their current extensions. We will then have to factor in the fact that second- and third-generation experiments are likely to be very international. For instance, it is difficult to imagine more than one 1-ton ^{76}Ge double β experiment. Comparison with the international evolution of accelerator and large astrophysics experiments and large earth science projects will be used as a guide.

The combination of these three points—the uniqueness of a U.S. facility (or facilities), growing demand, and intellectual collaboration with the facilities worldwide—should present a strong argument to NSF for the establishment of a U.S. deep underground laboratory.

4. Management of the proposed study

A key question is how to guarantee that the NSF-granted six-month project (probably December 2004 through May 2005) will present a fair and unbiased science case that is acceptable to all the competing sites and all scientific fields but is not watered down to the lowest common denominator. The following is our plan of organization:

4.1. The PI team: the Science Executive Committee

We have formed a Science Executive Committee composed of the six principal investigators, who have widely recognized science credentials and community consensus-building experience. Collectively, they represent geographic and institutional diversity of the community involved and a broad cross-section of the scientific fields. After consultation with the EarthLab Steering Committee, we have decided to have two earth science representatives among the PIs: Charles Fairhurst for geology and related engineering applications; and Tullis Onstott for geomicrobiology, a flagship program for DUSEL. We have also involved a prestigious microbiologist James Tiedje, to stimulate the interest of the microbial, cellular, and molecular-evolution communities about the exciting opportunities offered by DUSEL.

It was generally felt that in order to gain full confidence from the community, the Science Executive Committee members should not be strongly associated with any site (i.e., they should not be members of a site-specific proposal team in the NSF competition #2) but be acceptable nonetheless to each of the site teams. The members of the committee will be responsible for the coordination of the project and for guaranteeing the excellence of the science and fairness of the process (with respect to the sites and the disciplines). As co-investigators, they will answer directly to NSF.

4.2. Working groups and working group coordinators

As described above, we are organizing a number of scientific working groups. Each working group will be led by two scientists (or engineers), recognized specialists in their field, who should complement each other as closely as possible in terms of technical requirements, institutions, geography, and site involvement. It is not essential that they be site-attachment free, but, as we are striving to have a balance that guarantees a site-independent report, that they be committed to objectivity. The coordinators will

- Lead the working-group activities between August 2004 and June 2005, communicating with all scientists involved in the group through emails, websites, and conference calls, and by organizing discussions at workshops.
- Inform all Solicitation 1 participants about conclusions, as they develop, and coordinate with the PIs by holding regular phone meetings.
- Coordinate the draft writing of the relevant segment of the final study report (typically three pages per discipline), including technical appendices (e.g., technical requirement matrices) and web-based reference materials (expected to be around 30 pages).
- Interact with the report-writing team (which will include scientists and a scientific communicator).
- Answer the questions raised during the NRC-style review of the final report.

Up to three delegates from each site team, including at least one physicist and an earth scientist, will form a Site Consultation Group. The group will give input and participate in various stages of the process—choice/veto of the PI/coPIs, handling of different options, proposed scientific and priority choices, equal treatment of the sites, etc. The Site Consultation Group will have access to all information and will provide the PI team with their comments on the final report. (It also has had full access to and opportunity to comment on this proposal.) The Site Consultation Group does not, however, oversee the writing of any documents of the study, in particular those of science or facility requirements, lest the site-independent document appear to be unduly influenced. We do not want, though, to water down the final report, and the Solicitation 1 PIs should remain free to make any scientifically based recommendations, even if they may tilt the balance in the funding agencies' subsequent choices.

The current composition of the Site Consultation Group is as follows:

Cascades: Wick Haxton, John Wilkerson (U. of Washington), Phil Long (PNNL)
Henderson Mine: Chang-Kee Jung (SUNY Stony Brook), Mark Kuchta (Colorado School of Mines), and Bob Wilson (Colorado State U.)
Homestake: Kevin Lesko and Willi Chinowsky (LBNL/UCB)
Kimballton: R. Bruce Vogelaar, Bob Bodnar (Virginia Tech), and Tommy Phelps (ORNL)
San Jacinto: Hank Sobel and Bill Kropp (UC Irvine)
Soudan: Marvin L. Marshak and Earl A. Peterson (U. Minnesota)
Sudbury: Andrew Hime (LANL) and David Sinclair (Carleton U.)
WIPP: Roger Nelson and Lloyd Piper

4.3. Initiative Coordination Group

In a similar fashion, we propose to constitute an Initiative Coordination Group, with the national labs and other institutions, to help align the DUSEL study with major national initiatives, often supported by other federal agencies. Typical examples of potential initiatives that interact strongly with DUSEL include: long base neutrino supported by the Department of Energy (DOE), in which both Fermilab and Brookaven National Laboratory are interested; the new "Secure Earth" initiative in which a rapidly growing number of national laboratories are involved; and low radioactive background counting, promoted by the Pacific Northwest National Laboratory. A number of the DOE labs have strong interest in underground science.

The goal of the Initiative Coordination Group, (acting also as consultative body), is to prevent negative interaction between DUSEL and these initiatives, and to point out possible biases in the study; that is, unsubstantiated statements, which appear to favor one institution, site, or one version of an initiative over another, without deep scientific reasons. We believe that this group will also have a powerful influence on making other federal agencies interested in the DUSEL initiative, which, under the directives of OSTP, is coordinated by NSF.

The group's currently participating institutions and corresponding representatives are:

BNL – Tom Kirk and Nicolas Samios;
Fermilab – Kenneth Stanfield and Hugh Montgomery; and
LBNL – G.S. Bodvarsson and James Symmons.

We are in the process of inviting LANL, ORNL, PNNL, and SLAC to participate in this group.

The Initiative Coordination Group will usually meet together with the Site Consultation Group and the PI team either in person or by telephone. However, the Site Consultation Group has asked for the option of meeting alone with the PIs to discuss, for example, unresolved matters of rivalry between the sites.

4.4. NRC-style final review

As a further guarantee of the objectivity of the final report, we intend to have an external review process in the style adopted by the National Research Council; that is, two months before the submission of the final document, the Science Executive Committee will ask a number of referees to comment on a final draft, and the various working groups will be asked to respond to objections or modify their text according to the referees' recommendations.

4.5. Administrative management

The proposed grant will be administered by the Institute for Nuclear and Particle Astrophysics and Cosmology (INPAC), an official multicampus research unit of the University of California, headquartered in Berkeley and directed by Bernard Sadoulet. It will provide a convenient management location for the study and a small staff accustomed to contacts with other universities, consultant agreements and subcontracts, education and outreach events, workshop organization, and travel reimbursements.

We do not believe that this will prejudice the study in any way. INPAC researchers in the field of particle astrophysics are from the eight UC campuses and the three national laboratories managed by the University of California. These scientists have a diverse set of scientific interests and they are involved in at least five of the eight sites currently interested in the competition.

5. QUALIFICATION OF THE PRINCIPAL INVESTIGATORS AND RESULTS OF PREVIOUS SUPPORT

Eugene W. Beier served for nine years as the principal investigator of a ten faculty–member grant from the Department of Energy. For the past fourteen years he has been co-spokesperson (with Hamish Robertson) of the United States scientists participating in the Sudbury Neutrino Observatory project. He has been Chair of the American Physical Society's Division of Particles and Fields, as well as a member of the DOE/NSF High Energy Physics Advisory Panel (HEPAP), Particle Physics Project Prioritization Panel (P5), the Scientific Assessment Group for Non-Accelerator Physics (SAGENAP), the International Committee on Future Accelerators (ICFA), and a number of National Research Council panels and sub-panels.

Charles Fairhurst has expertise in rock mechanics, mining engineering and underground construction, and design of high level nuclear waste repositories. He has been a major leader in developing the field of rock mechanics, having introduced the first formal graduate-degree program in rock mechanics in the U.S. in 1958, at the University of Minnesota. He served as President of the International Society for Rock Mechanics from 1991-1995 and was founder-President of the American Underground-Space Association (AUA), now the U.S. representative in the International Tunnelling Association. He founded the interdisciplinary Underground Space Center at the University of Minnesota in 1976 to examine scientific, technical, social and psychological aspects of underground space use and occupancy. In 1982, he founded Itasca Consulting Group Inc, which is now the international leader in numerical modeling codes for geo-mechanics. He is a member of the U.S. National Academy of Engineering and the Royal Swedish Academy of Engineering Sciences.

T.C. Onstott has spent the past 10 years focusing on subsurface biogeochemical processes, initially as a scientific investigator in DOE's Subsurface Science Program. For the past 6 years he has lead an NSF/NASA supported multi-institutional investigation into deep subsurface microbiology utilizing the ultradeep gold mines of South Africa. Simultaneously, he established a DOE supported multi-institutional field site for bacterial transport and biostimulation within an aerobic and anaerobic shallow aquifer. He currently is co-lead investigator of the NASA supported astrobiology center investigating permafrost/subpermafrost microbial processes in an Arctic gold mine.

Hamish Robertson is the Scientific Director of the Center for Experimental Nuclear Physics and Astrophysics at the University of Washington. He is co-spokesperson (with Eugene Beier) of the United States scientists participating in the Sudbury Neutrino Observatory project and was Scientific Director of the project during 2003–2004. He has been Chair of the American Physical Society's Division of Nuclear Physics, as well as Chair of the DOE Nuclear Science Advisory Committee (NSAC), a member of the Scientific Assessment Group for Non-Accelerator Physics

(SAGENAP), and a member of a number of National Research Council panels. Dr. Robertson is a member of the National Academy of Science and a Fellow of the American Academy of Arts and Sciences.

Bernard Sadoulet works at the interface between cosmology and particle physics. In the last 20 years, he has focused on the search for Weakly Interactive Massive Particles (WIMPs), which may constitute the dark matter in the universe, and on the development of the novel low-temperature detection technologies needed for this task. He is the spokesperson of the NSF/DOE Cryogenic Dark Matter Search (CDMS) experiment, which is currently running in the Soudan mine and has recently published the best WIMP limit in the world (by a factor of 4). He was the director of one of the first generation NSF Science and Technology Centers—the Center for Particle Astrophysics—which had a profound impact on the measurement of the cosmic microwave background, the detection of dark energy and the search for WIMPs. He has served on numerous NRC committees dealing with particle astrophysics (most recently, on the Turner Committee), the Scientific Assessment Group for Non-Accelerator Physics (SAGENAP), and on the Scientific Committee of the Gran Sasso underground laboratory in Italy. He was a member of the Bahcall Committee on Underground Science.

James Tiedje has expertise in microbiology, especially in diversity, phylogeny, genomics and physiology. He has been a major leader in developing the field of microbial ecology, served as the first President of the International Society for Microbial Ecology, is the current President of the American Society for Microbiology, and serves on the NRC Board on Life Sciences. He has developed and still leads the multidisciplinary Center for Microbial Ecology, one of the original NSF Science and Technology Centers. This center shaped the field of microbial community dynamics, arguably lead the field of experimental evolution, automated and advanced the ribosomal database, the world's major tool for microbial phylogeny and identification, and, on the application side, provided the pace-setting field tests of bioaugmentation for clean-up of solvent contaminated aquifers. Relevant to the DUSEL project, he co-leads a joint project with a multidisciplinary U.S.-Russian team to explore the genomic basis of microbial adaptation to life in ancient Siberian permafrost.

6. Broader Impacts

This six-month study will have broader impacts than just the study of the characteristics needed by an underground laboratory. It will broadly advertise the unique opportunities of DUSEL. Ten abstracts have been submitted to the American Geophysical Union (AGU) December meeting. A DUSEL session will take place at the American Physical Society April meeting. We are requesting sessions at the spring meetings of AGU and the American Society of Microbiology. The study will also connect naturally with the underground science workshop organized at the Institute of Nuclear Theory in June and July 2005.

6.1. Multidisciplinary Science

Building on the first contacts of NeSS 2002, the Berkeley workshop continued to demonstrate the intense intellectual vitality of scientists from different fields gathered around the same project. The study provides an exciting opportunity for the physics, earth, and biological science communities to explore new interfaces.

This is particularly true in biology. Going beyond the small group of geomicrobiologists, whose pioneering work revealed that the subsurface is alive and with sometimes novel microbes, we will involve a much broader biology community with expertise in evolution, cell and molecular biology, genomics and proteomics, and systems biology. It is not often that biologists get to explore new frontiers in the field. DUSEL can provide such an opportunity and engage many disciplines of contemporary biology to probe the new ways these unique populations have succeeded. Equally important are the expected interactions among the various earth scientists and biologists. The understanding of the subsurface ecosystem is a result of the interplay of conditions, chemistries, and catalysts. The study will inspire new introductions among scientists around a new knowledge frontier, and will lead to new collaborations and insights.

6.2. Involvement of private industry and other sectors

Major opportunities exist for industry participation (worldwide) in DUSEL. Thus, the ability to have simultaneous surface and a large underground volume access offers unprecedented opportunity for improvement of petroleum technology, both in exploration and in production. Although sedimentary rock formations will be more favorable for some applications, there are many opportunities in other rock types, e.g., correlation of underground observation of hydraulic fracture propagation, using acoustic emission sensors, with surface tiltmeter measurements. Directional-drilling control techniques could be perfected; drill-bit induced vibrations could be studied directly at depth using surface drill rigs. The National Institute for Occupational Safety and Health (NIOSH), responsible for health and safety mines, would have opportunities not currently available to it. The Department of Energy OCRWM (Office of Radioactive Waste Management) could find DUSEL more convenient for R&D studies (e.g., drift degradation research) during the next two decades or so, when activities at Yucca Mountain focus on repository construction. Excavation equipment manufacturers could use DUSEL for equipment research. The Department of Defense is interested in underground excavation studies for a variety of purposes. Homeland Security would also be interested in the attributes of underground excavations for a number of applications. DUSEL will be an internationally unique facility and is likely to draw research interest from a wide community of potential users.

6.3. Education and outreach

The Berkeley workshop demonstrated a broad consensus among physicists, earth scientists and engineers that education and outreach (E&O) should be incorporated from the start in the design, construction and operation of the Deep Underground Science and Engineering Laboratory. The fascination with our universe—the cosmos, our planet, life, and elementary components of matter—offer DUSEL an exceptional opportunity to provide a unified program that integrates education and outreach (E&O) with the multidisciplinary research accomplished underground. As already emphasized in both the final report of the International Workshop on Neutrinos and Subterranean Science [NeSS 2002] and the EarthLab Plan [2003], DUSEL will give educators, students, and the public the opportunity to experience working science-facilities in ways that advance their knowledge and understanding of science and technology, and change their attitudes toward learning. DUSEL has, therefore, great potential to educate and mentor the next generation of scientists and teachers from diverse backgrounds.

Our study will address the following questions: (1) How should E&O be organized to reach local and national communities? (2) What are the challenges for DUSEL to effectively contribute to workforce and diversity development? (3) How do we identify and commit local and national partners to engage actively in education and outreach? (4) How should local populations and underrepresented minorities be recruited into DUSEL science? (5) What kind of infrastructure is needed to bring people to the site, and the site to the public? (6) How should the underground facilities be made attractive and stimulating? (7) How can tours and local housing be arranged for officials, media, participating research students and scientists? And, (8) how should E&O activities be designed so that they provide support in coordination, logistics, mentorship, and materials to students, scientists, and the community?

DUSEL will thus provide an opportunity for the scientific and engineering community working alongside education specialists to build a solid and lively E&O program. It will deepen our understanding of how to articulate such program in the broader efforts to improve our education system and general understanding of science, and how to develop more effectively a larger and more diverse workforce.

We also propose to experiment during this study with teleconferenced cross-disciplinary, multi-institutional seminar for graduate students and postdocs. We are planning a deep science and engineering lecture series at UCB in spring 2005, fully webcast and with internet-based multi-way teleconferencing capabilities. Our goal is to broaden the education of next-generation underground scientists and engineers and enhance interactions between physicists and earth scientists. This could be a prototype of DUSEL contribution to graduate education.

6.4. Involvement of local institutions and communities

The success of DUSEL will depend on the partnerships built with the local institutions, schools, industries and community organizations. These partnerships will not only advance the construction of the laboratory, but also contribute to the economy of and science education in the local communities.

The opportunities are particularly rich in the education area. The possible location of the site(s) in less-developed parts of the country and/or close to Native American communities will likely enhance the impact of the E&O programs. In any case, DUSEL should fully involve local minority serving institutions.

7. Conclusions

At the end of this complex process, we will attempt to deliver a fairly simple message. We will try to identify the "big scientific questions" along the provisional theme of "illuminating the dark side of the earth and the cosmos." We will define the scientific activities at the underground frontier—the most sensitive detectors searching for the most feeble signals from matter and the universe, the deepest observatory of the earth crust and of the dark life it contains, the most flexible "sand box" to gain mastery of the rock. We will characterize the likely impact of the DUSEL enterprise on society; for example, the training of the next generations of scientists and engineers, the strategic importance of a U.S. DUSEL, and the opportunities for international partnerships.

We will also strive to come up with a simple set of benchmarks and recommendations along the following lines (yet to be critically reviewed):

- Unique characteristics for a DUSEL site or set of sites
- Flexibility/evolution/expansion
- Multidisciplinary science and organization
- Need for R&D and prototyping (pre-DUSEL, at DUSEL)
- Control of laboratory management by the scientists—unrestricted access for non-U.S. nationals
- NSF leadership, multiple-agency involvement
- Single site or multiple sites under the same management umbrella
- Education and outreach included from the start
- Partnership with local community/institutions (and minority-serving schools)
- International coordination

Our goal is to define a viable path that does not bog down the process in overcomplex requirements, which would make establishing DUSEL an administrative nightmare or a too expensive proposition. It is in this context that we stress the importance of defining modules, sketched to show how a phased development could take place, and identify, when possible, an initial suite of generic experiments.

Finally, we see this study as a partnership between the scientific community and NSF, where we try to develop together the right concepts for the underground adventure.