2 DUSEL Science

It is obvious why researchers in the earth sciences would be interested in a laboratory thousands of feet underground. But what would microbiologists, particle physicists, or— most counter intuitively of all—astrophysicists be doing down there?

For physicists some exciting ways to study the universe involve neutrinos and other rarely interacting particles rather than photons. Neutrinos are nearly massless, hardly interactive at all, and moving as close to the speed of light as any particle could; neutrinos are often described as "ghostly." They are best observed not from atop a mountain but in the deep recesses of a mine, where the background noise of radiation is at a minimum and a large mass of detector material can be accommodated.

Biologists, as well, have discovered much of interest in the deep underground; even thousands of feet below the surface, profoundly isolated from the world of air and light, there are microbes. But are they like the microbes at the surface? Studying them might explain the evolution and survival of life as we know it and even give us a glimpse into possibilities for life, as we don't know it. New fields of science could emerge as scientists from many different disciplines meet and collaborate.

In this chapter, we give an overview of why a Deep Underground Science and Engineering Laboratory is of interest to so many different kinds of scientists. These scientific objectives are based on the report from the NSF site-independent study ("S-1"). Physics and astrophysics, biology, geoscience, and geoengineering are discussed, together with the anticipated synergy among them.

Later chapters (particularly Chapter 4) give details, with attention to why Homestake has advantages that are unique in the world as a site for DUSEL: its combination of depth, infrastructure, types of rock, freedom from the physical interference and competing priorities of a working mine, and outstanding community support.

2.1 Underground Universe (Physics and Astrophysics)

In 1514, Copernicus sparked a revolution when he demoted planet Earth from its position at the center of the universe and relegated it to the status of a planet revolving around a star. As observation technologies and interpretations continued to evolve, the Sun was found to be a quite average star, one of billions in the Milky Way galaxy, and rather far from the center at that; later still it was learned that the Milky Way is an ordinary spiral galaxy, one of millions. For centuries, this succession of discoveries seemed to signal the loss of any privileged position in the universe for Earth and its creatures. Recently this view of our tiny and undistinguished place in a tremendous universe has taken another leap: the kind of matter we can see is only perhaps one-fifth of all the matter that exists.

Atoms are vastly outnumbered by ghost-like neutrinos and photons (particles of light) by a factor of about one to a billion. In terms of weight, the mystery substance called dark matter outweighs atoms five to one (Figure 2.1). Furthermore, a mysterious force called dark energy that pushes the universe apart at ever-increasing speed fills the empty space of the universe. For that matter, why atoms and anti-atoms did not mutually annihilate as the universe cooled from the Big Bang is so mysterious that it will take another revolution in physics, as profound as the Copernican version, to explain it.

These are truly some of the most compelling questions in science today. In order to understand what the universe is made of, we need to see dark matter directly. To understand why we exist, we need to know why anti-matter disappeared from the universe, leaving the tiny bits of normal matter that we are made of. Underlying these mysteries, yet-unknown laws of physics explain the Big Bang and the evolution of the universe since. Many believe that the kind of unified theory of which Einstein dreamed will require these new laws of physics waiting to be uncovered. In many of these questions, neutrinos, the most ubiquitous form of matter in the present-day universe, must have played important roles.

The answers reveal themselves through signals that are in many cases extremely subtle. Trying to detect them on the ground is like trying to listen to a whisper in the middle of Manhattan street traffic. On the ground, sensitive devices in physics experiments are completely deafened by the chatter of cosmic rays. Coming from supernovae exploded millions of years ago in our galaxy, high-energy protons constantly bombard the atmosphere of the Earth. They create showers of particles that eventually decay to muons and neutrinos. In fact, thousands of muons go through our bodies every minute. They do not cause much harm to humans, but are a serious problem for a physicist who is trying to discover a phenomenon that happens maybe once a year. A deep underground laboratory offers a shelter from cosmic rays. Depth means fewer cosmic ray muons, hence a better place to "hear the sound of the universe."

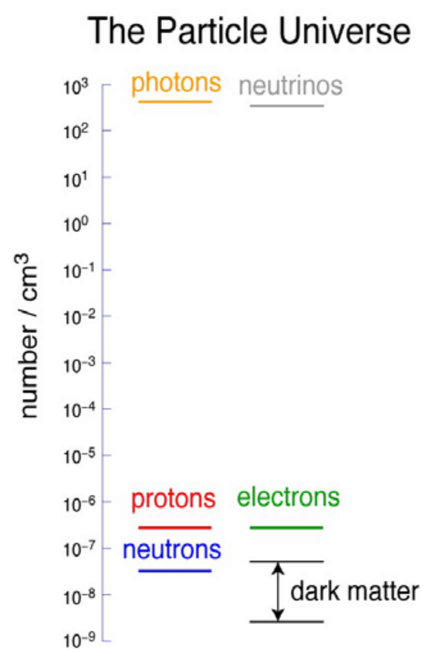
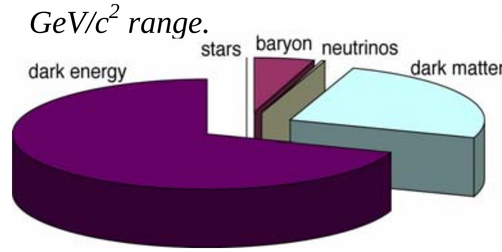


Figure 2.1 The number of various particles in the Universe, and their contributions to the energy budget of the Universe. It assumes a dark matter particle with a mass in the 10-1000 GeV/c^2 range.



2.1.1 What is dark matter?

Not only does dark matter outweigh ordinary matter five to one, but it also holds the galaxy together. Dark matter particles float around the galaxy, providing a gravitational pull strong enough to prevent the solar system from wandering out into intergalactic space. Dark matter particles are so elusive, even more so than the ghostly neutrinos, that they practically do not interact with atomic matter, and thus far have been revealed only indirectly (Figure 2.2).

In DUSEL, physicists hope to reveal the secret of dark matter particles by placing an ultrasensitive high-tech device in a quiet location deep underground. Undisturbed by human activities and cosmic rays, the detector will watch for the feeble signals of dark matter particles sneaking easily through thousands of feet of rock to give a tiny telltale *kick* in the device. By observing this subtle signal, physicists could directly establish the presence of dark matter that astronomical observations have identified in the Milky Way galaxy. Combined with the search for astrophysical signals of dark matter annihilation in the sky and with the direct production of dark matter particles at high-energy accelerators, underground dark matter observations would establish the true character of dark matter.

2.1.2 What are neutrinos telling us?

Neutrinos are the most ubiquitous matter particles in the universe, and they must have played important roles in shaping the universe today. Yet we are still learning much about them. This has been an extraordinarily difficult task because they interact hardly at all with ordinary matter. Trillions of them go through our body every second and we do not feel them at all. We need the largest feasible detectors in a quiet deep underground location to boost the chance of seeing these elusive particles.

Only very recently have physicists learned that neutrinos do not travel quite at the speed of light, as believed for decades. An implication is that they have tiny masses, a million times smaller than any other particle masses. Despite being individually almost infinitesimal, neutrinos are so common that collectively they may weigh more than all the luminous stars in the universe. Depending on this aggregate weight, neutrinos may have changed the way galaxies, and eventually stars, have formed since the Big Bang.

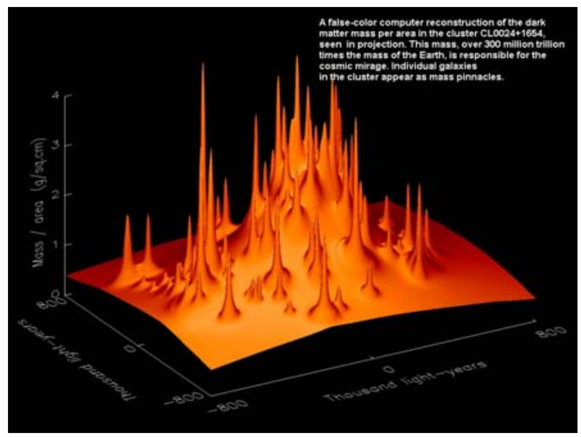


Figure 2.2 *Above left*: The blue light from a faraway galaxy is bent by the presence of mass in the foreground galaxy cluster. We can "see" the presence of dark matter by studying how much the light gets bent. *Above right:* The spikes are galaxies we can see in telescopes, while the big blob is the dark matter [7].

It is very difficult to determine the mass of such elusive and tiny particles. Physicists would like to try two different and complementary methods. One is to look for a phenomenon, called neutrinoless double beta decay, that would be impossible if the neutrinos had no mass, and (since we know now that they *do* have mass) can be measured to determine what their mass is. This decay may happen to any given atom only once in a billion billion billion years. Therefore we need to observe a detection mass consisting of a great many atoms to have a chance of seeing it, and we need a radiologically quiet location so as not to miss it. The other method is to shoot beams of neutrinos from particle accelerators across hundreds of miles into the detector. The way the neutrinos morph from one kind to another would tell us how much their masses differ.

This technique requires a large target device to detect neutrinos from a faraway source and therefore large underground cavities.

2.1.3 What happened to the antimatter?

Just as mysterious as the dark matter that must be there (but can't be seen), and the neutrinos that are everywhere (but are hard to see), is the antimatter that would be easy to see (but isn't there). Why not?

Every particle has an antimatter equivalent (many have been produced or observed in the laboratory), and there is reason to believe that antimatter was abundant in the early universe. In the modern visible universe, there is almost no antimatter at all, and what little there is can be explained by nuclear decays and by high-energy interactions of normal matter. This is fortunate, because when matter and antimatter meet, they annihilate each other in a burst of radiation—hardly a situation conducive to life. But whether antimatter was produced in the Big Bang in amounts equal to normal matter, and if not, what happened to it, are tremendously puzzling questions with important implications for our understanding of the origins and fate of the universe.

This is an exciting frontier of physics at this time. Very recently (late 2006) discoveries related to charge conjugation-parity or "CP" violation (a way of stating why nature seems to prefer normal matter), and "oscillation" between matter and antimatter states, have been announced by accelerator laboratories. DUSEL neutrino detectors with unprecedented active mass (ultimately more than 100,000 tons) could address matter-antimatter asymmetry amongst neutrinos, simultaneously with other important tasks. Long-baseline neutrino studies, using powerful neutrino beams produced by distant accelerator facilities and aimed at DUSEL, would also contribute to solving this mystery.

2.1.4 Are protons unstable?

Protons, the large positively charged particles in the nuclei of all atoms, were long thought to be stable. However, since the early 1970s, attempts to create unified field theories implied that they could (over a very long period) decay.

This might be relevant to the question of where the antimatter went, but experiments to date have shown that the proton lifetime exceeds 10^{33} years, whereas the universe is considered to be only about 10^{10} years old. In any event, proton-stability is an important fundamental property to determine in order to understand particles and fields. One of the most crucial and generic predictions of grand unification is that the proton must ultimately decay; one class of such theories also explains the origin of the excess of matter over antimatter. These theories involve a theoretical upper limit on the proton lifetime that is within a factor of ten of the current lower limit. Thus a next-generation experiment that looks for proton decay has high discovery potential. DUSEL, with its low background and ability to watch for signs of proton decay in a large detector mass, would be an attractive site for such experiments.

2.1.5 How did the universe evolve?

The Sun, as the Earth's closest star, has given us access to a wide range of science. Nowhere on Earth can we as readily study the forces that drive our universe – gravity through heliocentricity, nucleosynthesis through stellar fusion, general relativity through its bending of light, dense plasmas through helioseismology, and neutrinos through their oscillations. In each case new knowledge has been gained, modifying our understanding of the solar system and providing new insights into areas beyond, such as particle physics and cosmology.

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 is that the heavy-element abundances at the surface of the Sun are present at the center. The fourth is that neutrino "mixing"—the aforementioned morphing of neutrinos from one type to another—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 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.

2.2 Dark Life (biology)

One of the most mysterious and intriguing aspects of the deep underground was recently in the news. Far below the world of the surface are microbes that call this inner world home – "dark life." Isolated from the world of sunlight and other forms of energy and material used by surface life, they must be inextricably coupled to physical and chemical processes occurring in this underground environment. Their inputs, stresses, outputs, and effects thereof are necessarily different than what we find at, or at least in communication with, the surface. These microbes represent an extreme of life as we know it, and might even give us a glimpse of life as we don't know it, or life as it once was, as illustrated in Figure 2.3.

Among the questions that dark life might help answer is one of the most profound and basic of questions: when and how did life begin? Some scientists hypothesize that life, in its earliest and most primitive form, might have originated beneath the surface, or at least that the deep environment might have served as its bomb shelter early in Earth's history, during the aptly named Hadean eon, marked by frequent heavy impacts from space.

A deep underground laboratory (ideally one that affords the ability to drill even deeper) would afford a priceless opportunity to study these organisms in an environment uncontaminated by surface life, and in their natural environment, with its heat, pressure, water chemistry, etc. It will also allow "biogeochemistry," the study of how they have altered their environment.

The major areas of research in geobiology are broad and interwoven, but may be thought of in three principal categories: Geomicrobiology, Geochemistry, and Biology. Because understanding life (especially at extremes) requires understanding its physical context, this research is also related to experiments in hydrogeology, rock mechanics, and the coupled interaction of processes related to the ensemble of all of these fields.

2.3 The Restless Earth (geoscience)

Expressions like "rock solid" greatly underestimate the dynamism and the amount of structural detail that geoscientists and engineers see in rock. In fact, many rocks are porous, fractured on small or large scales, or both. Many of the processes that we depend upon, like fluid production and injection, are predicated on the ability of fluids to circulate in "solid" rock. We need a better

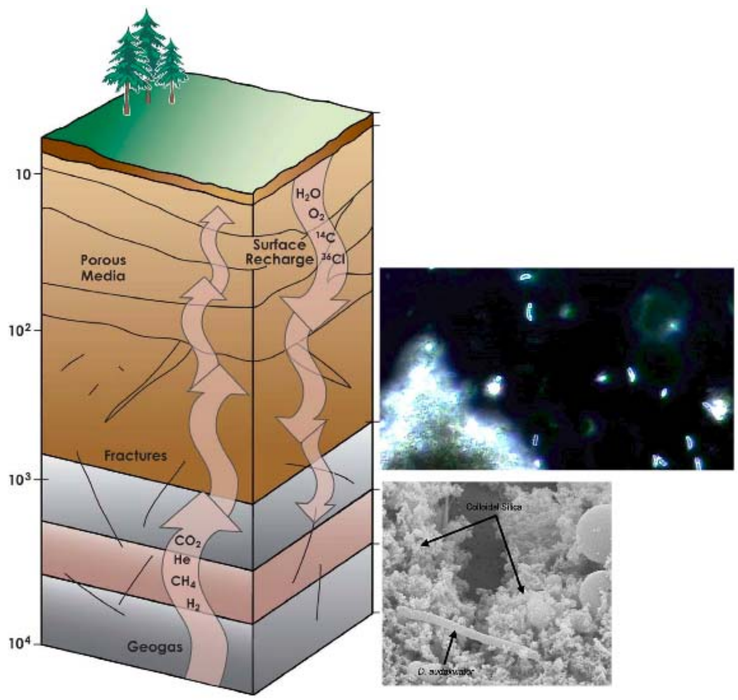


Figure 2.3 Dark Life found at depth without sunlight generated food for nourishment. The rod-shaped bacteria of ~ 4 μm in length were discovered at a South Africa gold mine, in water of several millions of years old, survived on chemical food sources derived from the radioactive decay of minerals in the surrounding rock. Figure adapted from [8] and EarthLab plan [9].

understanding of these matters both to make the best use of finite resources and to protect them against pollution. We also need to understand the mechanics of rock at the temperatures and pressures found deep underground in order to learn how to build on, or in, the earth. Ours is a "living" planet whose rock masses, set in motion ultimately by the geothermal heat, sometimes lurch against each other with devastating effect. A better understanding of rock mechanics deep underground would greatly aid the effort to understand and perhaps someday predict earthquakes. Many of the grand challenges in the study of our restless Earth can be addressed by DUSEL.

2.3.1 What are the interactions among subsurface processes?

Many processes underground "talk to one another." DUSEL will present a rare opportunity to examine these *coupled* thermal, hydrological, chemical, mechanical, and biological processes at length, under real geological conditions, and on a large physical scale. Rates of reaction of minerals under hydrothermal conditions would allow for investigation of strongly coupled processes that are important in many geological environments, but have never been studied under well-controlled conditions over long time periods and large spatial scales.

2.3.2 Are underground resources of drinking water safe and secure?

Hydrology, the study of how water (and, more generally, fluids) moves in the underground, will be a key area of DUSEL investigation, and a large number of questions remain to be answered in this important field.

If Homestake were selected for DUSEL, a wide range of earth-sciences disciplines would be rallied to investigation and collaboration almost immediately—dewatering the lower levels would provide a truly rare opportunity. The understanding of Homestake's low-flow, nearly-neutral-fluid setting with complex but relatively competent rock mass can shed light on deep circulation of groundwater systems, provide hydro-geochemical inputs to the dark-life investigations, and supply hydro-mechanical data to geological engineers.

Fluid flow and transport are active even at considerable depths, and despite the societal importance of these effects, 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 hydrologic science community would use a deep underground 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, physics of 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.

2.3.3 Can we reliably predict and understand earthquakes?

The S-1 report *Deep Science* points out how information gained from a deep underground laboratory enhances our understanding of earthquake mechanisms and rock behavior under the pressures and temperatures of the deep underground, a vital step toward earthquake prediction. DUSEL will "permit continuous, direct measurements of rock strain as a function of position and sampled volume at depth, both in the immediate vicinity of active faults and in the rock mass. These data would elucidate the influence of geology and human activity on tectonic strain and stress distribution in rock, allow direct observation of energy accumulation near faults and fractures, and provide insights into scaling fault slip processes to larger events."

2.3.4 Can we make the earth "transparent" and observe underground processes in action?

Geologists and geoengineers who study the deep underground are in almost as extreme a situation as astrophysicists and cosmologists who need to know about dark matter. They have to draw fact-based conclusions about something they can see only in tiny glimpses here and there. 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. In DUSEL, surface-based predictions of underground structure could be verified directly within a deep, three-dimensional rock volume that is accessible to back-excavation and known from past mining and core drilling.

The knowledge gained would have significant impact on our lives, such as devising 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. An ideal site for DUSEL would offer 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—scientists anticipate a fundamental paradigm change for data collections in rock physics and geophysics experiments.

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 cyberinfrastructure, are promising technologies called for in a National Research Council report *Geological and Geotechnical Engineering in the New Millennium: Opportunities for Research and Technological Innovation [10].*

2.4 Ground Truth (geoengineering)

As detailed above, the properties of rock—its integrity or lack thereof, ability to withstand a certain size of excavation at a given depth, the safety of working with it, the ability of fluids to flow through it—have a huge if easily overlooked impact on our lives.

2.4.1 What lies between the boreholes?

Rock fractures and faults play a critical role in the geological processes that take place continuously underground – a role impossible to investigate from laboratory research on rock samples alone. DUSEL would permit continuous, direct measurements of rock strain in the field, and would 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 afforded by DUSEL studies would lead to an improved understanding of how energy accumulates near faults and fractures, a vital step toward reliable prediction of earthquake timing or rock failure associated with civil structure. The depth dependence of fracture networks and associated rock mechanics measurements are of fundamental interest to determine if fractures displaying enhanced permeability for flow are also critically stressed.

2.4.2 How can technology lead to a safer underground?

Society depends upon the subsurface not only for fossil fuels, ores, and a great deal of its fresh water, but also for foundations, subways, tunnels, and other large pieces of infrastructure. The subsurface is complicated, varying from one site to another, from one part of a site to another, and even with time. It is hard for engineers to predict what they will find until excavation begins—figuring out "what lies between the boreholes" is a major problem, leading to costly and time-consuming issues such as excessive conservatism or changes of plans during a project.

DUSEL will enable firsthand study of how to remotely sense the characteristics of rock in all its complexity. Predictive models are important as well, and DUSEL will provide excellent opportunities to compare the results to "ground truth." Also to be explored will be the ways that rock responds to human activities such as underground construction. A figuratively and literally deeper understanding of how real rock behaves *in situ*, under full-scale real conditions of temperature and pressure, will be of tremendous benefit. The result will be cheaper, safer, and better-assured use of the underground.

DUSEL will be both a laboratory for and a beneficiary of these advances. Some of its experiments will require excavations that challenge the state of the art; and some of the activities of construction, such as blasting, can be monitored to obtain data.

2.4.3 How does water and heat flow deep underground?

Considering the high societal importance of fluid flow underground, it is not well understood in detail, especially at deep levels. DUSEL will provide an excellent opportunity for observation and experimentation in this area, especially from the standpoint of flow through fractured media. This opportunity will provide essential information on sustainably use and protection of aquifers.

Fluids are not the only things that flow under the earth with important consequences. 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 (the discovery of radioactivity was still decades away). A deep DUSEL, including deep boreholes, would offer an ideal setting to understand crustal heat transfer processes within the earth's crust at an unprecedented level. These measurements can be coupled with detailed analyses of the distribution of radionuclides to produce a detailed map of heat flow.

2.5 Synergy

Adaptation of concepts, techniques, and technology from other disciplines has been an important theme for all the disciplines included in DUSEL's Initial Suite of Experiments. DUSEL will provide exciting new venues for cross-disciplinary research that will mutually benefit earth sciences, physics, engineering and the other co-located scientific investigations. In addition to the incremental advances, it is plausible that new fields and research opportunities will emerge. For example, the temperature gradient and fluid movement within the earth's crust 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 geothermal energy extraction, underground radioactive waste storage and studies of geoneutrinos produced from the natural decay of uranium and thorium in the rocks. The sensor arrays installed within the underground facility will 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 major areas of research in geobiology are inherently synergistic and cross-disciplinary. Because understanding life (especially at extremes) requires understanding its physical context, this research requires an appreciation of the hydrogeology, rock mechanics, and the processes related to the ensemble of all of these fields. Many experiments may be combined into larger, coherent research themes, benefiting from coordinated and collaborative sampling campaigns and experimental efforts.

Physics experiments require sensitive detectors in large caverns at great depths and earth studies need substantial spatial coverage to quantify scaling and heterogeneity. Improvements in instrumentation can greatly enhance our understanding of processes and will be applicable to very different fields. For example, the photomultiplier technology for physics particle detection within neutrino, nucleon decay, and dark matter detectors could be applicable to fluorescent microbe and tracer detection. Furthermore, it is necessary for both physics and earth studies to conduct long-term experiments in a dedicated underground laboratory, to capture rare events, to improve statistics, and to quantify very slow and subtle geological processes.

The location of an expansive Initial Suite of Experiments in a single facility will "cross fertilize' these many efforts. There will be sharing of technologies between collaborations as well as disciplines that cannot be realized in a dispersed, non-centralized approach to underground science. Plans already involve the sharing of central facilities, such as low background counting, and ultra-low background material fabrication facilities. The large water-shielded facility, located in the Davis Cavity, is another example of shared infrastructure and synergism within the Homestake Facility. In several cases these fabrication facilities must be located at the site of the ultimate experiment to avoid subsequent cosmic ray activation. As technologies advance supporting ever-lower background environments for many physics research efforts, and as the earth science efforts are coordinated to take advantage of the long-duration opportunities provided by a dedicated facility, these research and technology advances will be freely and widely shared between all the users of the facility.

The education efforts and, importantly, the safety program will benefit from a single coordinated facility – both the exchange of information, but also to draw upon the experiences and advances within these fields to more effectively enrich the education and outreach program, and in the creation a world-leading safety program, one benefiting from underground experiences of the earth scientists and the diverse research experiences of the engineers, physicists and biologists.