4 Homestake Project Goals and Requirements

The Homestake project goals are primarily determined by the scientific roadmap for the facility and, in the first phase of DUSEL, by our proposed DUSEL Initial Suite of Experiments selected from the science and research topics delineated by the NSF S-1 Process [12]. The path to establishing the Initial Suite of Experiments to be included in the DUSEL Major Research Equipment and Facilities Construction (MREFC) application will ultimately require input and review by national review committees, as well as negotiations with funding agencies, including the National Science Foundation, the Department of Energy, and other agencies such as Department of Homeland Security and NASA. Though the MREFC proposal will be submitted separately and later, the scientific program must be considered now, because the fundamental properties of the host facility will influence the choice of experiments. The type of rock, size and capacity of the facility, and interferences and limitations imposed by potential shared uses need to be assessed. The experiments, in turn, influence the facility infrastructure, management, and operations requirements. In all the world, the Homestake site has unique advantages in high-quality siting of an impressive suite of scientific experiments and uses; Homestake DUSEL is designed to meet, and in most cases exceed, the S-1 requirements.

Central to our proposal for DUSEL is that the selection and development of the facility will be driven by the science. In our case, this will evolve from ongoing efforts at Homestake, initially funded by the State of South Dakota. The process of determining the scientific and educational uses for this "Homestake Interim Laboratory" has helped tremendously in establishing DUSEL's science requirements. Homestake Interim Laboratory is providing required underground space for scientific uses, and represents the first multi-disciplinary research facility of its kind

Under this state funding, we have established the functions necessary to

- solicit users with calls for Letters of Interest (LOIs),
- from the resulting response to the call, gather specific facility and operations requirements and collect them into a requirements database based on specific experimental proposals,
- evaluate the scientific proposals and match them to the facility, and
- establish preliminary roadmaps with reasonable estimates for timescales, depth and size requirements, and other facility requirements.

This ongoing work provides a head start on providing the required elements for the NSF-supported DUSEL facility.

4.1 The Homestake Interim Laboratory's Early Implementation Program

The closure of the Homestake Mine was announced in 2000. The mine was then prepared for closure and abandonment. This included a thorough cleanup and inspection by the U.S. Environmental Protection Agency through the South Dakota Department of Environment and Natural Resources. This inspection confirmed that the closure conformed to environmental and safety regulations. The facility was capped and sealed in 2003 and efforts were taken by Homestake Mining Company to preserve much of the infrastructure for subsequent use as an underground laboratory.

After capping, pumping of the natural inflow of water ceased and water began to accumulate. Flooding would reach the 4850 Level and its associated infrastructure in ~ 2008 if no action were taken. To preserve the site for DUSEL, the Authority is undertaking actions to reenter the facility, reestablish safe access, and install pumps to preserve the 4850 Level, including rehabilitating the Ross and Yates shafts and conveyances, reestablishment of utilities, and establishing sumps and pumps to expel water.

To achieve these necessary preservation goals, the State was required to obtain title to the facility. An agreement in principle between Homestake Mining Company and the Authority led to the Property Donation Agreement [13] shown in Appendix A6. The State subsequently passed all the necessary legislation and funded a plan to convert the Homestake mine into an interim scientific facility down to the 4850 Level, with funds sufficient to operate the basic facility infrastructure for five years. A summary of the legislation [4] is included in Appendix A3. The resulting Authority-funded Homestake Interim Laboratory, with major developments on the surface and the 4850 Level, serves as the starting point for Homestake DUSEL.

The Authority and the Homestake Scientific Collaboration undertook a study to outline a science program that would be likely to benefit from facilities on the 4850 Level and that would fit within their operating resources. This program in advance of DUSEL is called the Early Implementation Program and will include physics, earth science, engineering and education. Infrastructure for the Early Implementation Program will be funded, initially and primarily, from Authority-controlled resources now totaling $116M.

Having obtained the resources necessary for the conversion and operation of Homestake, the Authority, working with the Homestake Principal Investigators, issued a call for Letters of Interest on 1 November 2005. The solicitation for scientific and educational uses of Homestake, concentrated on, but was not limited to, the Homestake Interim Laboratory at the 4850 Level. Some 85 responses were received. These Letters of Interest span the disciplines of earth science, physics, education and outreach, engineering, biology, and homeland security.

A scientific Program Advisory Committee was established jointly by the Authority and the Homestake Principal Investigators. This standing committee's charge was to evaluate the Letters of Interest and establish recommendations for an Early Implementation Program of the highest scientific quality; to assist in planning for the reentry and rehabilitation of the facility; and to advise on staging the development of the Homestake facility. The Early Implementation Program comprises a phased path into DUSEL's Initial Suite of Experiments. To evaluate the Letters of Interest, the Program Advisory Committee heard presentations at the February 2006 workshop in Lead, South Dakota and held subsequent deliberations on conference calls and in face-to-face meetings. The collection of Letters of Interest, the membership of the Program Advisory Committee, evaluation criteria, committee charge, and final report are available through the Homestake Portal http://www.lbl.gov/nsd/homestake/ [14]. The Program Advisory Committee report [15] is included in Appendix A7.

The recommendations of the Program Advisory Committee and the shape of the Early Implementation Program are based on additional interactions between the Letter of Interest proponents and the Authority to optimize the requirements and match them to Homestake resources and capabilities. Following the first solicitation for Letters of Interest and the Program Advisory Committee report, we negotiated with several proposed experiments that are strong candidates to be included in the DUSEL Initial Suite of Experiments, or which would provide key infrastructure elements to DUSEL. We have developed or are in the process of developing Memoranda of Understanding between these collaborations and Homestake. Several of these users represent R&D work for major experiments. Several Memoranda are with technologically advanced experiments that will be ready for deployment in the coming years. The Early Implementation Program will include world-class physics, earth science and engineering endeavors integrally linked to education and outreach efforts centered at Homestake.

The Early Implementation Program will focus on the Homestake Interim Laboratory, primarily on the 4850 Level, the drifts connecting the Yates and Ross shafts, associated surface facilities included in the transfer and additional levels identified by the earth sciences community as being of particular interest.

The Early Implementation Program provides an opportunity to obtain time-critical data from Homestake while the facility is being reopened, including studies of the impact of flooding on the rock and living organisms—a rare and one-time-only opportunity to obtain knowledge that would otherwise be lost. Additionally, experiments benefiting from early access will develop techniques and prototypes so that they can rapidly produce scientific results as part of the DUSEL Initial Suite of Experiments. In particular, several of the physics experiments fit into this category. Several experiments require low background counting facilities and the development of ultralow background materials. A program to develop these screening facilities is included in the Early Implementation Program. Development will continue with access to the 300 Level in the early stages of DUSEL, where low activity materials can be produced for several collaborations.

In the following sections we present roadmaps for the disciplines and experiments expressing interest in DUSEL for both early and long-term utilization of the facility. The progression for many includes an initial component in the Early Implementation Program, an expansion into the DUSEL Initial Suite of Experiments, and subsequent development in later phases of DUSEL.

Several disciplines or experiments were not well suited to be included in the Early Implementation Program (requiring significant additional research and development); some of these are included in the DUSEL Initial Suite of Experiments, assuming the development can be completed in the pre-DUSEL years.

A few experiments will involve significant investment and development, requiring a commitment on a national scale. For these experiments, initial engineering and design steps are accommodated in the Early Implementation Program or initial phases of DUSEL while the cases for these experiments are developed and the experiments undergo further refinement and review. The Early Implementation Program permits this refinement and review to occur without a significant schedule penalty.

4.1.1 Program Advisory Committee Report

Following accepted practice at both accelerator and non-accelerator laboratories around the world, we formed a Program Advisory Committee composed of outside scientific experts to judge and aid in the formation of an Early Implementation Program of the highest scientific quality. The Homestake Program Advisory Committee was asked to review the Letters of Interest received prior to the announced cut off date. The committee was composed of Professors Frank Sciulli, Columbia, and Derek Elsworth, Pennsylvania State University, co-chairs; Sookie Bang, South Dakota School of Mines and Technology; Derric Iles, South Dakota Geological

Survey;, Ed Kearns, Boston University; Josh Klein, University of Texas; Bill Marciano, Brookhaven National Laboratory; Harry Nelson, UC Santa Barbara; Chris Neuzil, U.S. Geological Survey; Bill Pariseau, University of Utah; Charles Ruch, South Dakota School of Mines and Technology; and Hank Sobel, UC Irvine.

The Program Advisory Committee developed a first draft of the science program for the Homestake Interim Laboratory recommendations to assist with the plans to rehabilitate the mine and to be included in the Conceptual Design Report submission in June 2006. The Committee considered infrastructure limitations and facility limitations in crafting their recommendations for the Homestake Interim Laboratory. While the initial Program Advisory Committee report focused on the Homestake Interim Laboratory, they considered and provided advice on longer-term roadmaps for Homestake.

In addition to the written Letters of Interest, we hosted an open meeting for the Program Advisory Committee where all the proponents were invited to present short papers on their proposals. The slides from these presentations were then posted at the Homestake Portal [14]. The presentations were videotaped and are viewable from the web at http://linnproductions.com/clients/homestake/ [16]. The Program Advisory Committee held several conference calls and a face-to-face meeting prior to drafting their report on 12 May 2006.

We anticipate issuing approximately annual calls for Letters of Interest. The Program Advisory Committee will be requested to provide additional assistance in reviewing requests for occupancy at Homestake and in developing Homestake's scientific programs. We include, below, conclusions and remarks by the Program Advisory Committee in presenting our DUSEL Initial Suite of Experiments. We envision this process will continue, perhaps in an expanded fashion, for Homestake DUSEL.

4.2 DUSEL Initial Suite of Experiments

The proposed Homestake DUSEL Initial Suite of Experiments encompasses many fields, disciplines and essentially all the efforts discussed in the S-1 report. We anticipate that many experiments will benefit from initial research and development phases in advance of the main experimental efforts. The research and development activities and deployment schedules are based upon the Letters of Interest, presentations to the Program Advisory Committee, and recommendations of the Program Advisory Committee. Many of the experiments will require additional input from the funding agencies and community planning processes. However, our inclusion of these experiments in our DUSEL Initial Suite of Experiments reflects the capacity of Homestake and our ability to accept experiments in a staged and evolutionary manner.

We present in Figure 4.1 a summary of the Early Implementation Program and DUSEL Initial Suite of Experiments proposed for Homestake, along with the approximate scheduling of the experiments and their depth requirements. This figure is representative of the expansive and diverse DUSEL Initial Suite of Experiments program, an aggressive timetable, and the approximate infrastructure requirements for Homestake's proposal. The full schedule and infrastructure requirements are discussed in subsequent chapters of this Report.

4.2.1 Particle and Nuclear Physics

In general, particle and nuclear physics experiments require well-shielded underground laboratories with substantial overburden to reduce cosmic rays and cosmic ray spallation products. These experiments frequently require excellent personnel access to the experiments.

In several cases these experiments benefit from the low concentrations of uranium and thorium in the surrounding rock and from radon-reduced air provided to the experiments.

4.2.1.1 Dark Matter

Perhaps the greatest problem in studying the universe is that we can only see about five percent of the material and energy in it [17].

The evidence is compelling that the matter-energy density of the universe is close to unity (in units of the closure density—that is, we need further theory and observation to learn whether it will expand indefinitely or, in the very long term, cease expansion and begin falling back in on itself.) Of that density, only ~5% or less can be attributed to matter composed of ordinary baryons—the kind of matter that we normally see and interact with. The majority of the remainder is made up of "dark matter" (~22%), which neither emits nor absorbs electromagnetic radiation but does have gravitational interactions, and "dark energy" (~65%), of whose properties we presently can only speculate.

The evidence for this belief that something (in fact, a great deal of it) must be there, even though we have not been able to observe it directly thus far, comes from a wide range of astronomy and astrophysics experiments, including studies of galaxy rotation curves, galactic clusters, gravitational lensing, large scale structure, cosmic microwave background radiation, Type Ia supernovae, and Big Bang nucleosynthesis. Taken together, these data provide the basis for a consistent cosmological interpretation. Within that cosmology, other properties can be attributed to the dark matter.

One property is that it is composed of particles that interact through the weak nuclear force. A significant population of these particles, often referred to as WIMPS (weakly interacting massive particles) is expected to be in our own galaxy, and therefore should be amenable to direct detection as the solar system moves amid it. This cosmological evidence is complemented by evidence from experiments and theory (e.g., supersymmetry) in elementary-particle physics that such particles should exist. Searching for and understanding WIMPS has emerged as one of the most important experimental programs in particle physics, astrophysics and cosmology.

These fields, which one thinks of as operating at radically different scales as well as with different research methods, have found tremendous common ground in recent decades; indeed, the search for the direct detection of dark matter is intimately connected and complementary to new particle searches at the soon to be operating Large Hadron Collider.

This is how we arrived at the rather counterintuitive idea that key answers to some astrophysics and cosmology questions may be found in deep underground research facilities rather than on mountaintops or in outer space. The evidence that we seek comes to us in the form of particles rather than light. Underground, we can improve the odds that particles will interact within the view of detectors, and we find quiet backgrounds against which to detect them.

Direct detection experiments for dark matter present extreme technical demands. Very low count rates are expected, and the recoils in the detector will be of very low energy (a few keV), so the experiments require low background environments and sensitive new detector technologies. Present limits have been set by using detectors of modest size (a few kilograms) with novel experimental techniques based on cryogenic crystals or liquids. Expectations of theoretical cross

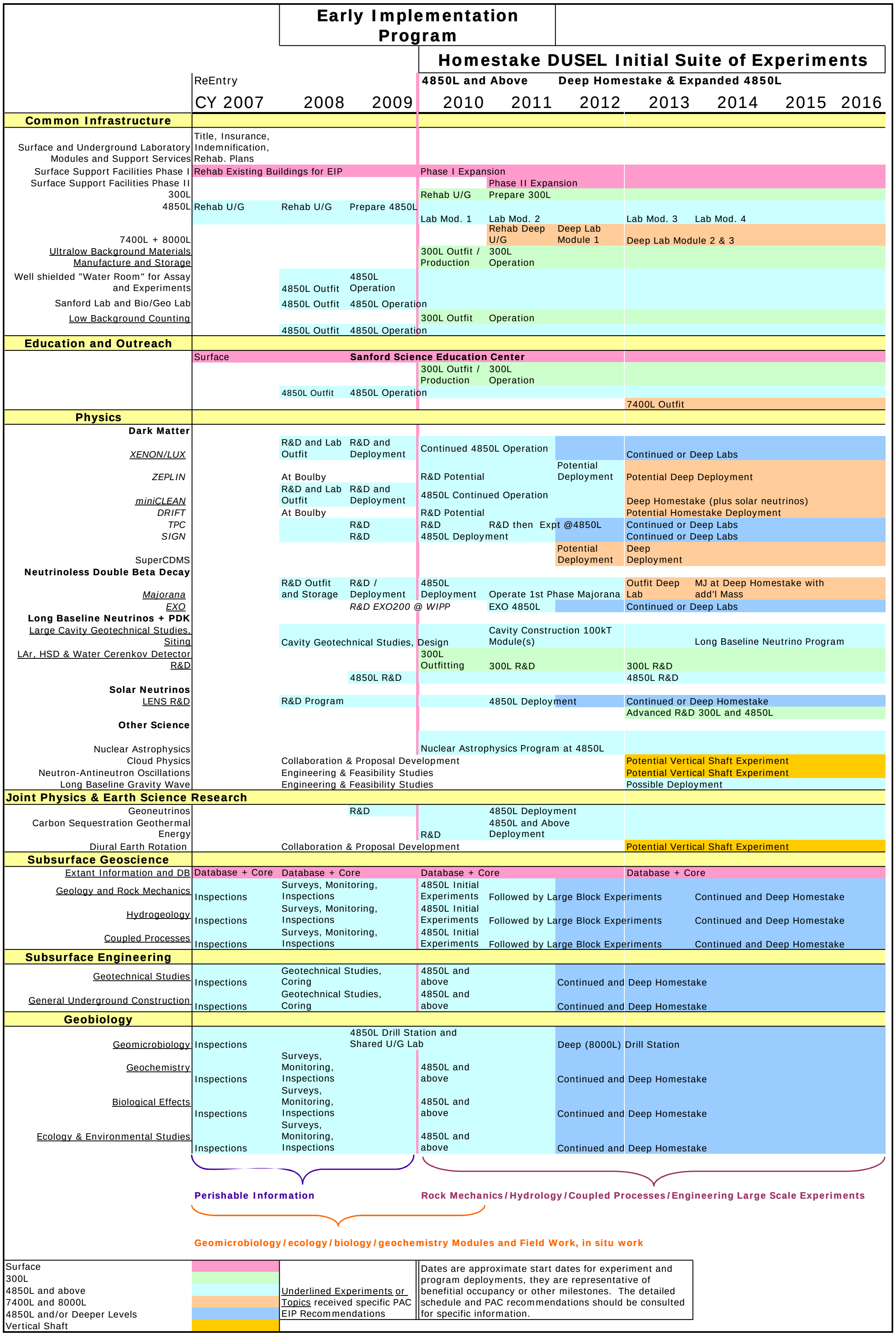

Figure 4.1 The Timeline of Homestake's Early Implementation Program and Proposed DUSEL Initial Suite of Experiments

sections are as low as 10^{-46} cm^2 (that is, the odds that they will interact with something are very small) so we must build detectors that are not only sensitive but also much larger. To achieve this, research and development will be needed in both detector and low background technology. A summary of the recent progress by several experiments is presented in Figure 4.2.

Because of several unique features, Homestake is poised to provide excellent facilities for dark matter programs, providing results on a time scale much faster than previously envisioned by the particle physics community. Among the Letters of Interest for dark matter searches considered by the Homestake Program Advisory Committee are seven (LOIs: 22, 48, 56, 58, 59, 63, 72) that need space and support facilities for either research and development or experimental operation or both. In terms of their readiness for research and development, maturity of technique, or depth requirements, they represent a full range of needs. Therefore an evolving plan for dark matter experimentation would fit well into the sequence of the phased development planned for Homestake. Here we cite some examples for the Early Implementation Program, DUSEL Initial Suite of Experiments, and longer-term future experiments at various depths and scales.

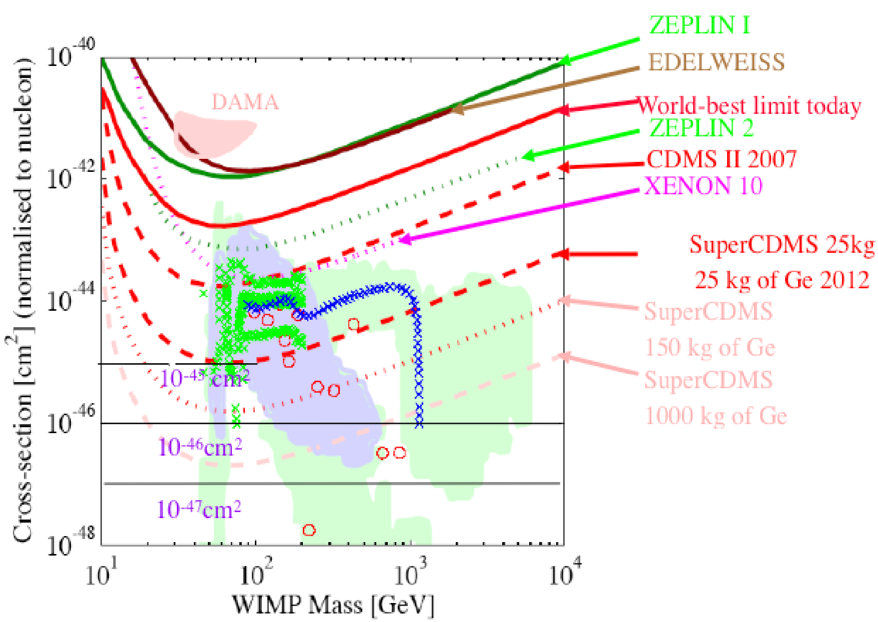

Figure 4.2 Dark Matter Detector Sensitivities for Proposed Experiments. Figure Courtesy of the CDMS collaboration

For the Early Implementation Program at the 4850 Level, the Program Advisory Committee considers two projects particularly suitable in terms of their present stages of development: XENON and miniCLEAN. XENON-10, presently successfully operating as a two-phase liquid xenon detector in Gran Sasso, wishes to expand to the next stage of much larger versions and at a depth greater than is available at Gran Sasso and with the expectation to go deeper at a later stage. Preliminary designs exist for a water shield for either XENON-100 or for a 500kg version (LUX) using the existing neutrino cavern at 4850 Level where Nobel laureate Ray Davis performed pioneering research; use of this cavern saves time as well as expense for excavation and lead-poly shielding. miniCLEAN is at an earlier phase of research and development but, if successful, could rapidly develop into a first operating stage using either liquid argon or neon as the detecting medium. For research and development, miniCLEAN would require less space than XENON-100 or LUX and, as cryogenic liquid techniques, both experiments would share many support facilities. If successful, miniCLEAN and the XENON-10 successor would be candidates for expansion to deeper levels at Homestake.

For the DUSEL Initial Suite of Experiments, in addition to XENON-100/LUX and miniCLEAN, which would be strong candidates, Super-CDMS could also be included. Super-CDMS, a U.S.-Canadian collaboration, was not included in our Early Implementation Program because of the Super-CDMS collaboration's stated preference for carrying out its first phase at SNOLAB. At this stage there could also be several candidates for research and development on emerging techniques, for example, SIGN and TPC, both judged by the Program Advisory Committee to have interesting potential. The former is a high-pressure neon modular detector and the latter a high-pressure gas mixture time projection chamber expected to have track direction sensitivity. The Program Advisory Committee has emphasized that the laboratories being prepared at the 4850 Level be extensive enough so that space should not be an issue if any or all of the above experiments prefer to locate there.

The longer term and/or greater depth candidates would include all of the above experiments, if successful, either to exploit discovery or to improve limits with larger scale, better shielded detectors. At this stage, two additional experiments from the Letters of Interest should be included. These are the ZEPLIN-I, II and DRIFT experiments, currently located at shallow depth (Boulby). ZEPLIN-I, II are successfully operating two-phase xenon detectors, and DRIFT is a low pressure Time Projection Chamber (TPC) aiming for the unique ability to sense WIMP direction. Both have expressed the intention that, should they desire to construct a new device of significantly improved sensitivity for their technique, they would prefer and require one of the deepest levels at Homestake. The indirect detection of WIMPs should also be mentioned as part of a longer-term program. If and when large advanced detectors suitable for proton decay, long-baseline neutrino work, supernovae or solar neutrinos became operational; they too could search for evidence of products from WIMP annihilation in the Sun or the galactic halo. All of the above mentioned experiments are currently under consideration by the Department of Energy/National Science Foundation panel, Dark Matter Scientific Assessment Group (DMSAG), for inclusion in the Roadmap for the future U.S. program in direct detection.

Homestake is especially well suited for dark matter search experiments. Initial assay of the Yates formation (the host rock unit of the proposed 4850 Level and 7400 Level laboratories) indicates that it is an order of magnitude lower in uranium and thorium than typical granite found at other sites including the Canadian Shield, the Rocky Mountains, and the Cascade Range. This is important because the decay of U and Th results in a background of high-energy gamma rays and neutrons from fission and alpha reactions; Homestake would be a particularly quiet place for the detector. Homestake plans to provide a source of radon-reduced air specifically for experiments that are sensitive to airborne concentrations of radon (and radon-decay daughters), thus reducing another troubling source of radioactive backgrounds.

Homestake will develop facilities at several levels. Of particular value is the drive-in access for Homestake DUSEL at the 300 Level. This is probably essential to the dark matter and other experiments requiring the use of low activity materials. Such materials can be processed in well-separated processing facilities using techniques such as electroformed copper refinement. Adequate supplies of materials low in cosmic-ray activation products can be stockpiled at this level. (Refinement of these materials frequently involves sizable chemical processing modules using caustic and acidic solutions. Separating main experimental programs from such chemical processes is a distinct advantage for the facility.) Materials processed at the 300 Level can be transported directly to all levels in the facility without bringing them to the surface, since the 300 Level has a horizontal underground connection to the Ross Shaft and thence other levels.

Detector components could be put together in special assembly areas benefiting from the reduced cosmic ray backgrounds.

Homestake plans on establishing in-house state-of-the-art low background counting facilities on-site to assist with the development of these experiments. Several dark matter experiments would use Homestake's Large Water Room for deployment.

4.2.1.2 Neutrinoless Double Beta Decay

With strong recent evidence that neutrinos have mass and that they transform (oscillate) between flavor states, further questions about fundamental properties of neutrinos have gained prominence. Most notably: What are the actual masses of the three neutrino states? Is the neutrino its own anti-particle (is it "Majorana in nature")? What is the mass ordering (hierarchy) of the neutrinos? What is the exact nature of neutrino mixing? Do neutrino oscillations exhibit CP violation? Of these questions, the first three are addressed by neutrinoless double beta decay ($0\nu\beta\beta$) experiments.

Neutrinoless double beta decay experiments have been reviewed, and their importance affirmed by several prominent studies [18]. Three experiments were selected by the Neutrino Scientific Assessment Group (NuSAG) for funding and given a high priority: CUORE, EXO, and Majorana (see Figure 4.3). All three of these experiments have prepared proposals. The U.S. Department of Energy has given Critical Decision Zero to $0\nu\beta\beta$ experiments in both High Energy and Nuclear Physics. The APS Study and NuSAG report both recommend a phased approach for $0\nu\beta\beta$, with increasing detector mass and specific goals for each phase of the experiment [19]. If necessary, detector masses on the ton-scale may be required.

Of these three experiments, Homestake Interim Laboratory has received Letters of Interest from both EXO (LOI-49) and Majorana (LOI-61). (CUORE is primarily an Italian experiment to be based in Gran Sasso.) The phased approach to the experiments matches the development plans for Homestake. The EXO experiment will be phased into various technology steps. The first stage, EXO200, will consist of 200kg of enriched ^{136}Xe and is currently funded. This phase will focus on measuring the two-neutrino double beta decay mode in a Xe-filled Time Projection Chamber and is scheduled for deployment at the Waste Isolation Pilot Plant (WIPP). In parallel with this deployment, the EXO collaboration plans on developing ion-identification methods to single out the daughter product from $0\nu\beta\beta$ and to subsequently enlarge the detector to ~ 1 ton scale. EXO200 is already on track for deployment in New Mexico and is not being considered for the Early Implementation Program. The second stage of EXO is appropriate for Homestake's DUSEL Initial Suite of Experiments. The 4850 Level provides adequate shielding from cosmic rays for EXO. The experiment, assuming EXO200 is successful and the ion-identification program matures, would be a strong candidate for Homestake's dedicated physics facility with deployment in the time frame of 2010-2012 and within the initial phases of Homestake DUSEL.

The Majorana experiment, an excellent candidate for the Early Implementation Program, proposes to develop an array of isotopically enriched ^{76}Ge semi-conductor detectors. The arrays of 57 detectors would each comprise approximately 60 kg of germanium. The long history of germanium detector and the use of mature segmentation technology promise to provide additional handles to identify and reject backgrounds. This experiment, as well as several dark matter searches, requires the development of ultra-pure materials, especially copper, and extensive low radioactive contamination screening facilities. Work could begin immediately on the copper production facilities, as well as low level screening. The initial deployment of the first Ge module could begin towards the end of the Early Implementation Program. The low background screening, copper manufacturing and initial stages of the Ge experiment would all be strong candidates for research and development funding in the next several years.

The Program Advisory Committee gave a very strong endorsement of the science and the two Letters of Interest for EXO and Majorana, as well as the suitability of Homestake to site them in Early Implementation Program, DUSEL Initial Suite of Experiments and the longer term. The Program Advisory Committee also recommended providing material fabrication and storage space underground. As Majorana develops into subsequent phases and requires additional shielding, it would be moved to lower campuses in Homestake. This move would not be required until after ~2012. The 300 Level or a similar near-surface facility would be well-suited for the copper refinement, purification and storage, low background screening and underground storage. The ease of "drive-in" access for these chemical processes is desirable and would produce rapid progress in the near future. These capabilities would very likely be shared with other experiments. Neutrinoless double beta decay projects could produce some of the first physics results from DUSEL.

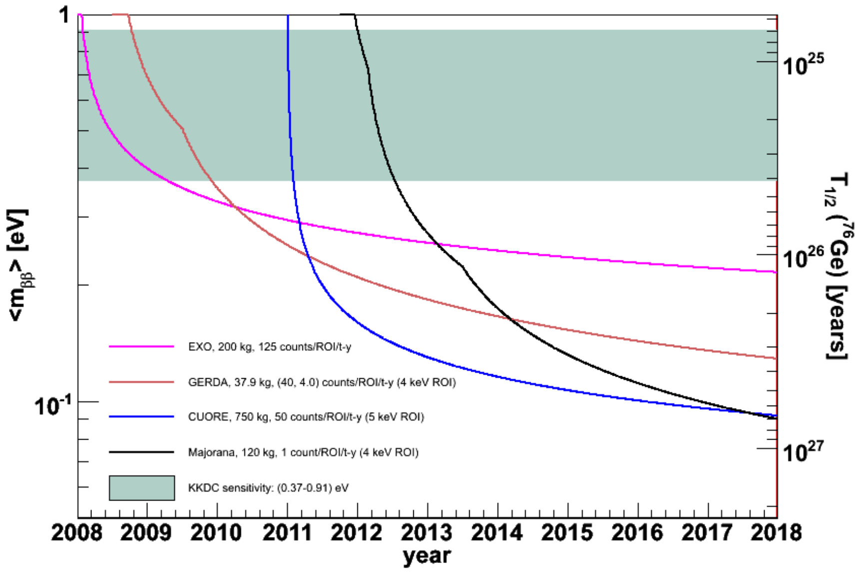

Figure 4.3 Majorana Neutrino Mass Sensitivity for Proposed Neutrinoless Double Beta Decay Experiments. Figure courtesy of the Majorana Collaboration

Neutrinoless double beta decay experiments are also well suited to Homestake. Similarly to the Dark Matter experiments, neutrinoless double beta decay experiments will benefit from the low activity rock and the radon-reduced air supply. Majorana would be a major occupant of the 300L laboratory for the refining of its copper components. The 300 Level assembly area, with its excellent access, and reduced cosmic ray flux would be an ideal site for much of the detector pre-assembly and detector characterization and initial calibration. Materials processed at the 300 Level can be transported to all levels in the facility via an underground connection to the Ross Shaft without bringing them to the surface.

4.2.1.3 Solar Neutrinos

At the core of the "Standard Solar Model" (SSM) are four key assumptions. The first is that the luminosity of the Sun as determined from photon flux matches consistently with the luminosity as determined by the neutrino flux (presently known experimentally only to within 20-30%).

The second is that the Sun is basically in hydrostatic equilibrium. The third, that the heavy elemental abundances at the surface of the Sun are present at the center. The fourth is that neutrino mixing through the Mikheyev-Smirnov-Wolfenstein (MSW) effect correctly explains the observed solar neutrino fluxes on Earth.

All four of these assumptions will be tested with the next generation of detectors, designed to accurately measure the remaining >90% of the solar neutrino flux not yet directly seen. Beyond being a test of today's theories, this round of experiments has exciting discovery potential. The first solar neutrino experiment was designed to measure the fusion model of the Sun, but unexpected deviations eventually led to a fundamentally different understanding of neutrinos. The recent four-division American Physical Society neutrino study consequently made the development of a low-energy solar neutrino detector one of its three executive recommendations.

These detectors will directly observe the low-energy proton-proton reaction neutrino flux, and the ^{7}Be flux is expected to be measured in the near future. At the anticipated event rate, the physics of the MSW mechanism would be confirmed and assumptions of the SSM tested. Deviations could indicate other sources of energy in the Sun, non-equilibrium solar evolution, possible dark-energy influence, resonant spin flavor precession, an unexpected importance of the carbon-nitrogen-oxygen (CNO) cycle, or several other possibilities. By measuring both charged-current and elastic-scattering reactions, the presence of sterile neutrinos could be revealed and better values of the neutrino mixing matrix extracted.

Since these detectors require a low-background environment, DUSEL is a natural home and would greatly facilitate their realization. Current elastic-scattering scintillator experiments in Italy (Borexino) and Japan (KamLAND) are measuring the ^{7}Be flux. Experiments discussed for Homestake DUSEL to measure the pp flux are LENS, CLEAN, HERON, MOON, TPC, SIGN and potentially others.

LENS (LOI-4) is a charged-current experiment, and is illustrative of the high-quality spectral information achievable with this method. Due to its triple-coincidence tag, the dominant background activity of the indium target material can be handled and only a moderate depth of ~2000 mwe is required. While extensive physics can be achieved by taking ratios of several energies, this experiment requires an independent overall calibration to obtain absolute efficiency. A 4% pp measurement should be achievable in five years with a 125-190 ton detector (8% indium by weight).

Several elastic-scattering experiments could provide the required counterpart measurement. These experiments have the advantage of larger rates and a well-known cross section, but suffer from less spectral information, lack of a coincidence signature and the need to be deep underground. CLEAN (LOI-56, including the miniCLEAN concept for dark matter) and HERON (not an Letter of Interest at this time) are cryogenic scintillation detectors, making use of their ability to have low intrinsic background.

The CLEAN concept involves liquid Ne and a wavelength shifter on the surface of the container where phototubes are mounted. Event positions can be reconstructed via the luminance distribution at the surface. HERON makes use of both the scintillation light and electrons liberated in liquid helium by ionizing radiation to reconstruct the energy and position within the fiducial volume, and to reject events that have multiple interaction sites, such as Compton interactions. TPC (LOI-63) proposes to explore development of a large gaseous Time Projection Chamber, which could have directional sensitivity to neutrino elastic scattering at energies above

100 keV in the pp spectrum. SIGN (LOI-72) is developing an array of high-pressure neon drift/scintillation tubes which could be utilized on the high energy solar neutrino flux via coherent neutral current scattering by the neon nuclei. Designed primarily for dark matter, its other goals include also solar and supernovae neutrinos. Finally, LOI-64, a high-current ion accelerator project, proposes to measure small cross sections relevant and important to the fusion reactions that take place in the Sun (see Sec. 4.2.1.5, Nuclear Astrophysics). These experimental techniques are presently in different stages of development, so they are not yet expected to be considered as full-scale candidates for Early Implementation Program. Nevertheless, the Program Advisory Committee has strongly endorsed research and development utilizing Homestake. We have included an active nuclear astrophysics program in our DUSEL Initial Suite of Experiments.

In general, solar neutrino experiments will directly benefit from the Homestake site in ways similar to the neutrinoless double beta decay and dark matter experiments. The lower activity of surrounding rock and low-radon air are particularly favorable aspects of this proposal. As an example, miniCLEAN, following its campaign of dark matter experimentation, is intended to evolve into a solar neutrino detector. It would then require greater depth to avoid spallation in the neon target by muons; The Homestake site is ideally adapted to accommodating the full sequence of required depths from Early Implementation Program to DUSEL within the same facility. The facilities at the 300 Level are of particular interest to solar neutrino experiments for the creation and/or storage of low-activity materials prior to their use in construction of larger versions in order to reduce cosmogenic radioactivity created in them earlier when on the surface; this will be an easily accessible common-use facility for detector preparation and commissioning.

4.2.1.4 Large Multipurpose Detector, Long Baseline Neutrinos, Proton Decay and Astrophysical Neutrinos

A large underground detector with an active mass greater than 100 kt could become a key *shared physics research facility* for the future U.S. particle, nuclear and astrophysics research programs. A sensitive large detector with appropriate technical capabilities will address questions of fundamental importance, such as nucleon decay and matter-antimatter asymmetry amongst neutrinos. The detector will also serve as a facility for continuously observing natural sources of neutrinos and cosmic rays. All these tasks are active *simultaneously*.

Homestake received two Letters of Interest and subsequent inquiries for consideration as potential programs for long baseline neutrino and nucleon decay physics. The Letters of Interest represented the two leading technology types being considered worldwide for constructing appropriate detectors: 100-1000kt water Cherenkov (LOI-8) and 100kt liquid argon tracking (LOI-52). While acknowledging the present uncertainties associated with the setting of policy for the entire U.S. particle physics program, the Program Advisory Committee emphasized and strongly endorsed the long term scientific significance of large detectors for this physics. Further, the Committee affirmed the suitability of Homestake's 4850 Level.

The large detector must have a mass in excess of 100 kt to have significantly greater statistical reach to search for nucleon decay and to collect enough neutrino interaction events from accelerator-based neutrino beams with very long baselines to measure oscillation parameters with greater precision. The detector needs to have a low energy threshold (< 5MeV) and good energy resolution to detect supernovae and solar neutrinos. It should have good pattern recognition, timing and particle identification capability to distinguish electrons from muons and pions. To exploit the full scientific potential of such a detector, it will have to be located deep underground to shield it from cosmic-ray background. Currently, only three technologies–water Cherenkov, liquid argon time-projection, and liquid scintillator–have been proposed to meet these requirements.

4.2.1.4.1 Physics Goal of Large Multipurpose Detector

There is now an abundance of evidence that neutrinos oscillate among the three known flavors ν_e, ν_μ, ν_τ, indicating that they have masses and mix with one another. Indeed, modulo an anomaly in the LSND experiment, all observed neutrino oscillation phenomena are well described by 3 generation mixing, which is described by 2 mass squared differences (Δm^2_{32}, atmospheric and Δm^2_{21}, solar), 3 mixing angles (θ_{12}, θ_{23}, θ_{13}) and a phase (δ). Atmospheric neutrino oscillations are governed by mass squared difference $\Delta m^2_{32}=m^2_3-m^2_2$ = +/- 2.5 10^{-3} eV^2 and mixing angle θ_{23}~ 45^o; findings that have been confirmed by accelerator generated neutrino beam studies at Super-Kamiokande and MINOS. As yet, the sign of Δm^2_{32} is undetermined. The so-called normal mass hierarchy, $m_3 > m_2$, suggests a positive sign, which is also preferred by theoretical models. However, a negative value (or inverted hierarchy) can certainly be accommodated and if that is the case, the predicted rates for neutrino-less double beta decay will likely be larger and more easily accessible experimentally. Resolving the sign of the mass hierarchy is an extremely important issue. In addition, the fact that θ_{23} is large and near maximal is also significant for model building. Measuring θ_{23} with precision is highly desirable.

In the case of solar and reactor neutrino oscillations, one finds $\Delta m^2_{21}=m^2_2-m^2_1$= 8x$10^{-5}$ eV^2 and θ_{12}~ 32^o. Again, the mixing angle is relatively large (relative to the analogous Cabbibo angle ~13^o of the quark sector). In addition, Δm^2_{21} is large enough, compared, to Δm^2_{32}, to make long baseline neutrino oscillation searches for CP violation feasible and in fact likely to yield positive results, i.e., the stage is set for a future major discovery (CP violation in the lepton sector).

Currently, we know nothing about the value of the CP violating phase δ ~ ($0 < \delta < 360^o$) and only have an upper bound on the as yet unknown mixing angle θ_{13} (< 13^o) or $\sin^2 2\theta_{13}< 0.2$. Knowledge of θ_{13} and δ would complete our determination of the 3 generation lepton mixing matrix and provide a measure of leptonic CP violation via the Jarlskog invariant.

$$J_{CP}^{Leptonic} =(1/8) \sin^2\theta_{12} \sin^2\theta_{13} \sin^2\theta_{23} \cos\theta_{13} \sin \delta$$

which could easily turn out to be much larger (with above parameters current limit is $J_{CP}^{Leptonic}$ <0.05 sinδ) than the analogous quark degree of CP violation J_{CP}^{Quarks}~ 3x10^{-5}. Based on our current knowledge and future goals, the DUSEL based neutrino program should include:

1. Completing the measurement of the leptonic mixing matrix
2. Study of CP violation,
3. Determining the values of all parameters with high precision including $J_{CP}^{Leptonic}$ as well as the sign of Δm^2_{32}
4. Searching for exotic effects perhaps due to sterile neutrino mixing, extra dimensions, dark energy, etc.

Among those future neutrino physics goals, the search for and study of CP violation is of primary importance and should be our main objective for several reasons outlined below. A single large detector at Homestake coupled to a Super Neutrino beam from FNAL or BNL can address all of these fundamental issues in neutrino physics.

CP violation has so far only been observed in the quark sector of the Standard Model. Its discovery in the leptonic sector should shed additional light on the role of CP violation in nature. Is it merely an arbitrary consequence of inevitable phases in mixing matrices, or something deeper? Perhaps, most important, unveiling leptonic CP violation is particularly compelling because of its potential connection with the observed matter-antimatter asymmetry of our universe, a fundamental problem at the heart of our existence. The leading explanation is currently a leptogenesis scenario in which decays of very heavy right-hand neutrinos created in the early universe give rise to a lepton number asymmetry which later becomes a baryon-antibaryon asymmetry via the B-L conserving 't Hooft mechanism of the Standard Model at weak scale temperatures.

Leptogenesis offers an elegant, natural explanation for the matter-antimatter asymmetry; but it requires some experimental confirmation of its various components before it can be accepted. Those include the existence of very heavy right-handed neutrinos as well as lepton number and CP violation in their decays.

Direct detection of those phenomena is highly unlikely; however, indirect connections may be established by studying lepton number violation in neutrinoless double beta decay (see Section 4.2.1.2) and CP violation in ordinary neutrino oscillations. Indeed, such discoveries will go far in establishing leptogenesis as a credible, even likely, scenario. For that reason, neutrinoless double beta decay and leptonic CP violation in neutrino oscillations are given very high priorities by the particle and nuclear physics communities.

Designing for CP violation studies in next generation neutrino programs has other important benefits. First, the degree of difficulty to establish a credible CP violation experiment and determine $J_{CP}^{Leptonic}$ is high but currently tractable. It requires an intense proton beam of about 1—2 MW and a very large detector (250-500kt Water Cherenkov or its equivalent). Such an ambitious infrastructure will allow very precise measurements of all neutrino oscillation parameters as well as the sign of Δm^2_{32} via ν_μ disappearance and ν_μ to ν_e appearance studies. It will also provide a sensitive probe of “New Physics” deviations from 3 generation oscillations, perhaps due to sterile neutrinos, extra dimensions, dark energy or other exotic effects.

In addition to its accelerator based neutrino program, a well-instrumented very large detector offers other physics discovery opportunities. Assuming that it is located underground and shielded from cosmic rays, it can push the limits on proton decay into modes such as $p \rightarrow e^+p^o$ to 10^{35}yr sensitivity or beyond, a level suggested by gauge boson mediated proton decay in supersymmetric GUTS. Indeed, there is such a natural marriage between the requirements to discover leptonic CP violation and see proton decay (i.e., an approximately 500 kt water Cherenkov detector) that it could be hard to imagine undertaking either effort without being able to do the other. Other significant topics for which such a large detector would also have additional physics capabilities are: a) Atmospheric neutrino oscillations with very high statistics. b) The predicted relic supernova neutrinos left over from earlier epochs in the history of the Universe, a potential source of cosmological information. c) Study of the 100,000 or so neutrino events from a supernova in our galaxy (should there be one during the operating period; they occur about every 30 years). The physics potential of a very large underground detector is extremely rich. The fact that in the same device it can also be used to determine (or bound) leptonic CP violation and measure all facts of neutrino oscillations gives such a facility outstanding discovery potential.

4.2.1.4.2 Feasibility of Large Detectors in Homestake

Of the technologies discussed, water Cherenkov appears to be the one capable of reaching 100 kt of fiducial mass or greater with minimum technical development. The advantage of a water Cherenkov detector is that it is a proven technology that has been perfected over several decades. It is also a technology that allows very large dynamic range in energy for event detection (from 5MeV to 50GeV) and therefore it is a natural choice for taking advantage of a low background deep environment. Water Cherenkov detectors are in operation in Japan (Super-Kamiokande with a total mass of ~50 kt) and in Canada (the Sudbury Neutrino Observatory, or SNO, with 1 kt of D_2O and 7.5 kt of H_2O). A large detector based on cryogenic liquid argon time projection technology has also been proposed for Homestake DUSEL. Such a detector has very high energy resolution and event recognition capability. This capability will allow such a detector to have high sensitivity to modes such as $P \rightarrow K^+$+anti-ν, which has final state particles that are difficult to measure. The key technical problem for a liquid argon detector is an engineering design that will allow scaling up from the current size of about 600 t, achieved in ICARUS in the Gran Sasso laboratory, to 100kt, needed for the next generation experiment. An additional technical challenge is locating this cryogenic noble gas in an underground environment. LOI-52 proposes to resolve these issues.

The Homestake DUSEL laboratory offers a number of advantages for the science and technology discussed above. They are: 1) the ability to make reliable, well-costed designs for large caverns (with total volume of >100,000 m^3) at great depths (4850 Level) in the Yates formation, 2) the likelihood of the timely implementation of large detectors if they are built modularly, and 3) sufficient distance from both Fermilab (1300 km) and Brookhaven National Lab (2540 km) for a long baseline neutrino experiment. These three features of the Homestake DUSEL site make it unique compared to any other potential detector site in the world (For reference, the distance from Homestake to CERN is 7370 km and to JPARC in Japan it is 8240 km). A preliminary plan (LOI-8) with an estimate for cost and schedule for a 300 kt water Cherenkov detector was presented to the Neutrino Scientific Advisory Group (NuSAG) on 20-21 May 2006 [19]; this presentation and a detailed document is available through the Department of Energy NuSAG committee and the U.S. long baseline study [20]. Figure 4.4 presents the 100 kt detector cavity concept. The plan as presented calls for simultaneous construction–over a 5-year period–on 3 detector modules of approximately 100 kt each so that considerable economy can be obtained. The total capital cost will depend on the aggressiveness of the schedule (a more aggressive schedule will mean lower total cost) and the total number of photomultiplier tubes needed for the technical requirements. The detector construction plan benefits greatly from the Homestake Early Implementation Program, during which extensive coring can be done at the 4850 Level site to make detailed engineering layout and estimates for the caverns.

The Program Advisory Committee was very support of the long baseline neutrino program based either on water or liquid argon technology.

Accelerator Neutrino Beam Feasibility: As part of a US long baseline neutrino study effort [20] a new accelerator produced Super Neutrino beam from FNAL, which is considered the primary choice for a source, has been examined. A previous design for a beam from BNL also exists. Here we focus on FNAL as the primary source. A conceptual design has been reviewed recently at FNAL to increase the total power from the 120 GeV Main Injector (MI) complex after the Tevatron program ends [21]. In this scheme, protons from the 8 GeV booster, operating at 15 Hz, will be stored in the recycler (which becomes available after the shutdown of the Tevatron program) while the MI completes its acceleration cycle, which can be shortened from the current 2.2 sec to 1.33 sec. In a further upgrade the techniques of momentum stacking using the antiproton accumulator, and slip-stacking using the recycler will raise the total intensity in the MI to ~1.2 MW at 120 GeV.

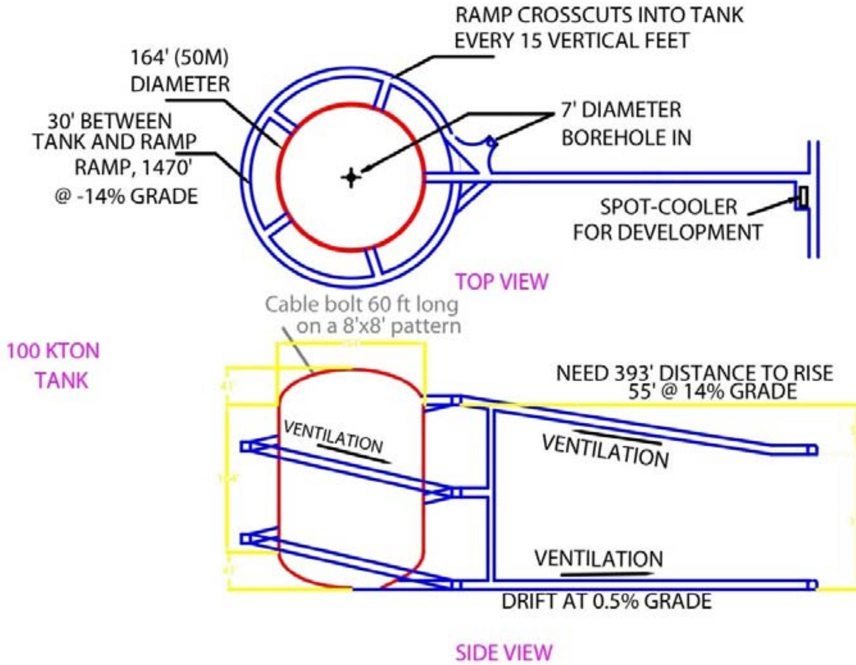

Figure 4.4 Preliminary design for a single cavity with nominal dimensions of 50m diameter and 50m height to house a 100kt mass water Cherenkov detector. The upper ramp for access to the cavity will be at the 4850 Level. A preliminary stability analysis for 50m span/height was conducted by the proponents.

Separately, a new neutrino beamline that exploits the current FNAL infrastructure and takes full advantage of the planned intensity upgrade, from FNAL to Homestake has been examined. The preliminary conclusion is that a new beamline from the Main Injector to Homestake could be accommodated on the FNAL site and the cost and schedule could be estimated with good confidence based on an appropriate extrapolation of the NuMI beamline construction experience. The new beamline would have a downward angle of 5.84^{o} (distance of 1289km to Homestake). The decay pipe of such a beamline can be up to 400m in length and 4m in diameter. Such dimensions, including an on-site near detector to calibrate the beam, can lead to a very intense and flexible facility. The intensity and spectra from such a beam have been reported as part of the US long baseline study. The neutrino baselines are presented in Figure 4.5.

4.2.1.4.3 Neutrino Measurements Using Accelerator Produced Beams

Summary of Simulation Studies and Projected Sensitivity:

With 120 GeV protons, the full power of 1.2 MW from the FNAL Main Injector can be obtained with annual yield of >10^5 events for total fiducial mass of 300 kt at Homestake. The choice of proton energy depends on optimization of signal versus background, which is not completed yet. At lower energy of 30-60 GeV with power level of 1 MW the event yield will be ~50,000/year in the absence of oscillations. These numbers will be modified by a factor of ~1/2 by oscillations and produce dramatic oscillated energy spectra that can be used for precise measurements. We

are still investigating the best use of these spectra and the tradeoff between event rate and backgrounds from high energy neutrinos for the best CP violation results. We have used the event yield from ~30 GeV protons and a simulation of energy resolution and backgrounds in a water Cherenkov detector. The sensitivity to various parameters is shown in Figures 4.6, and 4.7.

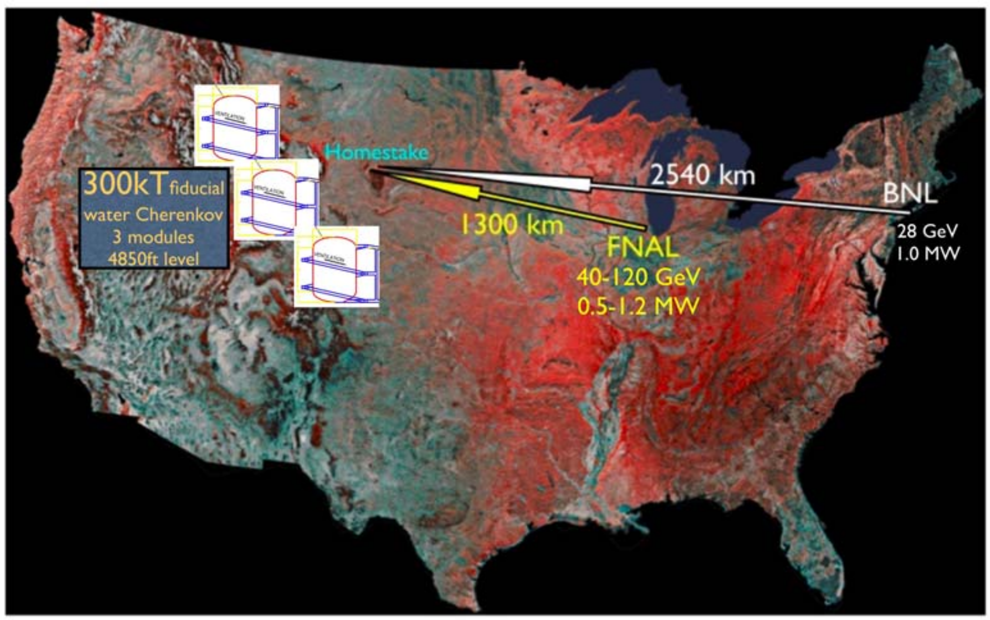

Figure 4.5 Possible long baseline accelerator neutrino experiment using a large detector at Homestake. The important parameters of the experimental setup are shown. A beam from both BNL and FNAL has been examined.

In these figures the currently known oscillation parameters are assumed to be at their central values with their respective errors. The results shown include the effect of varying the known parameters within their errors. The results are robust with respect to these variations and that is one of the strengths of performing this measurement with a longer baseline and a new beam that is designed to have signal events from a wide range of oscillation phases.

Although much optimization still needs to be performed, it is clear that with the planned size of the detector and beam intensity the sensitivity for $\sin^2 2\theta_{13}$ could be <0.005; the mass hierarchy and CP violation could be determined to values of $\sin^2 2\theta_{13}$ of about 0.008 also. Figure 4.6 shows the precision with which a joint determination of δ and $\sin^2 2\theta_{13}$ can be made with no ambiguities at the end of a decade long program of measurements. It should be observed from

Figure 4.6 that the precision on δ does not depend strongly on the value of $\sin^2 2\theta_{13}$, which is the leading variable in the rate of $\nu_\mu \rightarrow \nu_e$. This observation coupled with preliminary conclusions from the U.S. long baseline study shows that even if the current round of smaller scale experiments succeeds in finding a non-zero value of θ_{13}, a program of the scale we are considering here will be needed to determine CP violation in the leptonic sector. Observation of a non-zero θ_{13} will, in fact, add considerable motivation to this program.

It should be remarked that along with the crucial measurement of CP violation, it has been shown that the dramatic spectrum of muon and anti-muon neutrino disappearance will lead to a very precise (<1%) measurement of Δm_{32}^2, $\sin^2 2\theta_{23}$ and strong limits on CPT violation. Such a program of measurements alone is highly valued.

Separately, it has been shown that if one could build a 100 kt liquid argon time projection chamber [22] it would have similar reach to these parameters as in Figures 4.6 and 4.7. Such a detector would have better signal efficiency and background rejection capability to compensate for the factor-of-3 lower detection mass.

4.2.1.4.4 Improved Search for Nucleon Decay

Current status of experimentation

The "classical" proton decay mode, $p \rightarrow e^+\pi^0$, can be efficiently detected with low background. At present, the best limit on this mode ($\tau_{1/2} > 5.4\times10^{33}$ yr, 90% CL) comes from a 92 kt-yr exposure of Super-Kamiokande. The detection efficiency of 44% is dominated by final-state π^0 absorption or charge-exchange in the nucleus, and the expected background is 2.2 events/Mt-yr.

The mode $p \rightarrow$ anti-νK^+, is experimentally more difficult in water Cherenkov detectors due to the unobservable neutrino and the fact that the kaon energy is below the Cherenkov threshold. The present limit from Super-Kamiokande is the result of combining several channels, the most sensitive of which is $K^+ \rightarrow \mu^+\nu$ accompanied by a de-excitation signature from the remnant ^{15}N nucleus. Monte Carlo studies suggest that this mode should remain background free for the foreseeable future. The present limit on this mode is $\tau/Br > 2.2\times10^{33}$ yr (90% CL).

Requirements for the next decade

Since the lifetime of the nucleon could range from just above present limits to many orders of magnitude greater, progress in this search must be measured logarithmically: increases in sensitivity by factors of a few are insufficient to motivate new experiments. Thus, continued progress in the search for nucleon decay inevitably requires much larger detectors. The efficiency for detection of the $e^+\pi^0$ mode is dominated by pion absorption effects in the nucleus, and cannot be improved significantly. An order of magnitude improvement in this mode can only be achieved by running Super-Kamiokande for 30-40 more years, or by constructing an order of magnitude larger experiment.

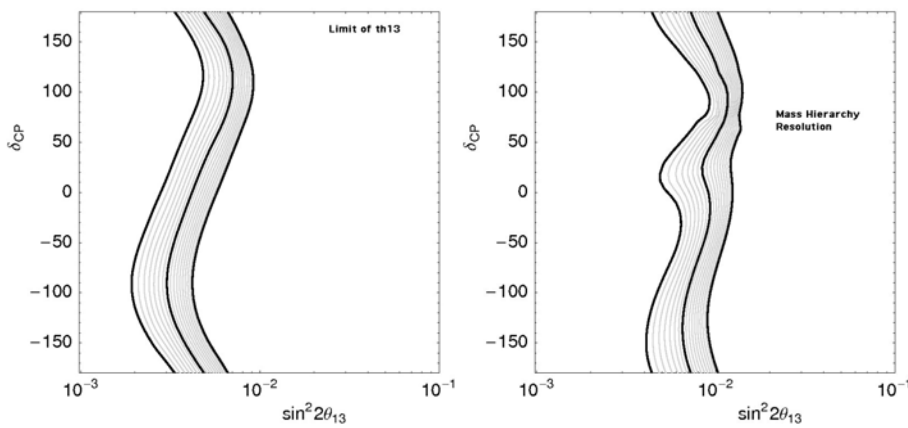

Figure 4.6 Discovery reach for $\sin^2 2\theta_{13}$ with 300 kt of fiducial mass and 5 yrs of neutrino and antineutrino running each (left). The right hand plot demonstrates the potential for resolving the mass hierarchy issue. The sensitivity is shown as a function of the CP phase δ and $\sin^2 2\theta_{13}$. The discovery can be made on the right side of the curves with confidence level of 3, 4, and 5 sigma from left to right (dark curves) [23].

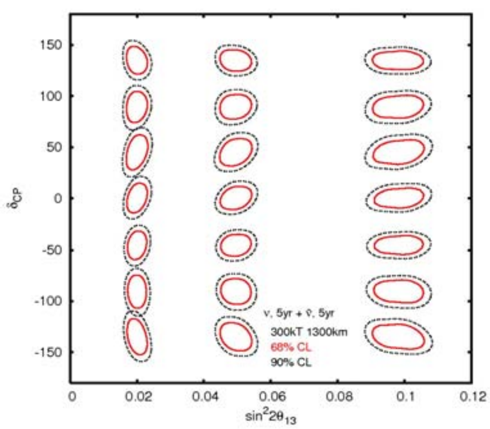

Figure 4.7 Simultaneous determination of δ (degrees) and $\sin^2 2\theta_{13}$ after neutrino and antineutrino running. The precision at 68% and 90% C.L. is shown at 21 different points. At each point we simulated the spectrum and calculated the measurement precision using the statistics of the simulated signal and background and the assumption of 10% systematic errors on the background [24].

The decay modes of the nucleon are also unknown and produce different experimental signatures, so future detectors must be sensitive to most or all of the kinematically allowed channels. Moreover, the enormous mass and exposure required to improve significantly on existing limits (and the unknowable prospects for positive detection) underline the importance of any future experiment's ability to address other important physics questions while waiting for the proton to decay.

<u>New facilities under consideration</u>

A variety of technologies for discovery of nucleon decay have been discussed. Of these, water Cherenkov appears to be the only one capable of reaching lifetimes of 10^{35} years or greater. Cooperative, parallel studies of a future underground water Cherenkov proton decay experiment are underway in the U.S. and Japan. The proposed designs have fiducial volumes which are about 20-25 times the Super-Kamiokande fiducial volume.

Other techniques, for instance liquid argon or scintillation, have been discussed and may have significant efficiency advantages for certain modes that are dominant in a certain broad class of SUSY theories. Liquid argon time projection chambers potentially offer very detailed measurements of particle physics events with superb resolution and particle identification. Liquid Argon feasibility will be demonstrated in the near future with the operation of a 600-t ICARUS detector. If expectations are correct, it should have a sensitivity that is equivalent to a 6000-ton water Cherenkov detector in the $p\rightarrow$ anti-$K^+\nu$ mode. The liquid scintillator approach is being explored with the 1-kt KamLAND experiment. It should also have enhanced sensitivity to this mode by directly observing the K^+ by dE/dx and observing the subsequent $K^+\rightarrow \mu^+\nu$ decay.

Performance and feasibility

Detailed Monte Carlo studies, including full reconstruction of simulated data, indicate that the water detectors could reach the goal of an order of magnitude improvement on anticipated nucleon decay limits from Super-Kamiokande. With sufficient exposure, clear discovery of nucleon decay into $e^+\pi^0$ would be possible even at lifetimes of (few) x10^{35} years, where present analyses would be background-limited, by tightening the selection criteria. For instance, with a detection efficiency of 18%, the expected background is only 0.15 events/MT-yr, ensuring a signal:noise of 4:1 even for a proton lifetime of 10^{35} years. A water Cherenkov detector would also provide a decisive test of super-symmetric SO(10) grand unified theory by reaching a sensitivity of a (few) x 10^{34} years for the νK^+ mode. The search for n-nbar oscillation is another test of baryon non-conservation. While this is not one of the favorite predictions of conventional SUSY grand unification, this process, taking place in the nuclear potential, can reach an equivalent sensitivity to baryon non-conservation of 10^{35} years.

As we have discussed, a much smaller liquid argon could do particularly well on the mode anti-νK^+ as the efficiency could be as much as 10 times larger than that in the water Cherenkov detectors due to the extraordinary pattern recognition capabilities. Due to this, a single observed event could be powerful evidence for a discovery. The $e^+\pi^0$ mode however would be limited by the smaller size of these detectors.

R&D towards more efficient and economical photo-detection – both improved conventional photo-multiplier tubes and more novel technologies – while not required to build the next large detector, could reduce its cost and increase its physics reach considerably. This R&D should be strongly supported, since it will also benefit a host of other research efforts.

4.2.1.4.5 Astrophysical Neutrinos

The detector technologies will lead to enhanced detection and study of neutrinos from natural sources such as the Sun, Earth's atmosphere and lithosphere, and past and current supernova explosions. There may also be previously unsuspected, natural neutrino sources that appear when the detector mass reaches the hundreds of kilotons scale. The liquid scintillator technique is of particular note here because it could allow the detection of low energy antineutrinos from Earth's lithosphere.

Solar neutrinos have already been observed in the Super Kamiokande and SNO detectors [25]. If the large detector concepts discussed here result in construction of the underground experiment, it may become possible to increase the observable event rate enough to clearly observe spectral distortion in the 5 to 14 MeV region. One could also measure the as yet undetected hep solar neutrinos (with end point of 18.8 MeV) well beyond the ^8B endpoint (~14 MeV). These measurements would require a comprehensive understanding of the detector systematics and energy resolution, but a better determination of the solar spectrum as well as detection of the day-night effect with high statistics would represent a significant advance in the evolution of solar nuclear physics measurements.

The observation of supernova neutrino events in a large neutrino detector of the type being discussed in this proposal is straightforward and has historical precedent. The SN 1987A supernova was seen by *two* large water Cherenkov detectors (11 events in Kamiokande-II (total mass~3 kt) and 8 events in IMB (total mass~7 kt)) that were active in proton decay searches at that time [26]. The predicted occurrence rate for neutrino-observable supernovae (from our own galaxy and of order 10 kiloparsecs distant) is about 1 per 30 years, so events will be very rare [27]. However, the information from a single event, incorporating measured energies and time sequence for tens of thousands of neutrino interactions, obtained by a very large neutrino detector, could provide significantly more information than has ever been obtained before about the time evolution of a supernova. In addition to obtaining information about supernova processes, the small numbers of SN1987a neutrino events have been extensively used to limit fundamental neutrino properties. Supernova processes continue to have very high interest because of the recent detection of the acceleration of the rate of expansion of the universe using type Ia supernovae. Recent work has shown that diffuse neutrino events from past core collapse supernova (which produce neutrino bursts) could be used in to gain independent knowledge on the cosmological evolution parameters [28]. Therefore we regard detection of supernova neutrinos, either as a burst from a single supernova or as a diffuse source from past ones, as a key mission of the DUSEL multipurpose detector.

With some 20-100 times the sensitive mass and, hopefully, a lower neutrino energy threshold (a few MeV), the energy and arrival-time spectra would have statistical power that the earlier detectors could not provide. The uncertainty of obtaining a supernova event may make this research topic insufficient to motivate construction of its own detector. But when this topic is added to the mission of a multipurpose detector, the increased science potential at virtually no additional cost to the integrated program is very compelling.

Finally, we note that there may be galactic sources of neutrinos that are of lower energy and greater abundance than the ultra high-energy neutrino sources to be explored by detectors such as the ICECUBE Cherenkov detector now being constructed deep under the Antarctic ice sheet by an NSF sponsored collaboration. Galactic neutrinos have a natural source in inelastic nuclear collisions through the leptonic decays of charged secondary pions. This source is expected to be of comparable intensity and energy distribution to the high-energy photons that are born from neutral pion decays in the same collisions [29]. Such neutrino sources, currently not detectable with Super-Kamiokande, could be seen by a megaton-class neutrino detector that runs for several decades.

4.2.1.4.6 Depth Requirements

Accelerator Neutrino Physics: A careful examination of the cosmic ray background shows that despite the strong rejection against cosmic ray induced background using the short (~10 μ s) time window keyed to the accelerator pulse, it is better to deploy a long baseline detector deep underground to minimize risk. Homestake allows such a possibility in a natural way.

We have calculated the approximate muon rate within the accelerator pulse in a 50m diameter/height cavity at various depths from the surface in Table 4.1. For Table 4.1 we have assumed one year of running corresponding to 10^7 accelerator pulses of 10μs length. For this same period of running with the anticipated beam intensities we expect ~10,000 events. To cleanly extract the beam related events without resorting to extensive pattern recognition and an active veto, the minimum depth required is ~1000 mwe. At the proposed depth of 4850 ft (4100 mwe) the Homestake detectors will have very little difficulty extracting beam related events. As we show in the next section this depth is also essential for non-accelerator physics and to maintain future potential of the detector facility.

Table 4.1 Rate of Cosmic Ray Muons within the beam pulse time (10μs) per year (10^7 pulses) for a 50 m diameter/height detector as a Function of Depth

In-time cosmic ray muons/yr	Depth (mwe)
5×10^7	0 (surface)
4230	1050
462	2000
77	3000
15	4400

The design impact of cosmic ray backgrounds on a water Cherenkov detector and a liquid argon TPC has been examined by the U.S. long baseline study group [20]. Their conclusion is that it is not possible to operate a very large (100 kt) water Cherenkov detector at or near the surface. For a fine grained detector, such as a liquid argon TPC, it is possible to collect data on the surface within the beam spill with good efficiency and reject most cosmic rays, but the ultimate rejection needed (10^8 for muon cosmic rays and 10^3 - 10^4 for cosmic ray photons) has yet to be demonstrated. For both technology choices a deep location (perhaps at a more modest depth for a liquid argon TPC) reduces the risk and increases the potential for physics. We should remark that Homestake also allows for the possibility of deploying a detector at shallower depths, including the 300 Level. Combination of the shallow and the truly deep capability will allow flexibility for future planning.

<u>Non-accelerator Physics</u>: It is difficult to consider all possible non-accelerator physics channels and precisely predict the optimal depth for either a water Cherenkov detector or a liquid argon detector. The answer could easily depend on various technical assumptions, but it is certainly clear that depth comparable to or larger than present detectors (Super-Kamiokande is at 1000 m of rock or 2700 mwe depth) is needed for the best physics reach.

Nucleon decay modes can be divided in two classes: ones where all of the nucleon energy is visible and ones where some of the nucleon energy escapes detection. In the first case, the total momentum and energy balance is a powerful tool for background reduction, and it has been often argued that these modes should require only modest shielding from cosmic rays. Indeed, most of the decay modes that were searched for in the first generation detectors required only modest depth. IMB operated successfully at a depth of 2000 feet. However, in a very large water Cherenkov detector, cosmic rays not only produce background, but also reduce the live-time of the experiment by keeping the detector occupied by frequent large energy deposits. If we require live-time to be more than 90%, a shallow depth of few tens of meters appears sufficient. This conclusion does not include consideration of the data rate, which is continuous for non-accelerator physics, and could be unmanageably high near the surface. The requirement of a reasonable data rate (<100Hz of muons) increases the depth required to approximately the Super-Kamiokande depth.

For the second class of nucleon decays in a water Cherenkov detector, a low energy tag from dexcitation photons may need to be used (For example $P \rightarrow$anti-νK^+ with a ~6.3MeV gamma from ^{15}N de-excitation followed by $K^+ \rightarrow \mu^+ \nu$ with lifetime of 12ns). These require low energy thresholds for photons. This is difficult with a background of fast-neutron (spallation products from muons in the detector or in the surrounding rock) induced low energy background events at shallow depths. Nevertheless, since the tagging photon is in-time to the main event (with time window of < 50 ns), one could conclude that these events also may not require much more than Super-Kamiokande depths. A subclass of events is, however, subject to fast neutron backgrounds. As an example of this, the mode ($N \rightarrow$anti-ν anti$-\nu$ ν) can be searched for by observing the de-excitation of the residual nucleus. The proposed Homestake detector depth (~ 4100 mwe) would reduce the muon background by about a factor of 10 with respect to Super-Kamiokande and increase sensitivity to these modes with low visible energy.

For a liquid argon TPC, much higher resolution may permit relaxation of these issues. In particular, the anti-νK^+ mode could be much easier to detect because the kaon could be identified by its energy deposit (dE/dx). Nevertheless, some minimum depth will very likely be necessary to reduce backgrounds from fast neutrons and to reduce the data rate to manageable levels.

For solar neutrinos in a water Cherenkov detector, the important issue is deadtime from spallation induced fast neutron backgrounds. At Super-Kamiokande this deadtime is ~ 20%. To maintain the same deadtime for a much larger detector, depth similar to or greater than Super-Kamiokande (2700 mwe) will be needed. For a liquid argon detector, there could be relaxation of this requirement because the dead volume around a cosmic muon could be better defined by tracking.

For a supernova in our galaxy (10 kpc), the signal level is so large (~10000/sec over a 10 sec burst), that the spallation background at depths as shallow as 500 mwe are manageable. For detection of supernovas in neighboring Andromeda (~750 kpc), however, greater depth (>1300 mwe) is needed. Optimizing depth for diffuse relic supernova neutrino search needs to consider the deadtime loss as well as spallation backgrounds such as ^9Li which sequentially beta- and neutron decays. This search may require depths similar to Super-Kamiokande or deeper, even if one could get the enhancement in signal to background from gadolinium loading.

In summary, the driving issues for depth consideration for future large water Cherenkov or liquid argon detectors will be backgrounds to low energy events from spallation products and data rates. If one wants to maintain sensitivity to specific important physics channels such as $P \rightarrow$anti-ν K^+ in a water detector, and solar and supernova neutrinos in either technology, depth in the same range as the current Super-Kamiokande detector is needed. Greater depth will enhance the physics reach of the detector. The depth chosen for the Homestake detector (4850 ft) allows full exploitation of the detector (with only 0.18 Hz cosmic muon rate for each 100kt module) and allows for future possibilities.

4.2.1.5 Nuclear Astrophysics

The Big Bang created the light elements: hydrogen, helium and traces of lithium. All other elements result from nuclear or neutrino interactions in stars. A variety of processes have been identified for different stages of stellar evolution. Initially, lighter elements are processed by nuclear fusion reactions, fusing protons into helium through the pp chain. At later stages, the helium is “burned” into carbon, and subsequently carbon into oxygen, silicon and heavier elements. Nuclear fusion terminates near iron at mass ~60. Heavier elements require sources of additional energy and particles. Supernovae and sequential neutron captures are thought to be responsible for the formation of heavier elements to uranium.

While nuclear fusion takes place at the center of stars at tremendous thermal temperatures, the effective energy of the individual ions is very low, typically below the Coulomb barrier. The reaction rates for these processes are controlled by the rapidly falling Maxwellian spectra of particle energies and the rapidly rising nuclear cross sections dominated by penetration of the Coulomb barrier. The overlap of these processes results in the *Gamow peak* in reaction rates. The center-of-mass energy for the Gamow peak is usually at ~10 keV and the reaction rates are extremely slow. Proper modeling of nucleosynthesis requires good understanding and measurements of these reaction rates. While the general form of nucleosynthesis has been understood for ~50 years, the exact details are only now being approached through measurements performed with underground accelerators and detectors. There remain 10 to 20 reactions that are essential for fully understanding the formation of the light elements.

Measuring these reactions in the laboratory requires extremely stable accelerators, high currents, high detection efficiencies, and the extremely low background rates only available in an underground location with natural shielding amounting to 1000 mwe or more. Recently, a dedicated accelerator facility was commissioned at Gran Sasso. Counting rates in these experiments are typically a few events per month. A measurement of a single cross section can take more than a year of data collection and associated calibration and determination of the systematics. The current facility at Gran Sasso (LUNA) is limited in space and restricted in its ability to mount new experiments. (Many experiments require a unique experimental design.)

In the U.S. there is a growing nuclear astrophysics community interested in pursuing these topics, including JINA at the University of Notre Dame, and efforts at a number of other facilities (Yale, Triangle Universities Nuclear Laboratory, Oak Ridge National Laboratory, and the LBNL 88-Inch Cyclotron). Homestake received a proposal (LOI-64) from a group developing a new high current accelerator to approach the $^{4}He(^{3}He,\gamma)^{7}Li$ reaction. The accelerator will require several years to develop. The initial experimental stages will take place above ground, in Berkeley. This effort does not fit in the time window of the Early Implementation Program, but the current efforts to develop new high current accelerators and significant advances in detector technology, including large arrays of segmented germanium gamma-ray detectors and charged-particle detectors, make this field attractive for the DUSEL Initial Suite of Experiments. We envision an enlarged program beyond this initial experiment. The current Letter of Interest focuses on the $^{4}He(^{3}He,\gamma)^{7}Li$ reaction as their first experiment. Other members of the active U.S. community would be encouraged to join with the authors of this Letter of Interest and develop a more extensive use of Homestake. See, for example, the website at http://www.jinaweb.org/dusel .

The Program Advisory Committee recommended that an underground high current ion accelerator, such as proposed in LOI-64, could form part of a high-profile activity at DUSEL providing first-rate scientific advances and also providing a useful and economical complement to larger projects in nuclear physics elsewhere, such as the Rare Isotope Accelerator. It also encourages the proponents and Homestake to work together to develop a plan for deployment of an accelerator into the laboratory at some time after the Early Implementation Program and matched to progress on the accelerator itself. It was also noted by the Program Advisory Committee that small groups, typically university-based, working in this field would significantly benefit from additional research and development funds to advance the development of these experiments and to prepare them for deployment underground.

In Homestake, the 4850 Level is well-shielded and would be a good location for an extensive nuclear astrophysics program requiring low cosmic ray fluxes. The current program at Gran Sasso, LUNA, is seeking a significant expansion and is experiencing competition for the limited floor space there for new accelerators and experiments. A representative of the LUNA collaboration visited Homestake and participated in the DUSEL planning. The availability of large rooms, well-isolated from other experiments sensitive to potential accelerator-produced radioactive fields makes Homestake an excellent location for an extensive North American nuclear astrophysics program. It would benefit from the good access to the 4850 Level with multiple conveyances, redundant power feeds to the underground, and custom-developed ventilation for the laboratory modules. The envisioned high-current, low-energy accelerators would require special attention by the environmental, health and safety program. Homestake's custom-developed EH&S program provides a good basis to coupling the accelerator safety issues to the special requirements for working underground. For the foreseeable future the 4850 Level would be adequately shielded for the p-p and CNO nuclear astrophysics programs. As additional accelerator/detector rooms are required, Homestake has an available footprint to host them.

4.2.2 Geoneutrinos

Neutrinos and anti-neutrinos are produced in many radioactive (beta) decays. The decays of the long-lived radioactive uranium and thorium chains and potassium produce anti-neutrinos with an energy spectrum extending to several MeV. While radiogenic heat production is thought to drive the Earth's mantle convection and cause plate tectonics and earthquakes, alternate hypotheses, including a naturally occurring critical mass of uranium at the core of the earth (georeactor), have been proposed. The observation of terrestrial neutrinos, effectively integrating over substantial volume of the surrounding crust and mantle (dimension ~100 km), termed geoneutrinos, could verify the origins of majority of the Earth's terrestrial heating as originating from radioactive decay in the mantle and crust. The experiment would also confirm or refute the georeactor hypothesis.

Recently the KamLAND experiment [30] in Japan reported the first observation of these geoneutrinos. This measurement was limited by backgrounds caused by the high flux of neutrinos from the nearby nuclear power plants. Additional geological studies indicate that the radiogenic concentrations significantly vary between continental and oceanic crust. A measurement that is clearly from a single region will be critical to solidify these hypotheses of the distributions of radionuclides in the earth. The Homestake site is well separated from reactors. A preliminary estimate concludes that the reactor background deep underground in Homestake would be ~ 7% of KamLAND's. A measurement at Homestake will provide valuable information for future reactor neutrino experiments and may improve the KamLAND results by constraining the geoneutrino backgrounds to their reactor neutrino spectrum.

LOI-71 expresses interest in just such an experimental program. The development of a geoneutrino experiment will require several steps before a proposal can be written and a collaboration developed for an experiment of this scale (~1 kt of detector mass). The collaboration has recently received LDRD funding to pursue Monte Carlo simulation of detector designs, and has requested FY07 funding to perform basic scintillator property measurements. This preliminary work and collaboration building place geoneutrinos out of the scope of the

Homestake's Early Implementation Program; however, these studies would be well suited for research and development during the Early Implementation Program period. A geoneutrino experiment, if adequately developed in the coming years, could be included in the DUSEL Initial Suite of Experiments. If a segmented geometry proves feasible, this is a particularly attractive option for rapid deployment in Homestake.

Measurements of geoneutrinos represent one of the synergistic purely-research-driven opportunities at DUSEL, with significant impact on both the earth science and physics disciplines. While concurring that this is not an Early Implementation Program experiment, the Program Advisory Committee recognized the importance of the science and encouraged the proponents to pursue this goal for inclusion at Homestake in the longer term.

In addition to detecting geoneutrinos, such an experiment would also be able to serve as a sensitive monitor for galactic-supernova neutrinos. It should be noted that the sensitivity to supernova neutrinos would be limited by the mass and be primarily restricted to electron anti-neutrinos, but could be sensitive to other neutrino flavors through elastic scattering if the internal radioactivity were low enough. This latter signal would be a model-insensitive measure of the luminosity and energy of non-electron type neutrinos from a supernova. If the internal radioactivity is adequately controlled and a deep site is selected, this experiment would also be able to monitor p-e-p solar neutrinos. Due to the shallow depth, the p-e-p neutrino signal is swamped by cosmogenic background at KamLAND. Borexino, with its smaller fiducial volume and shallower depth, is primarily aimed at the detection of ^{7}Be neutrinos.

Homestake is a particularly suitable site to host geoneutrino experiments. A modular detector design could be very rapidly deployed in many of the existing rooms in the facility with a minimum of preparation. A larger monolithic detector design would require a large room to be created, but there is ample evidence that the site can support cavities large enough for a 1kt geoneutrino detector. Homestake's ventilation plans and extensive laboratory design enables the necessary air supply and physical isolation of the geoneutrino as may be required for fire safety. Homestake's general position in the middle of the continental crust, far removed from power reactors, presents Homestake with a very low level of background neutrinos.

4.2.3 Biology, Geoscience, and Geoengineering

An aura of mystery surrounds the underground environment because of its paradoxical combination of immediacy and inaccessibility. Society depends on it tremendously for minerals, energy, water, and disposal of wastes. Even researchers on global warming associated with excess atmospheric CO_2 seek solutions to sequester the carbon within the earth. And, of course, much of society's infrastructure is underground, interacting with such disciplines as rock engineering and hydrology. Understanding this environment would inform humankind in using the subsurface more safely and efficiently and protecting it from contamination.

The subsurface is a complex environment, containing a multitude of different scales of heterogeneities and discontinuities as the result of the restless earth responding mechanically and chemically to various forces. Heat from radioactive decay of primordial, long-lived elements is dissipated. Fractures are often the conduits of fluid flow and rock-fluid chemical reactions, but not all fractures flow equally. Why do some flow but not others? Can we improve geophysical imaging technology to "see" underground processes? These are questions that have fundamental economic as well as scientific importance. And perhaps most intriguing of all, and recently in the news, is that deep within the subsurface environment are microbes that call this inner world home – "dark life." Inextricably coupled to physical and chemical processes occurring in this underground environment, dark life can tell us a great deal.

Multidisciplinary research teams are poised to investigate the central scientific questions about geologic processes and life and how they interact in the deep subsurface environment. These studies include those inspired by the economic implications of a site with a long history of mineral extraction, the prospect of finding extreme and exotic life forms, and studies of the fully-coupled earth system - mechanical, hydrological, chemical, biological and thermal – which are relevant to the nation's energy and environment problems. The ability to go *into* the earth provides ground truth for testing hypotheses and developing new methods of geophysical imaging to make the earth transparent.

4.2.3.1 Unique Attributes of Homestake for Earth Sciences and Engineering

The premise of the Homestake Scientific Collaboration is that the former mine offers golden opportunities for meeting the science objectives described by the S-1 document *Deep Science*. There many earth sciences and engineering disciplines can attack the wide range of questions open to study. The overall plan for the geosciences and geoengineering capitalizes on the unmatchable opportunities for access to the volume (more than 30 cubic kilometers!) and types of rock present at the Homestake site. *It may be the only facility in the United States that can accommodate such a wide range of experiments envisioned for an underground laboratory.*

Long-term geoscience and geoengineering experiments, such as those associated with creep monitoring or heating projects, are only possible in a dedicated facility. The absence of production activities at a site whose sole purpose is scientific and engineering research ensures that experiments are installed and maintained without concern for future interference or lack of access. The infrastructure associated with the Homestake Laboratory is unparalleled in terms of both vertical and horizontal dimensions. Having unfettered access ensures that suitable sites are available to a particular project–a tremendous asset. Finally, in many instances, the geosciences require a highly specialized situation where a particular type of environment is found; Homestake DUSEL offers a variety of rock types, degrees of isolation, and depths.

The dedicated Homestake DUSEL is well suited for isolating long-term experiments from interference from mission-oriented or active-mining-related requirements and considerations. The multiple existing levels, separated by ~150 ft, are connected by shafts, winzes, and extensive ramps, so access is excellent. The lateral extent of many levels is over 5 km. Homestake is located in a seismically quiet zone ideally suited for a deep observatory. Earth science studies can start in the upper levels and ramps accessible during the reentry and Early Implementation Program, then proceed to deeper levels during and after the rehabilitation and construction phases for DUSEL. The phased approach is perfectly suited for the depth-dependent interests and anticipated early results in earth studies.

Homestake penetrates a geology that has been folded and locally altered by intrusion of much younger igneous rocks, making it an ideal site for frontier research into the basic factors controlling all subsurface processes in heterogeneous media over a wide range of scales.

Although the Homestake DUSEL site is dominated by metasedimentary rocks, a variety of rock mechanical properties can be found within the sequence. This variety allows experimental programs that require either more ductile rock properties, e.g., the Homestake Formation, or stiffer units, such as the Yates Member of the Poorman Formation. In addition, some portions of the facility were intruded by rhyolite dikes during the Tertiary period, approximately 55 million years ago. These rocks extend through the 8000 Level to the surface and offer additional options for studies in geochemistry, mineralization, and rock mechanics. The extensive infrastructure in the subsurface ensures that experiments requiring three-dimensional access are not restricted to a simple tunnel configuration. From a standpoint of access to the rock volume, the Homestake Laboratory may be the only economically and physically viable option for some of the more ambitious and compelling rock mechanics and heating experiments.

The comprehensive investigations will not be confined to the active laboratories at the 4850 and 7400 Levels, but will make full use of the various rock environments in rock past the 8000 Level. For example, the geomicrobiology and water geochemistry investigations can characterize both shallow and deep micro-ecology within geo-volumes never before available. Working rooms exist at a depth of 8000 ft, and there is proven ability to drill down to 11,000 ft from the 8000 Level. This offers the possibility of geomicrobiology sampling deep enough at great depths to test the limits of life in both time and space. In addition, because Homestake provides vertical access as well as horizontal, it also provides access to older and more isolated strata than most or all other sites likely to be proposed for DUSEL. Indeed, much of the water in the deeper part of the mine has been isolated from the surface for millions of years. This provides a much more interesting habitat for exploring origins of life and biosustainability.

At present there are re-enterable test bores from the surface extending to a depth of 1.5 km. The network of multiple-branched, directionally-drilled surface-based boreholes further expand the spatial extent accessible from underground workings. This degree of access extends to the extensive system of boreholes throughout and adjacent to Homestake that can host monitoring instrumentation as anticipated by the "Transparent Earth" initiative. An important adjunct to the *in situ* access is the full access to more than 20,000 boxes of cores at the Homestake core library covering the immediate laboratory volumes and the surrounding area. This core library was donated to the Authority and will have a significant impact on studies involving mineralogy, petrology, and economic geology. The large library of existing literature and studies of the Homestake rock volume ensures that a very large amount of information and insight is already available about the site, allowing research to begin immediately.

The Homestake hydrological system is not particularly well understood, but offers the opportunity to study fracture flow ranging from the deepest parts of the underground to the surface. The hydrological system has made its importance known by the small, but significant, inflow of water into the 8000 Level through boreholes that were drilled downwards from that level. Although the inflows of water into the underground total only 700 gallons/minute, and much of that is from surface sources, the connection to deep water reservoirs and proximity to larger fracture systems at the intermediate levels opens interesting possibilities for the study of fracture flow, paleohydrology, water geochemistry, and fluid flow in general in the upper crystalline crust of the Earth.

The already close cooperation between the operational arms of the laboratory and the science and engineering research will provide advantages throughout the development of the laboratory. For instance, during the early construction activities, it is anticipated that studies in water geochemistry, microbiological ecology, microseismic investigations, and rock mechanics studies will start as soon as safe working conditions are reestablished. This ensures that both scientific and operational baseline studies are undertaken, providing all-important measurements to compare with conditions that develop during the course of the life of the laboratory. Studies of this sort will provide the operations management for the laboratory with important data as well. For instance, a very ambitious program of large-span excavations to support the physics experiments is slated for the 7400 Level. Detailed measurements of rock mass behavior during and after excavations will allow fundamental improvements in design and construction of long-span caverns, potentially resulting in substantial cost savings, reduced risk, and improved safety.

4.2.3.2 DUSEL Initial Suite of Experiments for Earth Studies

The ongoing process of developing the initial suite of Homestake DUSEL geo-experiments is based on an open solicitation of Letters of Interest submitted by single- and multi-member research teams. More than 60 earth study Letters of Interest were analyzed by the Program Advisory Committee in light of the activities necessary to carry out the Early Implementation Program, and the S-1 inputs for the DUSEL Initial Suite of Experiments. The breadth of interests represented by the more than 60 Letters of Interest emphasize the importance of both the large volumes and great depth of the DUSEL to push the boundaries of earth science and engineering.

The Homestake Scientific Collaboration is an open organization that welcomes innovative research, and the presently established collaborations will continue to grow and mature. Although many of the experimental programs that have been put forward are the product of individuals or small groups, the consolidation of these ideas into cohesive programs has progressed well during the past months. Development of a coordinated experimental program for the experiments was enthusiastically endorsed and promoted by the Program Advisory Committee.

The Program Advisory Committee grouped the earth sciences Letters of Interest around two unifying themes: the study of deep life, and the characterization of complex behavior of the crust. The first addresses fundamental questions regarding origins and evolution of life in an extreme environment, where life-sustaining resources are meager. The second examines the role of the complex interactions of stress, temperature, fluids, chemistry, and biology on the response of the Earth's crust and its fluids at large spatial and temporal extent. This knowledge is necessary for the safe engineering of the very large-span caverns proposed for the parallel physics program. Both deep life and coupled processes have been enduring central themes within the deliberations of the S-1 community.

For the Early Implementation Program and leading to the longer-term suite of experiments, the Letters of Interest were categorized as **Perishable Data**, **Geobiology**, **Hydrology**, and **Rock Mechanics**. The Homestake DUSEL Initial Suite of Experiments for earth studies encompass all *themes* identified by S-1 [31, 32], Appendix A8, and contributing to the establishment of laboratories identified in the EarthLab report [9]. This includes the Surface Laboratories for core, water, gas, and microbial analyses, experiments, and archives; ***Transparent Earth*** with the deep seismic observatory; ***Groundwater*** with the deep flow and paleoclimate laboratory and observatory; ***Rock Deformation*** with the induced fracture and deformation processes laboratory; ***Mineral and Energy Prospecting***, ***Coupled Processes*** with the deep coupled processes laboratory; and ***Deep Life*** with the ultra-deep life and biochemistry observatory. Figure 4.8 illustrates the feasibility of the Homestake site to incorporate all these experiments. The S-1 report described a significant set of goals for the geosciences and engineering in an underground laboratory setting, and posed a series of questions that could be addressed in that environment. The Homestake DUSEL earth studies are formulated to directly address some of the "Grand Research Questions" in the solid-earth sciences being developed by NRC for DOE, NSF, NASA, and USGS on origins of earth and life, how the earth works, and the interaction between life and the rock record [33].

Tables 4.2 through 4.4 correlate these goals and questions raised by the S-1 report to the interests shown in the initial Letters of Interest submitted to the Homestake DUSEL. Most of the earth science Letters of Interest propose to start with the Early Implementation Program and evolve naturally into the DUSEL Initial Suite of Experiments, with site selections for localities of longer-term experiments, mainly for coupled process testing in blocks. We discuss Letters of Interest related to Perishable Data and Mineral Geology; the Program Advisory Committee strongly supports these data gathering, assimilation and packaging activities and encourages the Authority to initiate them as soon as is feasible. Care must be taken to ensure that important suites of data are not lost, that the inventorying of core recovers all measurements of likely relevance to the broad suite of users, and that the ultimate mine/laboratory model be easily accessible to the community via electronic open-source access.

In the following three tables, the Letters of Interest are grouped by the S-1 grand challenges of Dark Life, Restless Earth, and Ground Truth, and for collaborations and specific approaches to address the questions and to implement the required tasks [34]. This represents a first step to further organize and encourage formation of multi-disciplinary, multi-institution, cross-cutting, and issue-driven collaborations.

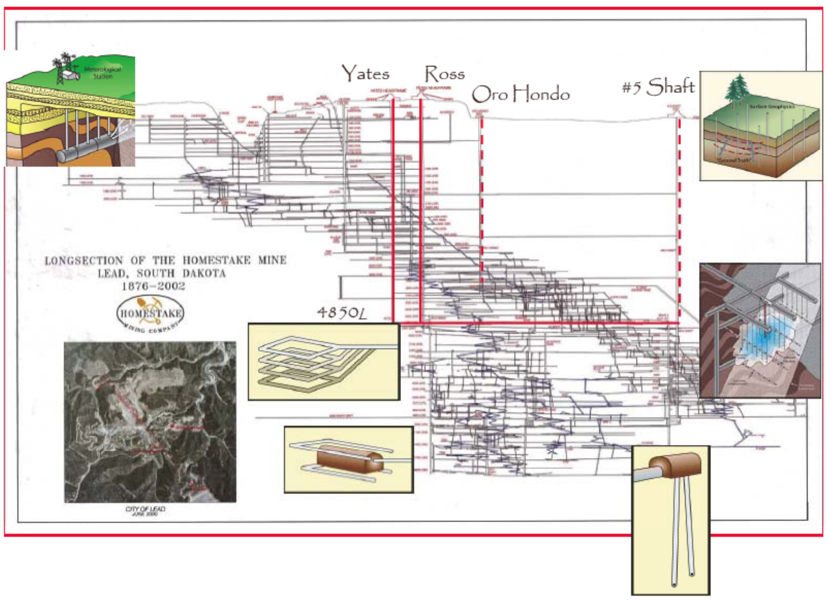

Figure 4.8 Earth Science experiments for Homestake Early Implementation Program leading to DUSEL Initial Suite of Experiments.

Inserts clockwise from upper left represent groundwater recharge studies and surface laboratory processing perishable data, seismic observatory for transparent earth, rock deformation measurements associated with induced fracture, deep boreholes for dark life search, site investigation and geotechnical engineering for large cavern excavation, and coupled block testing ([9] and [31]).

Table 4.2. Dark Life Questions and Geobiology Letters of Interest. See Table 4.3 for additional hydro-geochemical proposals related to geobiology.

Goals/Questions	**Collaborations for experiments that will address this issue (LOIs)**	**Specific approaches to implement required tasks (LOIs)**
How do biology and geology interact to shape the world underground?	Ecology/geomicrobiology – LBNL (38); Geomicrobiology on geochemistry, transport, corrosion – Princeton (75, 76, 77); Coupled Process, near surface to deep – Oak Ridge Nat. Lab. (78, 79)	Low radiation on human – Brookhaven Nat. Lab (14); Microbial evolution –U Tennessee (15); Soil, health physics, microbial population – SDSU (29, 30, 32); Microbiological analysis – U. Wisconsin (70)
How does subsurface microbial life evolve in isolation?	(38); Limits of life – New Mexico Tech. (80)	Microbial diversity – SDSMT (53)
Did life on earth originate beneath the surface?	(38); (80)	Autotrophy – SDSU (81)
Is there life underground as we don't know it?	(38); (80)	Bioprospecting – SDSU (28)

Table 4.3. Restless Earth Questions and Geoscience Letters of Interest. See Tables 4.2 and 4.4 for geomicrobiology and geoengineering proposals related to geoscience.

Goals/Questions	**Collaborations for experiments that will address this issue (LOIs)**	**Specific approaches to implement required tasks (LOIs)**
What are the interactions between the various processes controlling the subsurface environment?	Coupled process – LBNL (41); Block test of rock failure – Penn. State (55); Hydro/Mechanical - U. Wisconsin (65); (78)	Partitioning between hinges - Montana Tech. (10); Gold mineralization, role of iron, thermal history, breccia evolution, volatile in dikes – SDSMT (18, 20, 21, 44, 68); Faulting and fracture – U. Hawaii (43); Stress-Fluid Monitoring - Freie U. Berlin (60)
Are underground resources of drinking water safe and secure?	Hydrogeology, geochemistry – LBNL (36, 37)	
Can we reliably predict and control earthquakes?	Sensors – UCB (13); Geophysics – LBNL (39); (55)	
Can we make the Earth "transparent" and observe underground processes in action?	(39)	Cosmic Ray – LBNL (42)

Table 4.4. Ground Truth Questions and Geoengineering Letters of Interest. See Table 4.3 for geoscience proposals.

Goals/Questions	Collaborations for experiments that will address this issue (LOIs)	Specific approaches to implement required tasks (LOIs)
What are the mechanical properties of rock?	Mining Engineering - SDSMT (4)	Deformation, scaling, and stress in Yates - U Utah (1, 2, 3); Fracture network - Virginia Tech. (34)
What lies between the boreholes?	(13); (39)	Mapping/surveying-Montana Tech (9); Geological model, mapping - U. Minnesota (45, 46); Mapping – Virginia Tech. (47) Database, acoustic mapping – SDSMT (11, 62)
How does rock respond to human activity?	Rock mechanics geotechnical – LBNL (40)	(1)
How does water flow deep underground?	(36)	Dewatering, hydrological instrumentation, footprint – SDSMT (6, 12, 24)
How can technology lead to a safer underground?	Risk assessment – Virginia Tech. (35); (40)	(1); Robotics – SDSMT (25); Rock Bolting and Backfills - Montana Tech. (67)

4.2.3.3 Geomicrobiology–Dark Life

The Grand Challenge dark life questions and geobiology Letters of Interest are listed in Table 4.2. The integrated geomicrobiology approach can evolve from ecology and environmental studies to the search for life, with potential societal benefits including bioprospecting for useful microbial chemicals, more complete understanding of controls on microbial activity and growth in subsurface environments. In this latter case, the enhanced ability to predict the activity and distribution of microbes in subsurface strata will assist our ability to use these cells in subsurface processes. Such processes include alteration of fluid movement in the subsurface which could be used to manage carbon sequestration, biomining efforts, bioremediation, and repository security. The geochemistry Letters of Interest analyzed in this section are also an integral part of geoscience investigations of Section 4.2.3.4.

4.2.3.3.1 Search for Life

Microbial inhabitants of the deep terrestrial subsurface depend on energy and nutrients from ancient organic matter, inorganic sources associated with the host rocks and associated fluids, and a range of other abiotic sources, such as H_2 from radiolysis and hydrocarbon gases. Microbial populations are typically sparse, isolated in pores, slow growing/respiring, and sometimes starved or resource-limited relative to their surface-dwelling counterparts. The geological isolation of deep subsurface microbial communities elicits questions related to origin and requirements for life, evolution, diversity, coupled biogeochemical processes such as mineral formation and dissolution, as well as constraining limits for life on Earth or beneath the surface of Mars and other planetary bodies. Advances in our understanding of the origins, diversity, distribution, and function of microorganisms in deep, often extreme, subsurface environments will rapidly expand our knowledge of geomicrobiological and biogeochemical processes on Earth and beyond. DUSEL provides a unique opportunity to enhance the concurrent development of increasingly sophisticated tools for reconstructing the relationships among all parts of the Tree of Life.

4.2.3.3.2 Bioprospecting

Bioprospecting and the discovery of novel microorganisms from deep subsurface habitats provide opportunities for developing new pharmaceuticals, processes for biochemical and chiral-specific synthesis, biotechnological applications, environmental remediation and energy production. Deep under the Earth's crust, the diversity of microbes relies upon the variety of nonphotosynthetic biogeochemical processes that allow them to survive and force them to adapt to extreme conditions. Discovering how life persists under the extreme conditions of heat, pressure, lack of water and O_2, salinity, and extreme pH at depth on our own planet can open new avenues for basic and applied research. In general, non-photosynthetic chemoautotrophs are expected to be prevalent in Homestake geologic formations.

4.2.3.3.3 Ecology and Environmental Studies

Human and animal activities, e.g., mule-drawn ore cars, during 126 years at the Homestake Mine have certainly impacted local ecology by introducing a wide range of chemoheterotrophic surface microorganisms and offering unique opportunities to investigate evolution/adaptation. Early research would focus on the transport and adaptation of surface microbial communities to deeper environments. Processes to be investigated include mineral precipitation and dissolution reactions, geochemical evolution of groundwater (both long- and short-term), and bioprospecting for novel traits of indigenous microbial communities, as well as the transport and migration of the cyanide-degrading microbe isolated by the Homestake Mining Company which is used in surface remedial actions. In humid areas of the mine biofilms are apparent, not only on the rocks but also on structural materials containing corroded metals and decaying wood.

4.2.3.3.4 Integrated Geomicrobiology Approach

As DUSEL becomes accessible to researchers, the first attempt in geomicrobiology will be sampling at representative sites of soil, rocks, and groundwater. Multidisciplinary collaboration is essential for drilling and coring rock samples, which will provide critical information on geomicrobiology, geochemistry, geophysics, and rock mechanics. In particular, geomicrobiologists will examine the cores for signature microbes and their metabolic activities utilizing tracers. Access to the 4850 Level will enable detailed analysis of transport and migration of subsurface microbes, microbial adaptation and evolution in ancient sequestered groundwater, ecological genomics and gene transfer, responses to contamination (and to the presence of DUSEL), biofilm formation, function, and relation to fracture transmissivity, groundwater-rock reactions driving ecosystem energy flux (e.g., geogas), and other dynamic factors such as temperature, pressure, seismicity, and time of hydrological isolation.

As DUSEL proceeds to the 8000 Level, where the temperature may reach close to 60° C, it is of great importance to explore deep extreme microbial ecology in localized fractures, boreholes, and coreholes. As flooding at Homestake DUSEL has continued to expand its boundaries below the 5000 Level, it is pertinent to investigate the influence of flooding in the deep environments. There is an indication that "upwelling" below the 8000 Level may exist to limit the zone of influence, as a relative large inflow at the 8000 Level [35]–see Appendix A9–may be associated with the deep borehole to 11,000 ft drilled from the 8000 Level. The prospect of finding ancient bacteria at Homestake depths is very good, as deduced from the recent discovery of an exotic strain of microbes at a South Africa gold mine in a fracture zone at depth of 2.825 km (9268 ft) intercepted by an exploratory borehole into an unmined zone ~100 m above an ore contact [8]. The fracture water is millions of years old, and the microbes survive on nonphotosynthetically derived sulfide and hydrogen, suggesting that the deep crustal biosphere may be energy-rich in a way that can sustain microbial communities indefinitely.

Deep groundwater moves extraordinarily slowly, and microbes on fracture surfaces depend on flow-limited nutrient flux. In the absence of appreciable flow, microbes may also create micro-zones depleted in substrates that can be replenished only by diffusion. Because biomineralization and biogas formation hinder the nutrient flux by closing pore throats, these microniches may go through cycles of growth, steady state, and decay. The appearance of so many of the bacteria and 16S rDNA clone libraries in samples obtained from the deep subsurface hints at a strategy by which organisms in diffusion-limited habitats first grow, deplete their local nutrient supply, and then sporulate or become exquisitely efficient in order to survive. When local nutrient concentrations again become permissive, the spore then germinates and the cycle begins anew. In this situation, it is unknown how or whether spores can germinate or vegetative cells can divide when the environment imposes extreme spatial constraints, such as pore spaces that are only barely larger than the microbial cells themselves.

Deeper levels of DUSEL might have partitioned some areas into discrete zones, where hot, saline and old waters were segregated. Under the influence of fractures with various depths, widths, and frequencies, ancient microorganisms sequestered in these zones might have established distinct evolutionary lineage. Geological samples from greater depths of multiple holes in these segregated areas are therefore expected to provide fundamental information on the presence of life in deep extreme environments and further implication on the origin of life on Earth and limits of life in the biosphere. As an exceptional geomicrobial observatory, Homestake DUSEL will continue to provide unlimited, crucial information on Earth's history and its future path.

One of the abiding mysteries of our existence is the origin of life. Since we have no deep understanding of this problem, we have no way to constrain the time span or circumstances necessary for life to emerge from prebiotic chemistry. However, if we consider the possibility that the emergence of life is a relatively rare event, then either it was repeatedly extinguished during the period of Earth's heavy bombardment or it had a refuge from the surface chaos. This is one of the more compelling reasons to consider the subsurface as the preferred, and possibly essential, habitat for early life on Earth. If subsurface environments of today resemble those of early Earth, it is also reasonable to entertain the possibility that the deep subsurface still harbors the most ancient of life forms.

The dark life questions (see also S-1 report [5], Chapter 2, and Table 4.2) are addressed with specific approaches by the geomicrobiology collaboration. Example science questions and directions include:

(1) Have the cyanide-degrading bacteria that were backfilled with treated waste into the stopes survived, and are they active?

(2) Are there microbes of anthropogenic origin present in drifts of different ages? Do they represent a distinct microbial community structure signature that can be linked to mine activities and/or time of abandonment?

(3) Since the mine is so old and some drifts were abandoned more than 60 years ago, prior to the use of antibiotics, do anthropogenic bacteria that have survived represent an archive for unique studies, and are these pathogens and other bacteria that were just "discovered" also present?

(4) How long have microbes been separated from surface ecosystems? And can evolutionary rates be quantified?

(5) Is the mutational profile, inferred from sequence analyses, distinctive, reflecting expected differences in mutagenic processes?

(6) Do the remaining genes evolve faster or more slowly than surface counterparts?

(7) Do they exhibit genomic signatures characteristic of small population size?

(8) Do subsurface microbes show much greater spatial structuring of populations and smaller genetic population sizes? If so, is it linked to processes of genomic evolution?

(9) Are genomes reduced in size and streamlined relative to their surface counterparts?

(10) What roles do phage, lateral gene transfer and other mechanisms play in evolution?

(11) How is genome content evolved in the absence of host and higher cell densities?

(12) How have they adopted to different stress regimes since some are nonexistent (ultraviolet and oxidative stresses) while energy, nutrient, radiation, dehydration are continuous?

(13) How could macromolecules (e.g. nucleic acid, lipids, and proteins) remain stable for millennia? (Evolutionary gradients, eco-genomics, and primitive life; Fluid, energy, and organizational transport; Impacts of human intervention on subsurface ecology.)

The major research emphases of the geobiology Letters of Interest are broad and interwoven, but fall into three principal themes: Geomicrobiology, Geochemistry, and Biology. The endeavors proposed in these fields are also related to experiments envisioned for hydrogeology, rock mechanics, and in the coupled interaction of processes related to the ensemble of all of these fields. Correspondingly, as with other earth sciences efforts, many of the proposed Letters of Interest may be combined into larger and more coherent research themes, benefiting from coordinated and collaborative sampling campaigns and experimental efforts.

4.2.3.3.5 Geomicrobiology Letters of Interest

[LOIs 15, 28, 29, 32, 38, 53, 70, 75, 76, 77, 78, 79, 80, and 81]: Microbial studies proposed for the Homestake DUSEL cover the essential areas of the subsurface microbial ecosystem. Common research thrusts are gathered under the rubric of "Ecology/geomicrobiology collaboration for microbe evolution" envisioned by LOI-38. This vision encompasses almost all proposals related to geomicro-related research. LOI-70 also proposes a comprehensive research scheme, integrating geomicrobiology with geochemistry and geophysics. The geomicrobiology proposals can be further grouped into three major areas based on the scope of the proposed studies: (i) evolutionary/phylogenetic diversity [LOIs: 15, 29, 38, 53, 81]; (ii) metabolic diversity [LOIs: 28, 32, 38, 79], and; (iii) ecological diversity – interactions between microbes and deep underground environments [LOIs: 38, 70, 75, 76, 77, 78, 79, 80]. In particular, LOIs 78 and 80 address the importance of interactive studies in geosciences and propose multidisciplinary, long-term plans to characterize coupled processes of biology, geology, hydrology, chemistry, and engineering, and further understand the limits of life on Earth.

The majority of the Letters of Interest propose step-wise, phased approaches to research. As the 4850 Level becomes available, research foci are on the migration of surface microbes into the DUSEL environments, emphasizing evolutionary trends, adaptation in deep environments, and identification of novel microorganisms. At the 8000 Level, the research foci are further expanded and shifted to examine microbial activities in deep and extreme environments: metabolic uniqueness and divergence, novel metabolic pathways and biochemical components (membrane lipids), and the impact of underground geochemical properties on microbial communities. However, all Letters of Interest except 78 and 80 are ready to implement their experiments immediately after mine reentry is allowed.

The mainstream approaches are identified as: molecular studies for genomics and metagenomics of unculturables using PCR-based DNA cloning and sequencing; denaturing gradient gel electrophoresis (DGGE), DNA microarrays, etc.; visualization of biofilms with fluorescent in-situ hybridization (FISH); characterization of hydrocarbon-containing fluids with stable isotopes; selection of autotrophs and organotrophs; and identification of novel microbial metabolites.

4.2.3.3.6 Geochemistry Letters of Interest

[LOIs: 20, 21, 37, 44, and 68]: The chemical attributes of the rock and fluids adjacent to the proposed DUSEL dictate the characteristics of the deep environment. Abundant information is available on geological properties of the Homestake mine; however, it is important to examine in detail the evolution of gases, the composition of rocks, and the inclusion fluid that will affect the biological systems directly or indirectly. LOI-37 proposes a comprehensive step-wise collaborative research effort on the chemical evolution of fluids in the Homestake hydrological system. In particular, outcomes of the studies on thermal history, fluid flow and inclusion, and fracture-matrix interaction in rocks may provide important clues on life history and microbial evolution in Homestake. Various experimental approaches are proposed to determine and refine: the partitioning effects of gaseous and liquid CO_2 and other elementals; elements of litho-stratigraphy and thermal history; the role of iron formation; lithostatic pressure/fluid inclusion; crustal assimilation using isotopes; volatile evolution; and fluid flow and fracture-matrix interaction in the fractured rock system using conservative and reactive tracers.

4.2.3.3.7 Biological Effects Letters of Interest

[LOIs: 14 and 30]: The DUSEL environment is substantially shielded from cosmic rays that can cause negative impacts on human health at the genetic and behavioral levels. Two Letters of Interest hypothesize that ultra-low-level radiation can improve biological properties of the human cells, although potential adverse impacts may still exist. Proposed studies are intended to measure (1) the effects of low-level radiation on human cells, invertebrates, and small mammals and (2) the mutation rates and survival/repair of radiation (^{60}Co)-induced damage.

4.2.3.4 Subsurface Geoscience – Restless Earth

The grand challenge Restless Earth questions and geoscience Letters of Interest are in Table 4.3. An initial focus on the dewatering operations can rally the wide range of earth science disciplines to strengthen collaborations needed to solve many important, but sometimes taken for granted, issues. The understanding of low-flow, nearly-neutral-fluid setting with complex but relatively competent rock mass at Homestake can shed light on deep circulation of groundwater systems, provide hydro-geochemical inputs to the dark life in the last section and hydro-mechanical inputs to the ground truth geoengineering in the next section. Subsurface geophysical imaging is an integral part of geoscience with equal significance in geoengineering, to be analyzed in the beginning of the next section. It is prudent to point out that the geoscience Letters of Interest, analyzed by the Homestake Collaboration and evaluated by the Program Advisory Committee, will start with realistic tasks and tackle the grander questions in the long run.

4.2.3.4.1 Hydrology

Fluid flow and transport are active at considerable depths. Direct subsurface observations and experiments are rare. Samples of deep rock from drill holes are small and have been disturbed by the drilling process, making them unsuitable for testing of factors that control fluid flow. DUSEL would revolutionize the field by providing an opportunity for large-scale, direct observation and measurement, impossible by any other means. Deep flow and transport research is central to important societal concerns, such as the protection of drinking water and irrigation water supplies, the disposal of hazardous and nuclear wastes, and the remediation of contaminated aquifers. The hydrology community would use a deep laboratory to study fundamental processes that today, after decades of surface-based research are still understood in only the simplest of terms. Recharge and infiltration, fracture permeability, multiphase flow, flow in fracture networks and characterization of the networks, verification of well test and tracer test models, characterization of active flow systems and paleoflow systems, coupling of flow, stress, and heat, reservoir potential and permeability of tight rocks all need research. DUSEL would provide deep groundwater regimes that could be isolated and studied within an undisturbed setting.

4.2.3.4.2 Monitoring of Dewatering Operation

Upon initial reentry, sensors can be installed in winzes and along vertical boreholes to measure the elevation of the water table and electrical conductivity of water at various depths, and to monitor the rising and then falling water table and associated change in stress. During 126 years of mine operations, the flow field surrounding Homestake has been dominated by dewatering; that is, mine workings will continue to act as fluid sinks, and flow has been toward them even over the past several years of flooding. The monitoring of humidity and microclimate conditions along the drifts using microsensors, and the identification of water inflow zones at all levels are also planned before, during and after the dewatering operation. Dewatering has introduced air into the system, probably allowing fractures to desaturate near the drifts. Once desaturated, the permeability of a fracture can decrease dramatically and flow may even be diverted from drifts by capillarity. The rock mass will go through the transition from saturated to unsaturated states. Homestake with multi-drift access is ideal for studying the critical zone (the dynamic interface between solid earth and its fluid envelopes). The critical zone with the transition from saturated to unsaturated states is one of the specific areas that are ripe for major scientific breakthroughs as discussed in the NRC Report *Basic Research Opportunities in Earth Science* [36].

The hydrogeology collaboration envisions working with the Authority team during the rehabilitation period to identify zones of observable flows, collect rock and fluid samples and select sites with active flow characteristics suitable for additional experiments. A significant footprint from the existing mine will be maintained with the establishment of a scientific protocol to define unique and major features underground. In test sites identified, flow path modification experiments can be conducted with tracers, chemical solutions, microbes, and thermal and mechanical stresses to reduce or enhance the formation permeability and storage capacity. In active manipulation experiments, flow direction and magnitude can be changed by altering prevailing inflows or using boreholes from drifts to capture additional inflow or to inject water. In addition to dewatering of the deep levels, test sites around and below the open pit with levels connected by ramps are of interest for recharge studies for the determination of the cone of influence of dewatering and to define the interaction between recharge and regional flow field. Similar zones of ramps and levels accessible at the 4850 Level and the deep region above the 8000 Level are also candidate sites for fluid migration and coupled process testing in DUSEL.

4.2.3.4.3 Hydrogeology and Hydromechanical Letters of Interest

The types of access afforded at Homestake can be used to address a number of topics of fundamental interest, including fracture permeability and connectivity [LOI-36], solute transport and dispersion in fracture networks [LOI-36], and the effect of stress state on hydraulic and transport properties [LOI-65]. Examples of specific questions that might be addressed include: LOI-36: Is flow distributed across fractures, largely channelized within fractures, or largely along fracture intersections? LOIs 1, 3, 65: How does the stress state affect permeability and permeability anisotropy, and can these properties be predicted from the stress state? LOI-65: How do permeability and permeability anisotropy change with depth? LOIs: 2, 36, 65: How does permeability change with the scale of measurement? What roles do intergranular porosity, dead-end pores, and velocity variation in fractures play in dispersion and tailing, and does their significance change with scale? LOI-37: What is the source of water now entering the mine? What is the geochemistry of subsurface waters, and how has it been altered by mine activities?

Most if not all of the hydrogeology and hydromechanics research will rely upon background data from mine records and cores and from monitoring (which should begin as soon as possible). Synthesis of this background information will provide the framework necessary for planning experiments by (for example) delineating lithologic boundaries and geologic structures [LOI-45], identifying major fracture zones and extensive (continuous drift-to-drift) fractures [LOIs: 45, 46], identifying water inflow locations, and providing estimates of gross rock-mass permeability. Monitoring priorities include rate of water-level rise and concurrent deformations and/or displacements [LOI-12, 6].

Access to rock volumes at various orientations via shafts, drifts, and boreholes (either existing or future, drilled from drifts or from the surface) will permit geophysical characterization for integration with other data as a basis for later studies [LOIs: 39, 47, 60, 62]. Geophysical tomography is possible using energy sources and detectors along boreholes, shafts and drifts.

4.2.3.4.4 Rock Deformation

Rock fractures and faults play a critical role in the geological processes that take place underground – a role that is impossible to investigate from laboratory research on rock samples alone. DUSEL would permit continuous, direct measurements of rock strain in the field, and provide an opportunity to evaluate factors that control it and the resulting stress on subsurface rock. Improved understanding of stress and strain distributions within the rock would lead to an improved understanding of how energy accumulates near faults and fractures, a vital step toward reliable prediction of earthquake timing. The depth dependence of fracture networks and associated rock mechanics measurements are of fundamental interest to determine whether fractures displaying enhanced permeability for flow are critically stressed [37].

4.2.3.4.5 Rock Mechanics Letters of Interest

Letters of Interest relating to rock mechanics and to geohydrology [LOIs: 1, 2, 3, 4, 34, 35, 36, 40, 41, 43, 62, 67, and 11, 45] focus on an improved understanding of how rock masses respond to load. "Load" is understood in a broad sense and includes changes in the ambient stress field induced by excavation and loads imposed by gravity and by forces of tectonic origin in geologic time. These latter loads are responsible for the current configuration of the Homestake rock mass that is replete with fascinating folds on folds, distributed slip on foliation planes, kink bands in graphitic schists, late igneous intrusives that cross-cut relict bedding, occasional shear zones, and deep fractures bearing hot water under high pressure, and so on, including massive units that seem indurated to high strength but lack foliation. The great geologic variety and the presence of more than 600 km (370 miles) of development openings make the Homestake site a most attractive candidate for the study of rock mechanics over scales ranging from micrometers to kilometers. Most importantly, these scales can be related in a sound scientific manner at Homestake. The Program Advisory Committee comments that the rock mechanics studies have an important contribution to make to the safe operation of the laboratory, and to the provision of early experimental data in support of the design and construction of large caverns. In addition, there are more homogeneous rock volumes potentially well-suited to large cavity construction.

Over a shorter time scale of a decade, there are data that can be updated and used to good advantage in engineering research concerning time-dependent deformation mechanisms of Homestake Precambrian meta-sedimentary rock units (the Poorman, Homestake, and Ellison Formations are exposed in the Homestake underground). The lessons learned from these features could well have applicability to other rock masses as the underlying mechanisms are identified and quantified at various scales, including laboratory scale (several centimeters), intermediate scale (large block, pilot galleries of several meters), excavation scale (tens of meters for pilot scale cavern to full scale detector caverns), and the far-field scale (hundreds of meters).

A unique opportunity exists to investigate the mechanics of rock mass deformation in the Yates Member of the Poorman Formation exposed on the 4850 Level between the Ross and Yates shaft. The Yates Member is massive and strong and is a leader among several candidate sites for the 100kt neutrino detector caverns whose science is strongly supported by the physics community. Adequate space is easily available to increase the number of caverns to 10 or more as required by the requirements of the science. The Program Advisory Committee observed that having a dedicated facility where science and engineering have the first and only priority would aid considerably in advancing knowledge on a broad front of many disciplines and in achieving specific study objectives by teams of investigators who have expressed great interest in the Homestake site. There would be no surprises and delays such as could be encountered were the mine still operating as a mine with business as the first priority.

4.2.3.4.6 Crustal Heat Flow

Understanding heat flow within the earth has been a fundamental question in geosciences ever since Lord Kelvin's calculation in 1862 of a minimum age for the earth of 100 million years based on the temperature gradient in the earth's crust. This simple calculation underestimated the earth's true age by an order of magnitude, largely because it did not consider heat generated from decay of radioactive elements. DUSEL offers an ideal setting to understand crustal heat transfer processes within the earth's crust at an unprecedented level. The depth of the mine, coupled with deep boreholes will enable precise measures of temperature variations within the upper 4 km of the earth's crust. These measurements can be coupled with detailed analyses of the distribution of radionuclides in the Homestake system to produce a detailed map of heat flow. The diverse geological rock units within the Homestake will have different concentrations and distributions of radionuclides, affecting heat generation within those units. In addition, it will be possible to examine the impact of the degree of water saturation within the rocks on heat transfer processes and the re-distribution of heat-producing elements by examining variations in heat flow as the accumulated water in the deeper part of the mine is removed. The sensor arrays installed within the mine will also be used to determine the impacts of the large-scale Earth Sciences experiments (especially tests involving manipulation of temperature and/or chemical gradients within the rock). The anticipated results of these investigations will yield a unique understanding of heat flow in the continental crust.

These studies of heat generation and transfer within the Homestake system will also provide essential information for many of the other studies planned for the DUSEL. Heat transfer within the crust is clearly a fundamental issue for earth scientists and engineers studying the viability of sustained extraction and development of geothermal resources. The temperature gradient within the earth's crust also has major implications for the extent of life in the subsurface. Understanding the distribution and mobility of radionuclides in the subsurface is crucial for issues as diverse as underground radioactive waste storage and studies of geoneutrinos produced from the natural decay of uranium and thorium in the rocks.

4.2.3.4.7 Coupled Thermal-Hydrological-Chemical-Mechanical-Biological Processes

The depth and extent of Homestake shafts and drifts offer opportunities to conduct *in situ* experiments on different scales and at different depths. More importantly, they will allow access, at multiple orientations, *across* rock volumes of various sizes, permitting greater control of experimental boundary conditions than is usual. The Program Advisory Committee supports the varied range of activities proposed in the Letters of Interest, and the scientific questions which they propose to address. In particular, they enthusiastically endorse those which address issues of scaling in space and time, afforded by the large size and extended occupancy of the proposed laboratory, examine perplexing issues in the hydrogeology of fractured rock, and address the roles of coupling among geobiological, geochemical and geophysical processes.

The Homestake presents a unique opportunity to investigate coupled thermal, hydrological, chemical, mechanical, and biological processes in a very different geologic, mineralogic, and hydrologic environment than has been attempted previously. The largest underground thermal test in the world was performed at Yucca Mountain, Nevada, which is in Miocene-age high silica rhyolitic tuffs (granitic chemical composition) that had previously undergone little alteration or deformation. This test yielded invaluable geochemical and isotopic data on the evolved gases and aqueous fluids in fractured rock for over eight years in a system ranging in temperature from about 25 to over 200ºC. The test was a key breakthrough for the development and validation of computer models for reactive geochemical transport in fractured unsaturated rocks, which have since been successful in capturing the evolution of the water and gas chemistry over several orders of magnitude difference in the permeability of the fracture system compared to the welded tuff rock matrix. Yet the volcanic tuffs at Yucca Mountain are low in iron and are in the unsaturated zone, resulting in a relatively oxidized geochemical environment, and low in nutrients for microbiological activity. Being in the unsaturated zone at near atmospheric pressure results in a system that is dominated by steam generation and vapor transport, rather than fluid pressure-driven hydrothermal convection.

In contrast, the host rocks of the gold-bearing horizons at Homestake are Fe-rich, highly reduced metamorphic rocks (graphite is a common constituent), are strongly deformed, and are deep in the saturated zone. The abundance of reduced ore minerals make the geochemistry quite unique in terms of the coupled system of water-rock interaction and metal transport under hydrothermal conditions. The metamorphic mineral assemblage at Homestake is very different from that of the rhyolitic tuffs at Yucca Mountain. Reaction rates are highly dependent on reactive surface areas, which in turn are a function of the hierarchy of scale of fluid flow, geologic structure, and mineral fabric. Thus the well-developed metamorphic fabric of the Homestake iron formation and the adjacent lithologies would provide a unique system in which to monitor fluid flow and reaction-transport processes under a well-controlled thermal environment. The analysis of thermal waters using stable and radiogenic isotopes as well as major ion geochemistry would yield a wealth of information that could be used to validate coupled process models that include thermal, hydrological, chemical, and mechanical processes. For example, because the rocks are approximately 2.2 billion years old, the $^{87}Sr/^{86}Sr$ ratios of the individual minerals will be very different, owing to the different initial Rb/Sr ratios in the minerals. Therefore, shifts in the isotopic ratios of strontium in waters reacting with the minerals could be used to constrain their rates of reaction under hydrothermal conditions.

In terms of understanding thermally-induced fluid pressurization, hydrothermal convection, mechanical deformation, and mineral alteration, heating of these rocks under saturated conditions would allow for investigation of strongly coupled processes that are an important phenomenon in many geological environments, but which have never been studied under well-controlled conditions over long time periods and large spatial scales. Experiments at the scale of 100-meter or larger rock blocks could be sited between existing adits and monitored from adjacent adits. Because of the low thermal conductivity of rocks, the effects of heating would be localized to a relatively small region around the heated block. Many coupled processes and their effects could be examined, such as fracture generation and propagation, microseismicity, microbial and colloid transport and plugging. The experiment would also be a unique system to test novel geophysical techniques as well as *in-situ* thermal, chemical and biological sensors in extreme environments over long time periods.

4.2.3.4.8 Mineral Exploration Research Letters of Interest

There are several Letters of Interest related to the petrogenesis of ore bodies and economic geology [LOIs: 10, 18 ,20 ,21 ,44]. These proposed activities do not require early access to the mine, but are very well suited for the opportunities presented by the Homestake and associated mine records. The Homestake mine was operated continuously for 126 years until 2002. Although the occurrence of gold at the Homestake mine was studied extensively as part of the exploration and mining process, significant information about the gold and its host rocks remains to be discovered. Industrial and other uses of gold throughout the world are not diminishing and gold will continue to be in demand in the foreseeable future. By any standard, the gold at Homestake is a world class deposit, and an improved understanding of the genesis of gold deposits at Homestake has direct and immediate relevance to mineral development in the U.S. and the world. *Note that these are research interests whose results will be applied elsewhere. Mining and other commercial extractive operations will not be conducted at Homestake.*

4.2.3.4.9 Perishable-Data Letters of Interest

This activity preserves existing information related to the geology, hydrology, rock core archive, 3-dimensional layout of the facility, and other related data; takes advantage of a one-time opportunity to gather geologic, hydrologic, engineering, and biological information that will occur as the facility is reopened, and, gathers new information which can be used for planning and design of later experiments and underground laboratory space. The Homestake mine records include rock core, paper files, and information within a Vulcan mining software database. The rock cores have been transferred to the Authority and are available for scientific study. The approximately 20,000 boxes of core are being inventoried by the South Dakota Geological Survey. Important paper files selected by Homestake Mining Company from their archives have been donated to the Adams Museum in Deadwood, South Dakota. The rest of the information must also be compiled and put into database-ready format for linking with related information and dissemination via the Internet (LOI-11 addresses this activity). Chapter 8 describes in more detail the vast amount of reference materials currently available.

Collection of certain information related to the mine geology, mine hydrology, engineering properties of the rock, and biological properties of media such as mine water must be initiated immediately upon reopening of the mine or the opportunity to gather such information will be lost [LOIs: 1, 6, 12, 24, 36, 37]. Other proposals to gather similar information require early and ongoing, but not immediate access to the mine. Among the types of information to be gathered are stress-strain and geophysical characterization of the rock, measurement of water levels in the mine, water inflow rates to the mine, occurrence and orientation of fractures, biological signature of the stagnant and incoming mine water, 3-dimensional mapping of fractures, and 3-D mine or surface geology if further needs are identified [LOIs: 3, 40, 43, 65; possibly 39 and 45, 46, 55]. Several of the Letters of Interest regarding these subjects have common or related themes and could mutually benefit from combining research efforts resulting in the most comprehensive and best information. Additionally, the use of micro technology [LOI-13] should be considered wherever possible for purposes of subsurface monitoring or data gathering. Subsurface data collection might also benefit from the development of robotic technology for remote collection of data [LOI-25]. Such technology could prove valuable by reducing the requirements for ventilation in remote areas of the mine and minimizing risks to personnel.

4.2.3.5 Subsurface Engineering – Ground Truth

The grand-challenge Ground Truth questions and geoengineering Letters of Interest are in Table 4.4 of Section 4.2.3.2. Stability of underground excavations is a primary motivation for rock engineering. Collaborations among industry, academe, and national research institutions are paramount for the success. Many of the LOIs analyzed in the geobiology and subsurface geoscience sections are closely related to the geoengineering tasks.

4.2.3.5.1 Transparent Earth - Sensors and Geophysics

The development of imaging technologies is a primary goal of DUSEL. Just as medical imaging techniques have revolutionized nearly every field of medicine, accurate subsurface imaging would benefit every area of research in the geosciences and in rock engineering. Currently, seismic surveying from the surface or in and across boreholes is the main geophysical tool for imaging the deep earth. The geology through which the waves travel is typically inferred only through general knowledge or through rock samples from sparse boreholes. DUSEL would allow direct verification or “ground-truthing” of geophysical imaging. Surface-based predictions of underground structure could be verified directly within a deep, three-dimensional volume of rock accessible to back-excavation and known from past mining and core drilling.

DUSEL Transparent Earth is a plan to install and operate a permanent seismic observatory illuminating the volume of the Homestake DUSEL facility from all six possible directions. The Homestake DUSEL site offers a unique opportunity - the large volume of mine working of the deepest mine in North America is surrounded and underlain by literally hundreds of open boreholes, which can affordably be instrumented with accelerometers [38]. With access to depths away from near-surface noise, Homestake is ideal for observation of broadband signals from activities within the facility and from seismic events at local, regional, and teleseismic distances. This specialized seismic array can allow the community to image rapid dynamic changes in the rock mass. For instance, investigators can immediately begin to estimate seismic parameters of events associated with de-watering, excavation, and various rock mechanics experiments, and estimate source kinematics caused by activity within or near the underground facility. Given the damage location of the event determined by the array, the affected rock mass can be excavated to find the source damage in the rocks. When found, a direct connection can be made between the damage process and seismic waves generated. This fundamental knowledge would be applicable to any bedrock sites, and help answer important questions concerning the energy budget of fracture growth and dynamics, local frictional behavior within a rock mass, seismic scaling laws, and interpretation of seismic moment tensors.

Homestake DUSEL offers the opportunity to develop new geophysical imaging techniques. Knowledge gained would have significant impact on our life, such as devising reciprocity methods of detecting and characterizing underground structures and activity for homeland security applications. Signatures of pumping-induced seismicity can be used to elucidate stress and fluid dynamics. Homestake offers the opportunity to run hydraulic fracturing tests with geophysical monitoring, and then excavate the fractured rock to find ground truth. This fundamental evaluation of hydraulic fracturing has immediate application in geothermal energy extraction with enhanced well connectivity. Long-term monitoring of pressure and stress can also decipher the tidal, seasonal, climatic, and tectonic relaxation responses. Electromagnetic techniques are promising for both monitoring fluid and imaging fractures. The streaming potential is sensitive to fluid chemistry and works with both polar and nonpolar fluids, e.g., liquid CO_2. This imaging method has been demonstrated in the identification of hydraulic fracture precursors.

In the following years, seismic instrumentation in many boreholes and along drifts at the site will result in the most densely instrumented geophysical observatory in the world, providing high-resolution data for mapping fracture geometry, rock damage, *in situ* stress through scattering and attenuation of seismic waves by fractures and faults, normalizing non-continuum (and continuum) constitutive models, and more detailed inversion of dynamic source processes. With the rapid development in micro electromechanical systems (MEMS)–a proven technology–we anticipate a fundamental paradigm change for data collections in rock physics and geophysics experiments. The integrated circuit processing and micromachining greatly lower the cost and reduce the size of sensors, motors, structures, and electronic systems to the micron-centimeter scale. With self-assembling and networking capabilities through wireless communications, it is now feasible to deploy thousands of sand-grain-size sensors with microprocessors before excavation near new drifts and large-scale underground caverns or along tunnels for remote, real-time monitoring and testing, and long term monitoring after excavation to measure pressure and stress changes. MEMS, together with nanotechnology, biotechnology, and cyber infrastructure, are promising technologies called for in a National Research Council Geoengineering Committee report *Geological and Geotechnical Engineering in the New Millennium: Opportunities for Research and Technological Innovation* [10].

Even with all the advances in microelectronics the fact still remains that radio transmission through geomaterials is not possible in the practical sense. Given the high dielectric of water and rock, Maxwell's equations show that only a very few wavelengths can pass through the materials. If a high data rate is required, a high radio frequency is needed and the propagation distance is in the tens of centimeters. On the other hand, Sakata Denki (a measurement technology company) has developed an ultra low frequency device for the Japanese nuclear storage facility that can send a signal through 100m of granite. However, the ultra-low frequency severely limits the data transmission rates.

4.2.3.5.2 Large Cavities Geotechnical Engineering to Construct Detector Halls

During the life of the mine a number of permanent caverns were mined. In particular, permanent excavations of up to 10 m span are present on both the 4850 and the 7400 Levels. These openings notably include the cavern that housed Nobel Laureate Ray Davis's seminal underground experiment on solar neutrinos. The long-term stability of these excavations, sited at DUSEL depths, strongly suggests that the space needs of DUSEL Initial Suite of Experiments can be met using standard design and construction processes. Given this statement, it is believed that the core engineering tasks required to build the underground facilities can be performed by industry, using conventional contractor selection criteria and contract formats. Research conducted during this period will focus on complementing, supplementing and extending the collection of core engineering data and analytical processes required to support the facility design. Core tasks will be performed in close consultation between designer, constructor and partner researchers. Given the research objectives of the facility, this consultation will not only allow for the definition of site and experimental requirements and optimization of the excavations relative to *in situ* conditions, but will also ensure that the field research needs for work performed from investigation through operation are fully-integrated into the overall project plan [39]. General engineering research elements are further described in the next section. The balance of this section will focus on engineering issues pertaining directly to the design and construction of the physics facilities in general and the larger permanent caverns, in particular.

Within the context of a discussion relative to the construction of the underground facilities, it should be acknowledged that site-specific investigation work will be needed to confirm the suitability of the layouts and cavern sites that are adopted in this Report. However, we believe that the general geometry and geoengineering characteristics of the host rock units are already well defined within and adjacent to the mineralized areas. In developing the layouts we were able to reference a large core library, a mine-wide 3-D data base (Vulcan software), and a number of detailed engineering reports documenting the results of rock mass studies undertaken during the later working years of the Homestake Mine [40 - 45]. The rock engineering knowledge gained by reference to this extensive suite of documents has been supplemented by discussions with senior mine personnel, intimately familiar with conditions throughout the mine.

We believe that these data sets, used in combination, provide a very sound basis from which to develop an initial layout of the campuses and site the major permanent openings. This is not to say that the layout and site plans should be considered final. On the contrary, the plans shown in the Conceptual Design Report were primarily developed for scoping purposes, and the design remains flexible, pending acquisition of more site-specific information. Site-specific investigation is required in all rock mass volumes intended for DUSEL development to support the layout and siting optimization processes. Campus layouts and sites for all the major excavation may be subjected to modification, as necessary, to reduce, or ideally avoid, the possibilities of encountering adverse ground conditions during construction.

The site investigation work required to support the design of the underground facilities is scoped-out in detail elsewhere in this Conceptual Design Report. However, for the purposes of outlining potential areas of engineering research, associated with the construction of physics caverns, we envisage that the investigative work will be phased to allow the designers to first identify "stay-away zones," as might be associated with shear zones, contacts, or highly-fractured or burst-prone rock mass volumes; and second, select the best of the remaining rock mass volumes for the siting of major excavations. Thirdly, to facilitate the final design of these major excavations, a more detailed investigation of local strength and stress properties may be warranted. At these sites, exploratory galleries may also be required to permit large-scale, in-situ observation and testing, and allow for the pre-excavation installation of reinforcement and monitoring systems.

As noted above, several physics collaborations are calling for the excavation of major caverns. These permanent caverns, categorized for the purposes of this discussion as being 20m or greater in span, have been requested at all laboratory campus levels. In addition, on the 4850 Level, plans are developing [20] for the construction of one or more caverns to house a Long Baseline detector. As currently scoped, this experiment would require the construction of one or more very large caverns, ranging in span from 50 to 70 m with a combined excavated volume in excess of 500,000 cubic meters. From a rock engineering perspective, such large-deep structures would push the "precedent envelope" for large-span permanent underground facilities, mined at depth in hard-blocky rock formations. From a management perspective, such caverns will represent a major commitment of resources and potentially include a significant element of construction risk. The safe and cost-effective design and construction of such large-deep rock caverns will necessarily require the application of industry best practices. Given the largely unprecedented dimensions of the Long Baseline cavern(s) and likely price tag, cavern research may be worthy of consideration within the context of DUSEL's engineering research program. Successful completion of research tasks that can result in a beneficial impact on construction duration, cost and/or risk could warrant funding with a goal of improving the overall viability of the experiment and potentially improving industry practices.

As clearly demonstrated by the Letters of Interest submitted to date, exciting opportunities exist to incorporate compelling engineering research in to the DUSEL program. Research tasks in the areas of site investigation and characterization, rock-support modeling and construction monitoring can all contribute to a better cavern construction process and, on a more fundamental level, advance the state-of-the-art in hard-blocky rock engineering. Adroit collaboration between scientists and facilities engineers will be mutually beneficial to ensure that all research opportunities of value are recognized, seized and fully exploited. Early research conducted in the areas of geosciences and rock mechanics can provide complementary data sets that can enhance the definition of the rock mass materials and fluids and consequently support the design of improved structures. Engineering data sets gathered during investigation and construction can provide the geo-scientists and rock engineers with new insights in to the *in situ* behavior of the rock mass materials and fluids under the influence of a changing stress environment and provide the ground-truth data needed for remote-sensing validation. Synergies generated between scientists and engineers working in this shared geologic space can result in research advances that are far greater than either would have achieved if each were working individually.

The products of such research will not only benefit the cavern excavation process at DUSEL and contribute to our basic understanding of the DUSEL rock mass, but would also be applicable within a much broader scientific and engineering context. Homestake's hard-blocky rocks condition are, to first order, similar to many other metamorphic and igneous rock masses. Results from a Homestake cavern engineering research program could find immediate and broad application on many construction and mining sites, both in the U.S. and internationally.

4.2.3.5.3 Underground Excavations

With hundreds of miles of shaft and tunnel existing from depths of 300 to 8000 feet below the surface, the Homestake DUSEL site offers many diverse opportunities for research to be conducted across a broad spectrum of engineering topics, including site investigation and characterization, design and construction, rock engineering and mining technology.

During investigation and characterization activities, the parallel research effort will not only provide for a more thorough pre-excavation "baselining" of rock mass conditions within the site boundaries, but also allow for the performance of key peer-reviewed tasks. A preliminary list of peer-reviewed projects has been developed for the Early Implementation Program. These projects are aimed at improving the observer's ability to remotely probe and model the solid-earth for engineering purposes. Subsequent excavation within the modeled volumes will allow for "ground-truthing," recalibration and refinement of the design models. The incorporation of research at this stage will be critical if the full value of this scientific endeavor is to be garnered.

During DUSEL construction, it is also envisioned that research tasks will be performed. Engineering research during this period will focus on the development of instrumentation that allows for accurate comparison of as-modeled and as-observed ground responses and provide real-time design guidance to the construction process. The development of better predictive models and rapid feedback to the constructor can support a "design as you go" construction strategies that can contribute greatly to the development of a safer, more reliable and cost-effective rock excavation process.

During DUSEL operation, there will also be multiple opportunities to perform research at isolated sites within the extensive network of existing and newly-mined excavations. Sites can be designed for short or long-term study of large and small excavations and in-place rock mass volumes, under researcher-controlled conditions to investigate key areas for research of rock under stress and water flow in fractures. Sites will also be designated for testing excavation and support equipment, material innovation and personnel training. Once access and utilities are restored, this dedicated facility will open-up many opportunities for cross-discipline synergies.

4.2.3.6 Energy and Societal Benefits – Energy Prospecting

Each year, energy consumption increases and more greenhouse gases are emitted into the atmosphere. By 2020, one-third of the world's population may lack access to clean water, air, and affordable energy. That same year, it's estimated, U.S. energy demands will have risen 40 percent from today's levels, an increase that far outpaces the nation's energy production capabilities. If steps are not taken soon, later generations will inherit a world that looks vastly different than today's. DUSEL can play a leading role to address the nation's and world's urgent needs to sustain energy supplies and improve the environment, with focused research on processes and technologies critical for developing renewable energy and carbon neutral energy.

Specifically, we discuss the research potentials for geothermal energy and for carbon storage evaluations at Homestake DUSEL. **Energy Prospecting** is an S-1 theme for DUSEL.

4.2.3.6.1 Geothermal Energy Extraction

The natural heat of the Earth is virtually inexhaustible. The USGS has estimated that electrical energy producible from geothermal reservoirs to a depth of 3 km exceeds 100,000 megawatts electrical (MWe) for thirty years. The currently installed geothermal electric power production is less than 3,000 MWe. From a societal perspective, the grand challenge is to greatly increase the contribution of geothermal energy to the U.S. energy supply mix over the next 10 to 50 years. In addition, beneficial heat recovered from geothermal systems may be used for a variety of applications (e.g., heat pumps to heat and cool buildings, agricultural green houses, recovery of oil from tar sands, etc.). For geothermal energy extraction, enabling technology is needed to find or create, maintain, and control permeable fracture systems to sustain high flow rates. Upon reentry at Homestake, we can delineate flow paths and select sites for flow path modification experiments. DUSEL offers an ideal setting to understand heat flow at a previously unrealized level, with interests both from physicists on geoneutrinos associated with natural decays of U and Th in the rocks, and from earth scientists and engineers on sustained geothermal extraction and development of geothermal resources. The enhanced geothermal systems can use CO_2 as a heat transfer fluid, tackling geothermal extraction and carbon sequestration simultaneously.

4.2.3.6.2 Carbon Sequestration

Effective carbon storage in underground formations is impeded by leakages. For carbon studies, DUSEL experiments dedicated to understanding the sealing properties of faults and the interaction with CO_2 would provide valuable new information, with potential leakage paths accessible at multiple depths. There are existing winzes, dead-end drifts, and boreholes at Homestake for siting sand- or rock-filled experiments. There are also historic information and data available at Homestake for sand backfills [46] in stopes that have undergone long-term interactions in the presence of microbial communities. Since microbe-assisted conversion of carbon dioxide into methane is an attractive carbon neutral approach, we can assess if research of this or a similar innovative approach is feasible at Homestake.

4.2.3.6.3 DUSEL and SECUREarth

These research potentials are examples of the cross-cutting approaches needed to find solutions for energy and societal challenges. We strongly advocate coupling the DUSEL facility with the other national initiative: SECUREarth [47] (Scientific Energy/Environmental Crosscutting Underground Research for Urgent Solutions to Secure the Earth's Future), which is under development through the National Research Council for DOE, NSF, NASA, and USGS [32]. Like DUSEL, SECUREarth emphasizes a multi-disciplinary approach for research and development in underground science and engineering. Teams from academic institutions, industry, and national laboratories can tackle crosscutting energy and environmental problems, such as flow delineation, geochemical alteration, and biological conversion of energy sources to sustain the needs for clean energy and improvements in the environment. Both DUSEL and SECUREarth initiatives can be an integral part of the American Competitiveness Initiative [11].

4.2.4 Other Science

A number of Letters of Interest to Homestake do not readily fit into the main themes of Physics and of Earth Science and Engineering. The Program Advisory Committee found several to be of significant scientific interest and worthy of inclusion in the broader scientific goals of DUSEL. The Program Advisory Committee also noted that there are some features already available uniquely at Homestake which would allow the experiments to achieve their goals; further, it suggests two types of shared infrastructure for them.

One set of three experiments is related to measurements on the diurnal rotation of the Earth [LOI-23], controlled studies of the physical processes in clouds [LOI-33] and a search for neutron to anti-neutron conversion [LOI-7]. Need for an unimpeded vertical shaft on the order of a kilometer in length is common to these three experiments. Suitable space is available at Homestake in one or another of the access shafts. A brief discussion of the scientific significance of these three diverse projects is in order.

- A highly resolved knowledge of the diurnal rotation of the Earth is important in a variety of cosmological observations. The ability to improve measurements of the length of the day or the Earth's rotation rate beyond current knowledge using other means such as GPS, VLBI, LLR and SLR is feasible using an evacuated drop-tube facility.
- Water vapor within the atmosphere exerts an important control on the energy of the planet along with associated controls on an understanding of the weather, its modification and on the evolution of climate. Necessary scales of observation range from the sub-micron to the kilometer and present a challenge in observational science requiring observations at fine resolution but accommodating nucleation trajectories that sample the full scale and heterogeneity of the cloud structure.
- Neutron to anti-neutron conversion is a key test of an un-explained but fundamental symmetry, baryon number conservation. However, Grand Unified Theories of fundamental particles and their interactions have a common feature requiring violation of this symmetry. It is usually argued that the best tests of baryon number symmetry come from proton decay with a violation by one unit; however, n-n-bar oscillation (violation by 2 units) is highly complementary. The two techniques test at very different mass scales and now that lepton number violation has been discovered in neutrinos further impetus has been added to n to n-bar searches. This experiment proposes placing a research reactor on the surface of one of the vertical shafts and measuring neutrons and potentially oscillated neutrons at the bottom of the shaft. This source of neutrinos would potentially interfere with geoneutrino experiments and some solar neutrino experiments, but it is anticipated that the experiments would be significantly out-of-phase with each other and the reactor would be constructed after the completion of the other experiments.

While the Program Advisory Committee agrees that none of these three would be fully realizable as part of the Early Implementation Program and DUSEL Initial Suite of Experiments activities, there are essential preliminary studies which could be initiated and could be facilitated during Early Implementation Program or DUSEL Initial Suite of Experiments. For example, for n to n-bar experimentation, studies are needed to develop a full proposal and technical design, identifying a suitable shaft, engineering magnetic shielding, vacuum quality and safety in a long tube and compatibility with the diurnal rotation experiment sharing the same evacuated tube. Additional issues related to the location of a portable, low power reactor underground need to be worked out. Similarly, for the cloud physics project, design leading to construction of the unique large scale cloud chamber will require first hand knowledge of available space, evaluation of safety issues and compatibility with other experiments.

In addition to the three topics just discussed, there are Letters of Interest (17, 26, 42, 51, 57, 73) that concern the effects of energetic particles on electronic devices, biological systems and development of structure imaging from cosmic rays. In common, these proposals uniformly require access to an underground environment with low-background shielding. The idea is that variable-term-of-occupancy laboratory space be available underground as an incubator for experiments that may not conveniently fit within the more focused physics and Earth Science/Engineering focus of DUSEL. This incubator space would be available, via a review process, to experiments requiring such low-background protection. The potential availability of such space would be an enabling factor in allowing such projects to seek funding and appropriate clearances from their potential sponsors and regulators.

One of Homestake's unique features is access to several vertical shafts. Having a dedicated shaft with several kilometers of unobstructed access is feature unique in the world to this proposal.

4.2.5 Shared Infrastructure

Beyond the essential facilities expected and shared in the normal operation of the laboratory (e.g., safety, beneficial occupancy of underground lab space, experimenters' office space, surface handling for receiving and shipping, high speed internet access, etc.) there are some needs specific to particular experiments for which there is sufficient overlap that there are economies in avoiding duplication by creating some shared infrastructures. As the laboratory moves through Early Implementation Program and into DUSEL phases, these shared infrastructures are expected to increase or be added to as new elements of the science program are introduced. Co-location of some experiments is also considered as part of achieving economies and improved performance for some experiments. The program developing for the Early Implementation Program (and suggested by some Letters of Interest for later experiments) provides some examples being prepared for:

4.2.5.1 Low Background Counting

These capabilities, which will have widespread application to experiments and initial facilities on the surface and underground, will be required as part of the Early Implementation Program.

4.2.5.2 Large Water Room

The Davis cavity is slated for development into a large water shield room. The water shield would house multiple experiments that require significantly enhanced neutron shielding. The addition of gadolinium to the water would further enhance neutron capture and provide a test bed for additional research and development for possible supernovae and neutrino detectors. Preliminary design work indicates that several meters of water shielding could be provided for several collocated experiments.

4.2.5.3 Underground Copper Electroforming and Detector Assembly

The preparation of ultra-pure material frequently involves intensive refining processes utilizing large quantities of chemicals and rigorous quality control practices. These processes capabilities are desired by a small subset of experiments, and could be combined at a relatively low cost. They are greatly facilitated by the drive-in 300 Level; as would be the storage of materials to be brought later to deeper locations but which require shielding to prevent formation of cosmogenic activity in them. Furthermore, detector assembly that requires modest overburden but excellent access for personnel and materials would find the 300 Level a valuable facility. Certain detector

R&D activities would similarly benefit from near surface facilities particularly for early work with potentially hazardous materials such as cryogenic fluids.

4.2.5.4 Co-location of Shaft Experiments

Access to a vertical shaft is required by at least three of the Letters of Interest [LOIs: 7, 23, 33]. Collaborative use of a single shaft would significantly reduce infrastructure costs and increase viability of the individual experiments as part of an ensemble package.

4.2.5.5 Co-location of Underground Laboratories for Earth Science and Engineering

A large proportion of the experiments related to geobiology, hydrogeology, and rock mechanics, which will examine the interaction of coupling between chemical and physical processes (coupled processes) may benefit from co-location. This would include the provision of a laboratory, central to the experimental facility, and the sequencing of multiple but coordinated experiments on a well-characterized block (the coupled processes facility). A basic wet-chemistry laboratory and BioSafety Level 1 microbiology laboratory could also be considered for this grouping. This provision would, at the same time, allow the consolidation of infrastructure needs, and encourage collaborations not yet envisaged by the multiple proponents for the Earth science, geobiology, and engineering experiments.

4.3 Education and Outreach

The multidisciplinary nature of the research to be pursued at Homestake, with its broad base of science and engineering, affords unique opportunities for education and outreach—to spark interest among a local and tourist public (more than two million visitors per year to the Black Hills), to provide students and teachers with access to the frontiers of research, to deepen understanding of research content, to support kindergarten through 12th grade (K-12) teaching improvements, to enhance the already strong earth science research connections within South Dakota and its neighboring states, and to develop new university research opportunities in engineering and physics as well as within math and science education.

Education and Outreach will be among the first organized activities at Homestake and will speak to well-documented “pipeline” problems in math and science. Compelling descriptions of the need to improve math and science education appear in such places as the recent report entitled "Rising Above the Gathering Storm" from the National Academies [11]. Homestake programming will respond to this national need by encouraging pursuit of higher education and subsequent entry into the future workforce in Science, Technology, Engineering and Mathematics (STEM), especially among underrepresented minorities, women, and those from rural America. Programming will also address the need for enhancing understanding of, and appreciation for, scientific research among the general public.

Education and Outreach represents a major motivator for the State to invest in creating a lab at Homestake and plays a central role in the Early Implementation Plan. Serious education challenges exist throughout the region, especially in supporting Native American students. Across South Dakota, and also nationally, K-12 data reveal devastating achievement disparities between Native American and white students. Achievement and enrollment patterns among white students leave plenty of room for improvement, and the Homestake Collaboration is eager to lend support, but even higher in priority is helping to eliminate achievement and participation gaps associated with race and poverty. Within 200 miles of Homestake are Rosebud and Pine Ridge Indian Reservations, two of the poorest communities in the country, both facing significant challenges in meeting academic expectations. K-12 leaders from these communities, as well as higher education partners from Sinte Gleska University on the Rosebud Reservation and Oglala Lakota College on Pine Ridge, have been active in developing the Education and Outreach plans for Homestake.

South Dakota is home to numerous other populations, in addition to Native Americans, that currently are underrepresented in STEM fields. Women remain scarce in physics and engineering—two of the most prominent disciplines to be pursued at the lab. People from rural areas also tend to lack opportunities related to science. Connecting these populations with leading scientists and frontier research has excellent potential to encourage their entry into STEM fields in higher education and later professional life.

Adding to the keen interest and commitment of the State of South Dakota and its citizens, philanthropist T. Denny Sanford has pledged an amazingly generous $20 million gift to seed the establishment of a science education center at Homestake, the Sanford Center for Science Education. Through the creation of this center, Mr. Sanford, the SD Science and Technology Authority, and all of the project collaborators focusing on Education and Outreach show eagerness to contribute to the national effort to enhance the teaching and learning of mathematics and science.

Fiscal responsibility for education and outreach would not fall solely to the National Science Foundation once the Sanford gift has been exhausted, but rather, the Homestake Collaboration would seek synergistic resources from, and partnerships with, the world's most creative talents in the private sector as well. The partnerships would include strong intellectual and creative components above and beyond financial support. An instructive model for involving the private sector currently exists in the Business-Higher Education Forum with their focus on "Securing America's Leadership in Science, Technology, Mathematics, and Engineering" [48].

4.3.1 Planning History

Education and Outreach plans for a putative Homestake Lab were first developed in 2001. Four white papers form the base for currently planned program elements—a Visitor/Outreach Center; K-12 Education; Undergraduate Education; and Research Opportunities for Young Scientists.

In February 2006, an Education and Outreach-specific workshop was attended by ~75 international scientists, K-12 teachers and administrators, academic leaders from South Dakota's regental institutions, local tribal college and technical school faculty, teacher professional development experts, science museum personnel, education program managers for national labs, and state and local elected officials. Guidance was obtained from education staff at LIGO (Laser Interferometer Gravitational Wave Observatory), the Exploratorium Science Museum in San Francisco, Fermilab, Lawrence Berkeley, Oak Ridge National Lab, and Battelle [49]. Project leaders also received summary advice on best practices based on reviews of education and outreach programs at Department of Energy-funded labs and National Science Foundation Centers of Science and Technology. Eight relevant LOIs were submitted to Homestake's Program Advisory Committee for consideration in the Early Implementation Program.

In Fall 2006, another workshop was hosted at Homestake focusing on regional university involvement. A dozen administrative leaders from regional universities and from the South

Dakota regental system at large considered ways to expand their involvement with the lab. The focus of this workshop was broader than just Education and Outreach, but Education and Outreach was prominent. Ideas such as a mine safety-training program emerged, as did new contacts with tribal colleges and connections among regional science education centers.

4.3.1.1 Collaborating with Native American Communities

Since the earliest discussions of Homestake as a potential site for a DUSEL, proponents have been building relationships and seeking involvement of Native American institutions and individuals. A tribal elder offered traditional Lakota prayers to open one of the very first DUSEL-related workshops in Lead, and numerous members of area tribes and reservation communities have been engaged throughout subsequent planning efforts. This has been especially true within the area of Education and Outreach, which represents one of the most fertile areas for collaboration.

Ownership of the Black Hills is a sensitive topic. Some within the region feel that the states of South Dakota and Wyoming are illegally occupying the Black Hills, having violated treaties the United States made with the Great Sioux Nation in 1851 and 1868. The U.S. Supreme Court has ruled in favor of monetary compensation for the land, but to date that compensation has been refused. The Homestake Collaboration acknowledges this history as important context to the overall initiative and seeks to engage Native American leaders in finding a shared vision for moving forward. Already, representatives from tribal colleges and from K-12 school districts that serve large populations of Native American students have contributed important ideas about how a national science and engineering facility could support their students. Homestake Collaboration members are building on strong relationships that already exist, learning about the educational challenges at hand, and partnering to meet the needs of Native American students. The Homestake Collaboration is deeply committed to including Native American voices and serving Native American audiences.

4.3.2 Major Components of Homestake's Education and Outreach Program

What follows are key categories of programming envisioned over the next five to ten years. This listing is not meant to be exhaustive, but rather, to set a foundation upon which additional innovations, currently unforeseen, can be built. The Sanford Center for Science Education at Homestake, complete with funding beyond what National Science Foundation is able to provide, is expected to help extend the frontier of math and science education.

4.3.2.1 Visitor and Public Outreach Center

The Authority plans to restore and renovate an existing historic building originally used as a fabrication area on the Homestake site to provide exhibition and auditorium space. Hands-on exhibits will illustrate the underground science and engineering; the Ray Davis Nobel Prize-winning neutrino experiment at Homestake will be prominent. The center will feature the history of Homestake (connections to Homestake-Adams Research Center are discussed in Chapter 8), Native American history, culture, and science (drawing upon existing initiatives such as the NSF-funded Native Waters project), and environmental engineering and reclamation.

Exhibits will be developed in collaboration with staff of the Exploratorium, a well-known museum in San Francisco, not far from UC Berkeley and LBNL. These exhibits will be designed to engage the general public, to provide for more extended study by school groups and teachers, and to support university coursework. Plans will draw upon recent experiences at the LIGO project exhibit hall in Livingston, LA. Portable exhibits for use at distant science museum facilities will be created to emphasize the research at Homestake, broadening dissemination and drawing visitors. A proposed new science education center in Butte, MT, representing a regional collaboration with Montana Tech, would be among primary target sites. Permanent IRIS displays of geological forces in Washington D.C., New York, Pittsburgh, and Albuquerque museums are other examples.

Visitors at Homestake would gain important insights by entering the underground, even if only at shallow depths. The 300 Level, with horizontal egress, provides a plausible option for safe underground experiences that would feature scientists at work on accessible research projects.

The surrounding Black Hills area is well suited to directed nature trails that highlight geology and ecology. Among the focal points would be views into the mine's open cut, zones of forest fire recovery, and environmental engineering applications such as ponds of cyanide-consuming bacteria. The trails would provide students and teachers organized access to surface sample-collection sites as well. An outdoor classroom and an astronomical observatory are planned for later development.

4.3.2.2 Research Experiences

Providing research opportunities for pre-college students, undergraduates, K-12 teachers, and even for faculty from less research-intensive institutions is central to the Homestake plan. A program of summer internships that embed students and teachers within scientific research teams is a widely recognized, successful approach. Resident Education and Outreach staff will aid scientist mentors, coordinate logistics, introduce participants to the research facility, arrange safety training, and expedite transfer of research experiences to classroom practice.

Homestake will be an attractive locale to host National Science Foundation REU sites (LOI-16a). Geology field camps (LOI-5) and an underground mapping laboratory for undergraduates (LOI-9) have been proposed. High School Science Academies, to be developed in partnership with South Dakota school districts, would function as focused learning communities within existing schools and serve their most highly talented and motivated students. In times of limited fiscal resources, the most motivated and talented students all too often find scarce enrichment opportunities, yet they represent the nation's future in science and mathematics. Academy students would be introduced to scientific research at Homestake and work within a research team to gain a deeper appreciation of the content, process, culture, and excitement of science.

4.3.2.3 Professional Development for Teachers

Teachers represent a critical leverage point. Elementary teachers typically have limited content knowledge and sometimes are fearful of teaching science. Secondary teachers have difficulty staying current in their scientific field and often struggle to convey the excitement and inquiry-based nature of the scientific enterprise. Among the scientists within the Homestake collaboration are a number who have supported large-scale, systemic teacher professional development initiatives. Scientists will be enlisted to share their enthusiasm, to help teachers expand and deepen content knowledge, and to advocate for more authentic, inquiry-oriented instruction. Research scientists will connect Homestake science and engineering with basic concepts in courses to be offered as summer institutes at the visitor/outreach center, supplementing the research experience. Education and Outreach staff, research scientists, expert K-12 educators, and participants will jointly prepare instructional materials and make extensive use of exhibits. Education and Outreach staff will attend to logistics and training.

Other efforts will focus on the preparation of future teachers through pre-service training. Black Hills State University, South Dakota's largest producer of teachers, and other nearby institutions, including Oglala Lakota College and Sinte Gleska University, that have significant teacher preparation programs will be enlisted as partners. Student teachers will benefit from research experiences at Homestake and from classes and lectures by visiting and resident scientists. Using LIGO’s successful program as a model, the visitor center will serve as a focal point for teacher preparation coursework. Teachers-in-training will participate in exhibit design, development of children’s programming, and educational research.

4.3.2.4 Engineering

Deep underground excavation procedures will be illustrated at the center. Examples of intriguing mechanical devices such as hoists, pumps, and fans will be displayed. Robotics will be a focus, as robots are likely to be used to explore drifts, collect samples, and attend to issues of lab safety. Plans include providing instructions to visitors to build and test their own robotic devices in simulated conditions on the surface and at the 300 Level. Homestake will serve as a focus to connect engineering research with faculty and students at local and regional university engineering departments and at K-12 schools.

4.3.2.5 Distance Education

Homestake Education and Outreach will make extensive use of Internet-based distance technologies. An online course, “Trace Element Geochemistry,” has been proposed (LOI-85) in connection with a Low Radioactivity Measurement Lab. Every South Dakota school district is wired with its own videoconference studio, which will facilitate dissemination of public lectures and help to maintain contact between scientists, K-12 students, and teachers throughout the academic year. Distance technologies will also be helpful in connecting visiting scientists whose time at the lab may be limited, but are interested in participating in outreach efforts.

4.3.2.6 Lecture Series, Conferences, Workshops & Short Courses

Education and Outreach staff will arrange informal learning lectures for audiences ranging from the general public, to students and teachers, to other professionals, as well as assist in organizing the logistics for scientific workshops and conferences. Hospitality, comfortable residential quarters, and enriching content are all critical to the creation of a vibrant and synergistic intellectual environment.

Homestake will offer a venue for conferences and short courses on specific scientific topics as well as science education. A safety training facility being considered in collaboration with the Mine Safety and Health Administration and regional universities would use the extensive surface and underground infrastructure to develop mining techniques, mine rescue and underground safety practices. Homestake is pursuing near-term opportunities for collaborative training facilities in partnership with industry.

4.3.2.7 Physics Education Programs I – Cooperation with South Dakota Board of Regents

A collaboration of the South Dakota Board of Regents and UC Berkeley Physics Department and Lawrence Berkeley National Laboratory has been established to enhance the physics education programs in South Dakota and the surrounding regions. White papers have been developed and short term goals for enhancing physics education are defined. Proposals are being drafted for curriculum, course, and laboratory module development.

4.3.2.8 Revolutionizing Education

Central to the Education and Outreach enterprise, especially through the science education center, is the notion of revolutionizing the teaching and learning of science, technology, engineering, and mathematics. To this end, two new doctoral programs are under consideration, one in science education and the other in mathematics education. No South Dakota institution of higher education currently offers either. These academic programs, through their faculty (some local, but also nationally recruited), scientist collaborators, students, and other creative partners, will serve as an engine for innovation. Dissertations and journal publications will serve as mechanisms for dissemination.

4.3.3 Education and Outreach Infrastructure

4.3.3.1 Physical Infrastructure

The Authority plans to provide and operate a visitor/outreach center that will be the initial Education and Outreach hub facility. Dedicated space will be available for teachers, students, and scientists with furnished and equipped labs, classrooms, and meeting rooms. These will be enhanced and expanded with DUSEL.

4.3.3.2 Programmatic Infrastructure

Education and Outreach staff, already provided for within the Authority's budget, will be drawn initially from local experts involved in existing programs and will ultimately draw national luminaries as well. The staff will recruit, select, and prepare teachers and students to participate in programs. The Education and Outreach program will provide scientists with opportunities for involvement that range in time commitment, nature of work, and target audience. Scientists will be encouraged to explore core problems of science education and be strategic in leveraging their impact. Resident Education and Outreach staff will advise on requests to build individual education programs specific to scientists' own research interests.

4.3.3.3 Education and Outreach Advisory and Management Structure

Management will include an Education and Outreach director who is supported by associate directors with specific responsibility for the visitor/outreach center's maintenance and operation, for K-12 education, and for teachers' programs. Homestake Lab management will recruit and appoint an advisory committee composed of lab members and local, regional, and national leaders in science, education, and industry.

4.3.3.4 Education and Outreach Early Implementation Program

The DUSEL Education and Outreach plan is to build on existing educational programs, existing infrastructure, and local capacity. Education and Outreach programs are already underway and ready, consistent with conditions of the supporting grants, for adaptation, expansion and consolidation with likely new programs at Homestake DUSEL.

A primary example is South Dakota's Center for the Advancement of Mathematics and Science Education (CAMSE). This Center, with a staff of ten, funded through the State Board of Regents, now resides at the Black Hills State University. Its program includes professional development for K-12 teachers; enhanced preparation of future teachers; enrichment for K-12 students; research on teaching and learning; and evaluation and dissemination of classroom resources. The NSF, the U.S. Department of Education, and South Dakota fund its current 30 projects with an annual budget of $1.8 million. CAMSE brings Ph.D.-level expertise in science and science education, experience with federal grants and projects, and strong relationships across the state and surrounding region. These relationships span South Dakota's regional system and extend into the tribal colleges, the S.D. Department of Education, hundreds of school districts, and thousands of teachers and students.

Through a recent MOU between the Authority and Black Hills State University, CAMSE is currently reorganizing itself into two divisions—one at Black Hills State University and a second at Homestake—and transitioning staff and materials to the Homestake site. One example of a CAMSE project to be adopted is “Science-on-the-Move,” in which two tractor-trailer trucks provide rural schools with access to state-of-the-art equipment and instruction. These trucks represent a ready means for extended outreach of DUSEL-related content.

A second candidate is a NSF-funded local systemic-change grant, the Black Hills Science Teaching Project. Relying heavily on practicing scientists to help elementary and middle school teachers deepen their content knowledge, it works in close collaboration with South Dakota School of Mines and 10 regional school districts that span 10,000 square miles.

A third is South Dakota's NSF-funded Experimental Program To Stimulate Competitive Research (EPSCoR) Research Infrastructure Improvement (RII) Initiative (2006-09). This initiative includes a focus on STEM education within Native American communities and another on informing K-12 audiences and the general public of forefront science. A nationally renowned educational research firm is currently under contract through the EPSCoR RII to explore and document strengths and challenges within South Dakota's educational infrastructure.

4.3.4 Evaluation Plan/Benchmarks

An external evaluation team will be retained to work in partnership with Education and Outreach staff. Rigorous, ongoing evaluation components will make use of participation data, needs-assessments, participant surveys, focus groups and interviews, and expert review panels to assess impact on content knowledge, conceptual understanding, and attitudes. Evaluation will provide formative feedback for program refinement and to inform related efforts at other national facilities. Reports will be posted and papers published in peer-reviewed journals.

4.3.5 Education and Outreach Opportunities

A dedicated science and engineering facility at Homestake presents outstanding opportunities to serve the public through Education and Outreach. Committed support is strong and broad, from philanthropist T. Denny Sanford, to the governor, to the secretary of education, across the university and K-12 systems, and throughout the local population. The region has high needs, and it welcomes the support that a national STEM facility could provide. Small universities and tribal colleges, including significant teacher preparation programs, are close at hand and will benefit from contact with the lab. Effective immediately, existing local Education and Outreach entities, including South Dakota's Center for the Advancement of Mathematics and Science Education (CAMSE), are transitioning programs, educational materials, and staff to allow for rapid and strategic scale-up. Given the proximity of two national parks, as well as Devil's Tower National Monument and Mt. Rushmore, a significant tourist audience already exists. With the addition of a national lab and world-class visitor center, the region could evolve into a major science-oriented tourist destination. The multidisciplinary nature of the science, coupled with such themes as the history of science, the history of mining, the science of mining, environmental engineering and restoration, and Native American culture ensure broad impact of a Homestake DUSEL.

4.3.6 Broader Impacts

The broader impacts are limitless. Regional education from kindergarten through college and beyond will be strengthened. Public understanding of scientific content and appreciation for scientific research will be enhanced. Research findings generated within the educational sciences will inform national efforts to improve science, technology, engineering, and mathematics education. Special attention will be paid to attracting and serving members of Native American communities, residents of rural America, and other audiences currently underrepresented in the disciplines to be pursued at the lab. K-12 teachers as well as teachers-in-training are also key audiences for programming. Investing in teachers, current and future, is especially strategic and will heavily leverage the impact of the scientists, engineers, and education experts at the lab.

4.4 Near-Term Goals, Early Implementation Program and Initial Research Efforts

4.4.1 Common Infrastructure

4.4.1.1 Low Background Counting Facility

A collaboration comprised of UC Berkeley, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, University of South Dakota, South Dakota State University and Augustana College has proposed to develop a state-of-the-art low background counting facility. Following initial assembly on the surface and then depending on the availability of space this will initially be deployed at the 4850 Level. At least two large volume, low activity germanium gamma-ray counters and associated shielding would be deployed as early as 2008. This facility, operated by the South Dakota collaborators, would provide low level assay and direct γ-ray counting services to all users and specifically to the Homestake Early Implementation Program.

4.4.1.2 Large Water Room

A proposal to develop a large, water-shielded, shared-used facility have previously been submitted to the National Science Foundation (Major Research Instrumentation proposal from Brown and Case Western Reserve). More recently, an enlarged collaboration with participation from Brown, Case Western Reserve, UC Davis, UC Los Angeles, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Lawrence Berkeley National Laboratory, UCI, Texas A&M, Boston University, and University of Rochester has proposed research and development of an enhanced water room. This room would pursue multiple research and development tasks, including gadolinium doping of the water to enhance neutron capture and detection. Homestake would host this shared-use application in the Davis Cavity. It would be large enough to host several large experiments including some of those listed below. Homestake proposes to commission the Large Water Room in 2009.

4.4.1.3 Dark Matter Searches

Large volume noble-gas dark matter detectors recently demonstrated [17] dramatic sensitivity gains and potentially excellent scalability. Not surprisingly, investigators have approached Homestake with three proposals, including two based on xenon and one based on argon/neon.

4.4.1.3.1 Large Underground Xenon - LUX

The LUX collaboration (Brown, Case Western, Texas A&M, UC Los Angeles, UC Davis, Lawrence Livermore National Laboratory, and Lawrence Berkeley National Laboratory) proposes to develop a ~ 500 kg xenon detector based on the Xenon10 currently operating in Gran Sasso. LUX would be deployed in the Large Water Room.

4.4.1.3.2 Xenon100

The Xenon100 collaboration (Columbia) proposes a phased deployment of cryogenic xenon dark matter detectors. The Xenon100 collaboration would deploy in a room at the 4850 Level and would not use the Large Water Room at the 4850 Level.

4.4.1.3.3 MiniCLEAN

The miniCLEAN collaboration (Yale, Los Alamos National Laboratory, Boston University, NIST, and Queen's University) proposes to develop a cryogenic dark matter and solar neutrino detector based on argon and neon. The first phases would be hosted at the 4850 Level.

4.4.1.4 Neutrinoless Double Beta Decay – Majorana Project

The Majorana Collaboration (http://majorana.pnl.gov/) proposes to construct a scalable Germanium-diode array. Majorana would make use of the 300 Level to host chemical engineering efforts (copper refining), detector component assembly and storage of materials to reduce cosmic ray activation. The main detector deployment would be at 4850 Level for the first phases (up to 120 kg). Subsequent phases may require redeployment of the array to the 7400 Level laboratory; phasing and deployment options will be refined when better timescales are determined. Majorana would be a major user of the low background counting facility along with the dark matter experiments.

4.4.1.5 Perishable Data

As highlighted in the Program Advisory Committee report, establishing the initial conditions of the laboratory before re-entry and rehabilitation is a high priority.

4.4.1.6 Seismic Array

A collaboration (UC Berkeley, LBNL, and South Dakota School of Mines and Technology) proposes to install an array of surface seismometers using the large number of boreholes. The array would be deployed in 2007.

4.4.1.7 Water Sampling

A collaboration (LBNL, South Dakota School of Mines and Technology, Black Hills State University) proposes to collect water samples at the base of the Yates shaft and analyze the water for biological and chemical components as well as evidence for contamination that would require mitigation. In addition, the collaboration proposes to establish surface monitors and sampling of different surface water sources to establish a database for potential analysis of subsurface water.

4.5 Homestake DUSEL Long Term Goals

As discussed above, our design approach for Homestake DUSEL is to enable phased development and future expansion of the facility without impacting ongoing research. We propose initial implementation of major research campuses at the 300, 4850, and 7400 Levels. In addition to these campuses, much of the workings of the former mine will be available for inspection, monitoring, and assay research that may require periodic or temporary access to the existing 600 km of drifts. The long drift at the 2000 Level and the drifts and ramps beneath the Open Cut have received some attention by earth scientists. Plans for rehabilitating deep levels include maintaining access to nearly all of the 8000 Level, including the existing drill room, which has approximately 24 ft vertical clearance. This room is appropriate for drilling activities and other geoscience support facilities for investigations at the deepest level of the mine.

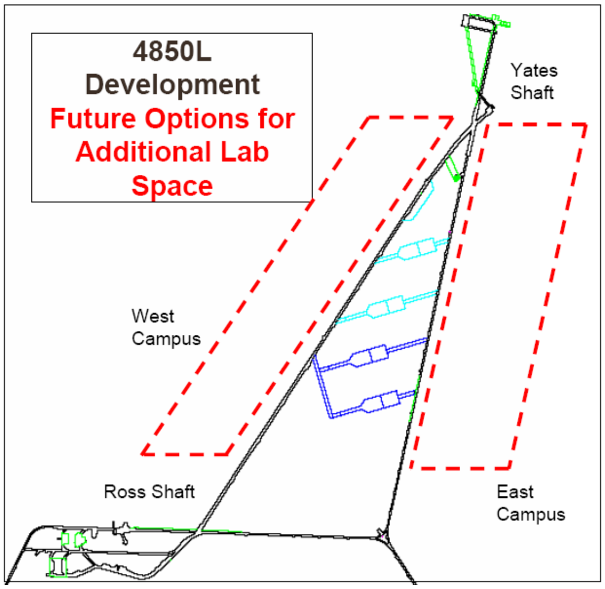

Figure 4.9 Optional areas for future development at 4850 Level to construct additional lab modules or purpose-built chambers for large-detector experiments and other research instrumentation.

Our initial assessment for very large cavities for Nucleon Decay and Long Baseline Neutrino Experiments places these at the 4850 Level (Figure 4.9). Detailed site investigation, rock mechanic studies and geotechnical data for engineering analyses will be accumulated during the Early Implementation Program to identify specific sites for the ~50 m diameter cavities for these experiments. Initial site investigations at the 4850 Level will evaluate rock properties in the region North and West of the main Yates-Ross drift. Locating large chambers in this region places the cavities in the highly competent rock of the Yates Member and facilitates construction access and waste rock removal via the Ross Shaft. The Ross shaft terminates at the 5000 Level, including an existing skip pocket for ore handling. With cavities that may exceed 50 m in height, the top of the cavities may be located at the 4850 Level for personnel access, which situates the bottom of the cavity at a convenient level for rock removal.

4.6 Summary Requirements

Presented in Table 4.5 is our initial development plan for space in at the Homestake Interim Laboratory and DUSEL. Both surface and underground development, the area and volume laboratory space and access drifts are presented. The initial construction schedule presents estimates of the availability of this space.

Homestake Interim Lab and DUSEL Summary of Development of Space and Availability (Underground space fully outfitted and ready for detector installation)	Labs, Shops, Offices Usable Floor Area		Excavation Volume (including access drifts)		Preliminary Construction Schedule (*to be revised*)	
	sq. ft.	sq. m.	cu. yd.	cu. m.	Start	Finish
4850 Level Subtotal	**107,351**	**9,973**	**111,115**	**84,903**		
Ross Shops for Construction Staging	12,469	1,158	5,738	4,385	Apr-08	13/31/8
Davis Lab, Sanford Lab, and Bio-Geo Lab	15,738	1,462	13,543	10,348	Sep-08	Jul-08
Lab Module #1 and Common Facilities	26,464	2,459	25,155	19,221	Oct-10	Sep-12
Lab Module #2	17,560	1,631	21,433	16,377	May-11	Apr-13
Lab Module #3	17,560	1,631	23,121	17,667	Sep-13	Jul-15
Lab Module #4 (excavation only, without lab outfitting)	17,560	1,631	22,125	16,906	Aug-14	Jul-15
7400 Level Subtotal	**63,588**	**5,907**	**98,477**	**75,246**		
Lab Module #1 and Common Facilities	28,468	2,645	29,594	22,613	Jan-12	Mar-14
Lab Modules #2 and #3 (excavation only, without lab outfitting)	35,120	3,263	68,883	52,633	Dec-12	Jan-14
300 Level Subtotal	**8,668**	**805**	**14,007**	**10,703**		
Lab #1, Shops, and E&O Rooms	8,668	805	14,007	10,703	Nov-10	Nov-11
Surface Subtotal	**98,000**	**9,104**				
DUSEL Offices and User Support Areas,Phase 1	10,000	929			Dec-10	Jun-12
Sanford Clean Room and Assembly Shop	6,000	557			Dec-10	Jun-12
DUSEL Offices and User Support Areas,Phase 2	32,000	2,973			Jul-11	Jun-13
Sanford Center for Science Education	50,000	4,645			Sep-09	Sep-11
Total	**277,607**	**25,790**	**223,599**	**170,852**		

Table 4.5 Development schedule for underground and surface facilities at Homestake's Interim Laboratory and DUSEL.

4.7 International Participation

The Homestake Interim Laboratory and then DUSEL at Homestake will be international facilities, with participation by researchers and educators from around the world. The deepest scientific facility in the world, it will attract participants and researchers from physics, earth science, engineering, biology and Education and Outreach. The initial call for Letters of Interest included foreign participation from ten nations including Japan, Canada, Great Britain, Germany, Italy, Spain, Russia, Switzerland, Portugal, and Scotland. These Letters of Interest included some scientific investigations solely sponsored by foreign collaborations.

It is anticipated that scientific participation in experiments and uses of Homestake will be the primary avenue for international participation in DUSEL. In particular, the larger experiments, such as neutrinoless double beta decay, proton decay, geophysics and geomechanics, and collaborations, will naturally include significant international participation.

As the Homestake Interim Laboratory issues subsequent calls for Letters of Interest in the coming years, we anticipate increased international participation in the Program Advisory Committee and perhaps the Board of Overseers. For Homestake DUSEL, we would also anticipate international participation in the Program Advisory Committee, in the consortium of Homestake Users, and in the DUSEL Board of Directors. Communication between the Laboratory Directors will be stimulated with an International Advisory Committee, Program Advisory Committees, and Board of Directors of the major international underground facilities, including Gran Sasso, Kamioka, and SNOLAB, is expected to stimulate coordination between the facilities and maximize the scientific reach of all underground facilities.

Foreign national participation in the DUSEL scientific program impacts the use of DUSEL for National Security and Homeland Security interests. The facility is large enough to provide adequate separation and isolation for these uses so that international participation in the main program will not be impacted. Homestake DUSEL will be, fundamentally, an open laboratory where qualified and adequately supported researchers from all fields and affiliations will have access based on the scientific merits of their proposed work, and will have freedom to publish in the open literature.

4.8 Connections to Other Underground Research Laboratories and Synergy with Other Agency Missions

Homestake Interim Laboratory will be an independent state-operated facility hosting U.S. and international experiments. Funding for the experiments is anticipated to be from traditional funding agencies for such work: the NSF and the Department of Energy. The Homestake Principal Investigators have initiated discussions with management of several other North American research labs, including SNOLAB, WIPP, and Yucca Mountain, to define roles and create an active dialog among the facilities' managements; and with researchers of EarthScope program [50] to strengthen common interests in deep earth science. As the Homestake Interim Laboratory develops, we plan on expanding these discussions to include Gran Sasso, Kamioka, Grimsel, and additional international research laboratories. The Homestake Interim Laboratory is advised by a senior advisory panel. We plan on expanding the 2006 membership to include additional senior researchers from the U.S. and from international laboratories to advise Homestake on the operation of the Early Implementation Program.

Advice to laboratory directorate on the scientific program, operations, and facility development will be obtained from several committees, including an International Advisory Committee; a Program Advisory Committee with representation from international users as well as industrial, educational, and homeland security communities, and an Users Group Executive Committee.

To facilitate both intra-agency discussion on underground science and to maximize DUSEL's impact internationally, the S-1 report, *Deep Science*, proposes a cross-agency Deep Science Initiative. This initiative would stimulate collaboration between the U.S. agencies and integrate the U.S. program and other national initiatives into DUSEL and to fully integrate DUSEL in the international arena. We imagine that the Deep Science Initiative would be hosted at DUSEL and that the Homestake Interim Laboratory would be included in the initial discussions.