SOUDAN: A Proposal for a National Underground Science and Engineering Laboratory (NUSEL)

Project Description

1.0 Introduction and Context

1.1 Underground Science: Underground science is an emerging, multidisciplinary field of scientific and technological studies directed towards environments within the surface of the Earth. Underground science has evolved in two interrelated branches. Some studies in underground science aim at achieving better understanding of the underground environment—for example, its geology, rock mechanics, geophysics, geochemistry, geohydrology and geomicrobiology. Applications of these studies include more efficient mineral extraction methods, better understanding of environmental contamination issues, improved ability to construct tunnels and other underground structures and more efficient utilization of scarce underground water supplies. A paradigm-shifting opportunity is the possibility of identifying new extremophiles, organisms that thrive in high pressure, high temperature and/or non-pH-neutral environments. Such organisms may have been decoupled from life on the surface of the earth for more than a billion years. Their discovery and assessment would likely provide insight into the probability for existence of extra-terrestrial life forms. The second group of underground science studies uses the isolation of the underground environment to enable very large, highly sensitive detectors to probe for the most rare phenomena in the Universe. These investigations include tests of the Standard Model of Subatomic Physics and efforts to probe beyond this Standard Model. Science topics include neutrino masses, couplings in the lepton sector, possible lepton CP violation, nucleon decay and dark matter searches. Opportunities for paradigm-shifting discoveries include unification of the fundamental forces in the Universe and new understanding of the origin of the Universe's matter-antimatter asymmetry. Technological applications include development of low background materials, enforcement of nuclear anti-proliferation accords and more sensitive techniques for trace analysis in environmental emission studies. Another technological application of the underground environment is high capacity, deep pumped hydroelectric energy storage. Efficient, adaptable energy storage is essential to development of renewable energy sources such as wind and solar power.

1.2 Underground Laboratories in the United States: During the past several years, at least five national panel and committee reports have identified both the opportunities for significant progress in basic and applied underground science and the scarcity of facilities in the United States to pursue these opportunities. Indeed, the United States trails a number of other countries in the world in multiple areas of underground science and technology. The world's most advanced countries in underground minerals extraction are Australia, Canada and South Africa. Companies headquartered in Scandinavia, Germany and Switzerland manufacture the world's most advanced underground mining equipment. Underground hard rock mining engineering is nearly extinct in American universities. American underground civil works projects have achieved far less challenging objectives than those outside the United States. For example, the world's longest highway tunnel is the 24.5 km long Laerdal Tunnel in Norway. More than 75 highway tunnels outside the United States are longer than America's longest tunnel—the one lane, combined road/rail 4.2 km Anderson Tunnel in Whittier, AK. Several of these long, deep tunnels elsewhere in the world (Gran Sasso, Mont Blanc, Frejus and Canfranc) have associated underground science laboratories, while sensitive scientific detectors in the United States have usually been installed as ancillary activities in operating mines.

Thus, while American science originated the concept of sensitive detectors deep underground with Nobel Laureate Raymond Davis's Homestake Solar Neutrino Detector, most newer detectors are located outside the U.S. The Homestake Detector itself was decommissioned in 2002, due to the termination of mining at the Homestake Mine. There is general agreement among scientists and engineers working in this field, that second operation ancillary to mining is now even less desirable for the next generation of highly sensitive, complex and costly detectors. The United States now has only two underground laboratories. The University of Minnesota has operated the Soudan Laboratory[1] in St. Louis County in northeastern Minnesota (latitude 47.82° N, longitude 92.24° W) since 1980. At Soudan, science is a symbiotic activity with a State Park visitor operation. The Soudan Laboratory is located at a depth of 710 m (2,080 meters of water equivalent or mwe) and includes two major rooms, each about 15 m horizontally by 15 to 16 m high in cross-section. The Soudan 2 Lab is 70 m in length. The MINOS Far Detector Lab is 90 m in length. Soudan is the target of the Neutrinos at the Main Injector (NUMI) beamline, which originates at Fermilab, 735 km to the southeast. Current experiments (see Section 1.5) at Soudan are MINOS, the Main Injector Neutrino Oscillation Search, and CDMS 2, the Cryogenic Dark Matter Search. Past experiments include the Soudan 1 Detector (a 30 tonne[2] proportional tube detector begun in 1980), the Soudan 2 Detector (a kilotonne tracking calorimeter that recorded data for more than 12 years) and a $\beta\beta$ decay detector. About 250 scientists and engineers are now involved in experiments at the Soudan Laboratory. The full-time staff is 28 people, down from a peak of 31 people because of increased efficiency in MINOS Far Detector installation. The other functioning underground laboratory in the United States is the Waste Isolation Pilot Plant (WIPP) project, about 25 miles east of Carlsbad in southeastern New Mexico. WIPP is located in salt at a depth of ~1,600 mwe.

1.3 National Underground Science and Engineering Laboratory Concept: The concept of a National Underground Science and Engineering Laboratory (NUSEL) in the United States emerged in the early 1980's under the leadership of Professor Alfred Mann of the University of Pennsylvania. Several other countries, most notably Italy at the Gran Sasso and Russia at Baksan, built multipurpose underground laboratories. The U.S. NUSEL concept gained momentum during the past five years with a series of discoveries in underground neutrino physics and the announcement of the closing of the Homestake Mine in late 2000. Since then, at least five panels and committees have recommended establishment of a U.S. NUSEL. In chronological order, the first is the *ad hoc* National Underground Laboratory Committee (the Bahcall Committee). This report (March 2001) consists of three parts—a paper entitled *Underground Science*, which presents the scientific case for NUSEL, a committee report regarding sites and a report of the Bahcall Committee's Technical Subcommittee, which discusses in detail criteria for underground laboratory site selection. The Bahcall Committee report emphasized significant depth as an essential feature of a new underground laboratory. The National Research Council (NRC) panel report *Connecting Quarks to the Cosmos: Eleven Science Questions for the New Century* (April 2002) identified neutrino mass, dark matter and proton stability as three of eleven key topics for ongoing research and discovery. Progress in all three of these areas requires deep underground detectors. An underground labo-

[1] Institutions currently participating in scientific research at the Soudan Laboratory are MINOS Collaboration: *(United States):* Argonne National Laboratory, Brookhaven National Laboratory, California Institute of Technology, Fermilab, Harvard University, Illinois Institute of Technology, Indiana University, Lawrence Livermore National Laboratory, Macalester College, University of Minnesota, Minneapolis & Duluth, Northwestern University, University of Pittsburgh, University of South Carolina, Stanford University, University of Texas at Austin, Texas A&M University, Tufts University, Western Washington University, University of Wisconsin; *(United Kingdom):* Cambridge University, University College London, Oxford University, Rutherford Appleton Laboratory, University of Sussex; *(Russia):* Institute of Theoretical and Experimental Physics (ITEP), Moscow, Institute for High Energy Physics (IHEP), Protvino, The Lebedev Institute; *(Greece):* University of Athens; *(France):* College de France; CDMS 2 Collaboration: Brown University, Case Western Reserve University, Fermilab, Stanford University, University of California at Berkeley, University of California at Santa Barbara, University of Minnesota; *(bb Decay):* Pacific Northwest Laboratories.

[2] We use the term "tonne" to indicate the metric unit, that is, 1,000 kilograms.

ratory would likely also contribute to understanding answers to another three of the panel's key questions: origin of the Universe, stellar nucleosynthesis and the nature of high-temperature, high-density matter. The Nuclear Science Advisory Committee (NSAC) report *Opportunities in Nuclear Science: A Long-Range Plan for the Next Decade* (April 2002) evaluated "compelling opportunities for nuclear scientists to explore fundamental questions in neutrino physics and astrophysics" in an underground laboratory as an essential element of its plan for the next decade. The High Energy Physics Advisory Panel (HEPAP) report *The Way to Discovery: Particle Physics in the 21st Century* (April 2002), while designating a linear collider as the field's highest priority, also recommended construction of a deep underground laboratory in the United States. Most recently, another NRC panel, the Neutrino Facilities Assessment Committee (NFAC), again recommended the establishment of a deep underground laboratory in the United States (December 2002). NFAC determined three important criteria for this laboratory: (1) a maximum depth of at least 4,500 mwe (1,520 m in standard rock with flat overburden; 1,675 m in a hemispherical mountain) with an option for 6,000 mwe; (2) a location ≥1,000 km from Fermilab or Brookhaven (BNL); and (3) several depths for location of detectors. NFAC also noted an urgent need for underground prototyping facilities, even if they are located at a relatively shallow depth. A BNL study (December 2002) published about the same time as the NFAC report described a rich, multi-decade program of neutrino science, including possible CP violation in the lepton sector, that could be investigated with a ~2,000 km neutrino beamline terminating at a deep underground laboratory.

1.4 Underground Science and Engineering Frontiers: The underground science and engineering challenges that NUSEL will address are discussed in Section 2 of this proposal. These questions and the reports discussed above lead us to believe that a U.S. NUSEL must progress over existing world facilities on three main frontiers—depth, size and ability to safely use difficult detector materials. *Depth* refers to the ability to provide an environment with low background fluxes due to cosmic rays. The current deepest laboratory in the world is the Sudbury Neutrino Observatory (SNO) at a depth of ~6,500 mwe. *Size* is both the volume of cavities available for detectors and the dimensional and weight limitations on access of single large items to the underground detector locations. The current world standard on detector volume is Super-K, with a gross single cavity volume of $<10^5$ m^3. The current access standard is Gran Sasso, which provides access for fully loaded semi-trailers, carrying, for example, 40 foot international shipping containers. *Difficult materials* are most likely cryogens, such liquid argon, nitrogen and xenon, and flammables, such as mineral oil-based liquid scintillator. The current world limits on difficult materials are 600 tonnes of liquid argon in Icarus at Gran Sasso and 1,000 tonnes of liquid scintillator at Kamland and Boraxino.

The design for a U.S. NUSEL should exceed or equal current world standards on all three of these frontiers. A Soudan NUSEL will be deeper than SNO, permit excavation of larger cavities than Super-K, allow access for fully loaded semi-trailers with 40 foot international shipping containers and facilitate safe use of larger quantities of cryogens and liquid scintillator than Gran Sasso and Kamioka.

1.5 Conceptual Design of the Soudan NUSEL: The conceptual design of the Soudan NUSEL starts with the ongoing scientific investigations and the facilities that already exist or are currently under construction. Ongoing studies include the Cryogenic Dark Matter Search (CDMS 2) Detector, which seeks to discover dark matter in the form of weakly interacting massive particles (WIMPs). CDMS 2 requires simultaneous deposition of energy by ionization and phonon excitation to distinguish WIMP candidates from background. The second ongoing experiment is the Main Injector Neutrino Oscillation Search (MINOS) Far Detector. MINOS seeks to measure the parameters of muon neutrino to tau neutrino oscillation, using a 735 km long baseline neutrino beam from Fermilab to Soudan. The MINOS Far Detector is a 5,500 tonne magnetized iron-plastic scintillator tracking calorimeter, which is currently more than 98% installed in the Soudan Laboratory. Although not specifically part of the current scientific program at Soudan, Fermilab P-929, the NUMI Off-Axis Neutrino Detector, which seeks to study tau neutrino to electron neutrino oscillation, is part of the growing "critical mass" of scientific activities in the immediate geographical area of Soudan and the NUMI beamline. Existing and under construction facilities at Soudan include the two fully-equipped laboratories described in Section 1.2, a surface storage and receiving facility with a floor area of 640 m^2, underground access and utilities facilities maintained by Minnesota State Parks and the NUMI neutrino beam.

The Soudan NUSEL conceptual design includes three phases, which can proceed in overlap. Phase 1 is continuation of the existing program with the MINOS and CDMS 2 detectors and renovation and re-use of the ~750 m^2 of equipped underground laboratory space at a depth of 710 m that will become available in Summer 2003 upon completion of the installation of the MINOS Far Detector. The current highest priority for this renovation is the construction of a clean-room, low-background counting facility for development and prototype work for later larger detectors at Soudan and other laboratories. Phase 2 is access improvement to both the existing laboratories and deeper levels. The time critical path is the driving of a 20 m^2 cross-section, 1:7 decline from the 710 m level, first to the 1,450 m level and then to the 2,500 m level. This decline (see Section 3) is modeled after the existing access to the 1,410 m level in the Inmet Pyhäsalmi Mine in Finland. The decline will follow the shape of a race track style (two straights, two 180° curves) helix, excavated in basalt and centered about 1.5 km east of the current laboratory. The decline will be connected to the existing laboratories through the mostly existing 27th level east drift, which will be slashed out to a 5 m by 4 m cross-section. The decline will have cut-outs at selected points along its entire length that can be used either for vehicle passing or to house core drilling rigs for studies in geomicrobiology and economic geology. The second major element of Phase 2 is the raise boring of a new shaft from the 710 m level at a point tangent to the race-track decline to the surface. A new friction hoist will be installed in this shaft to increase the Soudan hosting capacity from the current 300 tonnes per day at 710 m in the existing No. 8 shaft to 3,000 tonnes per day at 1,450 m in the new shaft. The third major element of access improvement is the extension of the "race-track" helix decline from the surface to the 710 m level, thus eventually providing full access for semi-trailer sized vehicles with a 40 foot international shipping containers to laboratories at 710 m, 1,450 m and 2,500 m. Phase 3 of the Soudan NUSEL conceptual design is the proposal-driven construction of new laboratory space at the 710 m, 1,450 m and 2,500 m levels. The laboratory for the megatonne-class neutrino and nucleon decay detector will likely be located at the 1,450 m level. Laboratories for cryogenic or flammable liquid detectors can be located at any of these three levels. Fire and blast-resistant bulkheads and doors and isolated, raise-bored ventilation shafts, along with fire suppression and other life-safety systems, will permit safe use of such detectors.

1.6 Why Soudan? American scientists and engineers have suggested multiple possible sites for the U.S. NUSEL. We discuss the advantages of the Soudan site for specific science and engineering investigations in Section 2. In Section 5, we discuss the strength of the Soudan NUSEL management team, whose underground science and underground laboratory management experience far exceeds that of the management proposed for any other site. Section 6 specifically compares Soudan with sites at Homestake, San Jacinto, the Waste Isolation Pilot Plant (WIPP) and the Phelps Dodge Henderson Mine. Here, we summarize the advantages of the Soudan site for NUSEL.

(a) Soudan is currently the largest, deepest, most experienced and most active underground science and engineering laboratory in the United States today. It is the only underground laboratory in the United States with an ongoing, funded scientific program. Soudan NUSEL would begin with an ongoing scientific program and would benefit from the lower regulatory and public acceptance threshold that applies to expansions as contrasted to “green-field” projects.
(b) The NUMI beam from Fermilab to Soudan is the only funded long baseline neutrino beam in the United States—and one of only three in the world. While the value of that beam for future scientific research depends on the precise (and currently not well known) value of Δm_{23}^2, the cost of the NUMI beam is ~$150 million. This beam is thus a unique asset of the Soudan site and duplicating it elsewhere will require a substantial expenditure.
(c) The properties of Soudan’s pre-Cambrian basalt appear well suited to the requirements of a deep underground NUSEL. Low radioactivity and low rock temperature facilitate construction of low background, low noise detectors. The rock hardness and homogeneity are conducive to mechanical excavation. The rock strength and stability facilitate large, stable cavities, as demonstrated in part by the 18-year history of the Soudan 2 Laboratory with no observable cracking of either the shotcrete lining or the poured concrete floor.
(d) The conceptual design for Soudan results in a laboratory with a completely modern infrastructure, access to multiple depths (710 m, 1,450 m and 2,500 m) as recommended by the NFAC report, the ability to drive-in with semi-trailers to all parts to the entire laboratory and low ongoing costs for maintenance and operations. The current Soudan laboratories produce no measurable water and no water is expected in the new deeper laboratories. The cost of pumping the entire historic mine (water flow ~3 l/s) averages $3,000 per month, paid by Minnesota State Parks. Soudan has no history of mine fires, rock bursts or similar events. Access to the surface over the laboratory and to multiple underground levels separated by <1,000 m enables the use of relatively low-cost, mechanical raise boring techniques to construct as many isolated ventilation shafts as required to permit safe use of large quantities of difficult detector materials such as cryogens and flammables.
(e) The Soudan Laboratory has existing, well-equipped underground laboratory space that can be used to jump start new scientific and engineering activities. A Soudan NUSEL avoids the problem of funding ongoing maintenance of an inactive site, while awaiting scientific proposals and sufficient funding for new capital investment.
(f) Soudan has an existing workforce skilled in assisting in the installation and operation of underground science detectors and 23 years of successful project management and operational experience. The Soudan Laboratory staff collected physics data with the kilotonne Soudan 2 Tracking Calorimeter Detector for more than 12 years. The highly successful, smooth installation of the MINOS Far Detector is strong evidence of the capabilities of the staff at Soudan to manage and operate state-of-the-art scientific and technological detectors and projects.
(g) The Soudan site has no requirement for ongoing interaction with a mining company and essentially no remnant liabilities for mining activities. Mining activities at Soudan were limited to extraction of hematite with no ore processing other than crushing, no tailings ponds and no use of chemicals. Mining activities at Soudan ended more than 40 years ago and no environmental liability claims have arisen since the cessation of mining in 1962.
(h) Soudan has an ongoing program of public outreach and education, primarily in cooperation with Minnesota State Parks. During 2002, more than 6,000 members of the public and school groups paid admission for State Parks tours of science at Soudan. The Soudan Laboratory has also used media including National Geographic Today, live broadcasts on the Minnesota Public Radio network and newspapers and magazines to inform the public about the excitement of

underground science. Section 4 of this proposal discusses the past and future education and outreach program in more detail.

(i) The Soudan Laboratory has a primary sponsoring institution, the University of Minnesota, which is interested, experienced and financially capable of managing the responsibilities and risks of a major underground laboratory. The University of Minnesota views any liabilities associated with Soudan as ordinary business risks to be aggregated with other risks in its $550 million per year sponsored research program. The University expects to fund such risks from its standard indirect cost recovery at the rate negotiated for all off-campus, federally sponsored research and will not seek direct payments for insurance or escrow funds by scientists and engineers or their sponsors. The University is interested in partnering in laboratory management with the national and international scientific and engineering communities, as discussed in Section 5.

In summary, Soudan is a real laboratory that has demonstrated experience managing real science and technology projects on budget and on schedule. Communications at Soudan are transparent and are based on 23 years of experience and precedents. These relationships provide the best possible context for managing NUSEL as a complex, but straightforward project.

2.0 Scientific and Technological Motivations

The scientific and technological motivations for a National Underground Science and Engineering Laboratory are discussed in multiple papers, reports and talks. The Bahcall Committee paper entitled *Underground Science* is included in this proposal as Appendix 2. This paper provides an excellent summary of the scientific and engineering opportunities available underground in the areas of solar neutrinos, double beta decay, dark matter, nucleon decay, atmospheric neutrinos, long baseline neutrino oscillations, supernovae neutrinos, nuclear astrophysics, geoscience, materials development and technology, monitoring nuclear tests and geomicrobiology. Appendix 3 of this proposal is the report of the National Academy of Sciences/National Research Council (NAS/NRC) Neutrino Facilities Assessment Committee (NFAC). The NFAC report discusses many of these same areas of science and technology and strongly recommends the establishment of NUSEL in the United States. As described earlier, further support for NUSEL comes from another NAS/NRC report, *Connecting Quarks to the Cosmos: Eleven Science Questions for the New Century*. NUSEL will contribute significantly to progress in neutrino mass, dark matter and proton stability and will be useful to progress in origin of the Universe, stellar nucleosynthesis and high-temperature, high-density matter. Strong support for NUSEL is clearly indicated in the Nuclear Science Advisory Committee (NSAC) April 2002 planning report *Opportunities in Nuclear Science: A Long-Range Plan for the Next Decade*. While enthusiasm in elementary particle physics planning documents is mostly directed towards the Linear Collider, the March 2003 *High Energy Physics Facilities Twenty Year Roadmap* categorizes the scientific potential of double beta decay, the neutrino super-beam and the underground detector as “absolutely central.”

Since the scientific and engineering opportunities of NUSEL have been strongly and repeatedly endorsed, the more relevant topic is the impact on the scientific and engineering opportunities of the selection of Soudan as the NUSEL site. While the impact of the Soudan site is discussed topic by topic in Table 1 below, we emphasize three general points. First, Soudan NUSEL is designed to be better or at least equal to every existing or proposed underground laboratory in the world in the three key areas of depth, size of detectors and access and ability to use cryogens, flammables and other difficult detector materials. Thus, we believe that no site is better than Soudan in any of these key features. There are, however, some less important characteristics, such as ultralow uranium-thorium content or ability to easily excavate with mechanical roadheaders in the salt at WIPP that might make other sites somewhat better than Soudan for some particular detectors. Second, the information in Table 1 clearly indicates that the "racetrack decline" feature of Soudan NUSEL is an important programmatic element, not just an efficient way to move large equipment and instrumentation to the deep underground laboratories. The decline will expose of order one cubic kilometer of rock to ready access by short hole core drilling. Passing/drilling areas distributed around the decline will enable all kinds of geological, geobiological and geophysical studies that have never previously been feasible. The final important feature for the Soudan site for all science and engineering topics is feasibility. As described elsewhere in this proposal, the Soudan site has a demonstrated ability to deliver underground science as evidenced by its past ongoing scientific program and the historical record and experience of its project management team. The Soudan site is the low risk approach to achieving NUSEL's scientific and engineering goals.

Table 1 provides both general and Soudan-specific information on 16 science and engineering topics that research at NUSEL can address. Three topics that have not received previous extensive discussion—neutron anti-neutron oscillation, studies in economic geology and research and development in deep underground pumped hydroelectric energy storage—are described more fully in the text below.

2.1 Neutron Anti-neutron Oscillations: Experimental observation of nucleon instability is one of the missing components required for the understanding of baryon asymmetry of the universe (BAU). Traditional proton decay with the modes and rates predicted by the original (B−L)-conserving SU(5) GUT scheme has not been experimentally observed. It also is not a sufficient explanation of BAU. A possible explanation for observed BAU is processes violating (B−L) at the energy scale above the scale of electro-weak non-perturbative (sphaleron) transitions. Such processes need to be searched for in new generation of experiments requiring underground facilities These processes include (a) non-traditional nucleon decay into lepton+X (for example $n \to$ [illegible], $nn \to$ [illegible]), (b) neutrinoless double-beta decays where ΔL = 2, and (c) most spectacularly, the process of neutron to antineutron transition. The last process has unambiguous signature and can be searched for in an experimentally controlled environment. With present techniques, the sensitivity of $n \to \bar{n}$ search can be improved by a large factor of ~ 1,000. In the modern theoretical brane-world models, global charges like baryon and lepton numbers are not conserved as a result of quantum fluctuation of the brane world volume into higher-dimensional space. With a low-energy gravity scale of ~ 100 TeV, such processes can lead to neutron-antineutron transitions, while the proton decay processes are suppressed. Thus, observation of $n \to \bar{n}$ could be the first experimental manifestation of the existence of extra dimensions in nature.

We anticipate construction of a new $n \to \bar{n}$ search experiment at the Soudan NUSEL facility. The proposed experiment would likely include a dedicated research 3.4 MW intense neutron source of the TRIGA type (to be purchased from General Atomic Company) with an annular core and encasing a vertical tube holding the cold moderator, which will provide the source of neutrons. This neutron source would be installed on the top of a vertical, raise bored shaft, either 710 m or 1,450 m long with diameter of several meters. A focusing neutron reflector would be installed in the vertical vacuum chamber (vacuum better than 10^{-4} Pa). The Earth's magnetic field inside the vacuum chamber would be compensated by active and passive magnetic shields down to the level of few nT. Antineutrons transformed from neutrons during the flight through the vacuum chamber would be detected by an antineutron annihilation detector located at the 710 m or 1,450 m level of Soudan NUSEL. An inverse configuration with the neutron source at the bottom and detector on the top is likely also feasible.

2.2 Studies in Economic Geology:

2.3 Deep Underground Pumped Hydroelectric Energy Storage: The United States and the world will likely need ever increasing supplies of energy. Because of concerns about nuclear power and greenhouse gases, renewable energy technologies such as wind and solar power are likely to become increasingly important in the future. A major drawback of these technologies is that wind and solar power are not *dispatchable*, that is, power capacity can only be determined on a statistical basis. Wind and solar power can be made dispatchable by construct either energy storage facilities or peaking plants, such as those using gas turbines. Peaking plants, of course, use fossil fuel and contribute to greenhouse emissions. Various energy storage technologies have been investigated, including batteries, fuel cells and flywheels. Among these technologies, pumped hydroelectric energy storage is attractive because it has high efficiency (nearly 70%), uses straightforward technology, requires low maintenance costs and has good load-following capabilities. The major disadvantage of pumped hydro is that mainly proposed projects use low heads between the two storage reservoirs. Low head means large volume of water per megawatt hour, which means large reservoirs and significant environmental effects.

The advantage of deep underground pumped hydro energy storage is that gravitational potential energy is linearly dependent on the vertical height between the two reservoirs. However, the cost per unit volume of deep underground cavities increases only slowly with depth. Thus, the deeper the cavity, the lower the construction cost per unit of energy stored. Access to intermediate levels is important because it is not clear that an extremely high head can be used efficiently in a single drop. A more likely arrangement is multiple drops where the water exhausted from one turbine is immediately dropped again to feed another turbine. An additional advantage of the deep underground location is that one reservoir is completely concealed, minimizing environmental effects.

An easy calculation illustrates the potential of developing this technology at Soudan NUSEL. The lowest level at Soudan is 2,500 m. We expect to construct a ~1,000,000 m^3 cavity for a neutrino and proton decay detector. If we construct a second such cavity (or collection of smaller cavities with the same volume) for energy storage, the storage capacity will be $(10^9 \text{ kg})(2500 \text{ m})(9.8 \text{ m/s}^2)(0.85) = 2.1 \times 10^{13}$ joules or ~5,800 Mwh, assuming an 85% efficiency factor for the energy extraction phase. This amount of energy is equal to the entire output of an average nuclear power plant for most of a working day.

The potential for Soudan as a pumped hydro energy storage demonstration site is enhanced because Soudan is located midway along the Midwest power grid backbone that connects Manitoba Hydro with Chicago. Generally, Manitoba takes power in the winter and supplies power in the summer. Both Xcel Energy and the Minnesota Power Division of Allete have indicated at least preliminary interest in energy storage at Soudan. Xcel has a commitment to invest approximately $8 million per year in renewable energy and energy storage in return for its permit to construct nuclear waste storage casks at its Prairie Island nuclear plant.

We expect to further explore partnership and funding possibilities in this area during the preliminary engineering phase of this project.

Table 1: Soudan National Underground Science and Engineering Laboratory: Science and Technology Summary

<table>
<tr><th>Scientific and Technological Questions</th><th>Detector Requirements, Capabilities</th><th>Lab Requirements</th><th>Discovery Potential</th></tr>
<tr><td colspan="4">Neutrino Oscillations: Long-Baseline and Atmospheric</td></tr>
<tr><td>• What is the nature of the lepton mixing matrix?
• Is it possible to measure CP violation in the lepton sector?
• What is the order of the neutrino hierarchy?
• What are the values of measurable parameters of the matter effect?
• Can we better determine neutrino-nucleus cross-sections important for supernova and solar neutrino studies?
• What is the strangeness content of the nucleon?</td><td>• Need larger statistics for more precise measurements, that is, larger detectors
• Improved ability to detect tau appearance in CC neutrino interactions
• Better energy sensitivity for more precision in measuring L/E
• More statistics on neutral current events</td><td>• Depths ≥4,000 mwe
• Usable volume of 10^6 m^3
• Clean room space for construction and assembly
• Low radon levels
• Large staging area and ability to move large assemblies underground
• Ability to safely handle cryogens and mineral-oil-based scintillators</td><td>• Leptonic CP violation relevant to matter anti-matter asymmetry
• Direct observation of oscillation maxima and nodes
• Unnatural neutrino hierarchy
• New measurements of neutrino-nucleus cross-sections relevant to supernovae, etc.
• Understanding of GeV neutrino interactions in nuclei</td></tr>
<tr><td colspan="4">Neutrino oscillation studies at Soudan NUSEL will benefit from the currently under construction NUMI beam from Fermilab (735 km) and the MINOS Far Detector (5,500 tonnes). The BNL-Soudan distance is 1,710 km. The Soudan conceptual design meets or exceeds all of the “Lab Requirements” for neutrino oscillations.</td></tr>
<tr><td colspan="4">Solar Neutrinos</td></tr>
<tr><td>• Do we really understand the solar neutrino problem?
• Do we understand the nuclear physics of main sequence stars?
• Is the Standard Solar Model correct in all its details?
• Can we learn more about 1-2 mixing from solar neutrinos?</td><td>• Ability to directly observe p-p neutrinos, i.e., energy threshold of 200-400 keV and ultralow background radioactivity
• Detectors have multiple capabilities for solar, supernova, long-baseline and atmospheric neutrinos</td><td>• Depths ≥5,000 mwe
• Volume of 7,500 to 500,000 m^3
• Clean room environment
• Low radon levels
• Ability to safely handle cryogens and mineral-oil-based scintillators</td><td>• Neutrino mass mixing parameters and hierarchy
• Quantitative understanding of stellar evolution and nucleosynthesis
• Physics beyond the Standard Model
• Role of neutrinos in nuclear astrophysics and cosmology</td></tr>
<tr><td colspan="4">The thrust of future research in solar neutrinos is measurement of the p-p neutrino flux, which requires extremely low background, low noise detectors. The Soudan conceptual design, which provides access for large equipment and difficult materials to extremely deep depths, will facilitate p-p solar neutrino research. Low radioactivity, low rock temperatures and ample cooling at Soudan facilitates low threshold detectors.</td></tr>
<tr><td colspan="4">Supernovae Neutrinos</td></tr>
<tr><td>• Can we use the neutrino flux from supernovae to learn about the explosion mechanism and probe the properties of the proto-neutron star?
• Can we exploit supernovae to search for new phenomena, including the neutrino mass matrix?</td><td>• Flavor sensitivity and the ability to distinguish between neutrinos and anti-neutrinos
• Broad energy response with good energy sensitivity
• Sensitivity to events in the cooling curve tail</td><td>• Depths of ≥2,000 mwe
• Volume of 15,000 m^3
• Ability to safely handle cryogens and mineral-oil-based scintillators</td><td>• Supernovae neutrino is a key component of “supernovae watch,” involving gravity wave and optical detectors
• Possible time-of-flight measurement of neutrino mass
• Potential observation of tau neutrinos</td></tr>
<tr><td colspan="4">The key to supernovae neutrino research is long-term, stable, low maintenance detector and laboratory operation. The Soudan Laboratory has low ongoing maintenance and operating costs, an indefinitely long mission in cooperation with Minnesota State Parks and an existing 23-year long record of stable, efficient operation as a laboratory and 120 years as a mine.</td></tr>
</table>

Scientific and Technological Questions	Detector Requirements, Capabilities	Lab Requirements	Discovery Potential
Double Beta Decay			
• Is lepton number conserved? • Are neutrinos Majorana particles? • What is the absolute scale of neutrino masses? • What is the nature of neutrino mixing? • Can we learn more about phenomena beyond the Standard Model?	• Need sensitivities of $<m_{eff}>$ ~ 0.01-0.05 eV, i.e., detector masses of 100-1,000 kg, isotopically enriched materials, excellent energy resolution, ultra low radioactivity materials • Detectors may have multiple capabilities for solar neutrinos and dark matter	• Depths ≥ 4,000 mwe (~2,000 mwe for EXO) • Volume of 700 – 4,500 m^3 • Clean room environment • Low radon levels • Ability to safely handle cryogens • Special shielding from terrestrial radioactivity	• Lepton number violation in early Universe is crucial to cosmology • Opportunity to study rare second-order weak interactions in Nature • Absolute scale of neutrino masses is crucial to multiple topics in particle physics and cosmology
Double beta decay experiments have a wide range of characteristics depending on the transition that the detector aims to observe. Some ββ detectors, such as those fabricated from germanium, require extremely clean, extremely deep environments. The deepest level at Soudan will provide the best place on Earth for such detectors. Other ββ experiments, such as EXO, have better background rejection, but utilize cryogens. Some labs at Soudan NUSEL will be specially equipped for safe use of cryogens and other difficult materials.			
Nucleon Decay			
• Is baryon number conserved? • Are protons stable? • What new models lie beyond the Standard Model?	• Proton lifetime sensitivity $>10^{33-34}$ years requires mass >500,000 tonnes • Potential for full range of neutrino physics in addition to nucleon decay	• Depths ≥4,000 mwe • Volume up to 10 m • Clean room for construction, assembly • Low radon levels • Large staging area • Ability to safely handle cryogens and mineral-oil-based scintillators	• Baryon number violation is crucial to understanding cosmology and physics beyond Standard Model • Nucleon decay is a direct probe of GUT scale • Direct test of most grand unified theories
Soudan NUSEL is specifically designed to include the infrastructure required to support a megatonne class neutrino and proton decay detector at the 1,450 m level. Construction of such a detector could begin ~3 years after Soudan NUSEL approval.			
N Nbar Oscillations			
• Is baryon number conserved? • Is there a measureable rate for a $\Delta B=2$ process? • What new models lie beyond the Standard Model?	• Detector requires good energy and momentum resolution to separate n nbar annihilation from background, since incident nbar is not observable	• Large vacuum vessel in dedicated vertical shaft • Intense neutron source at surface • Laboratory at depth of at least 500 m. Deeper is better because of longer neutron path	• Baryon number violation is crucial to understanding cosmology and physics beyond Standard Model • Nucleon oscillation is a direct probe of GUT scale • Direct test of most grand unified theories
This science requires Soudan's somewhat unique ability to inexpensively raise bore a shaft. The task of permitting the TRIGA intense neutron source may be more straightforward at Soudan than at some other locations. Soudan NUSEL also offers a upgradeable choice of flight distances for the neutron to antineutron conversion.			
Dark Matter			
• What is the composition of dark matter? • How does dark matter interact with ordinary matter? • What role does dark matter play in cosmology, the evolution of the universe and structure formation?	• Extend sensitivities to regions predicted by minimal supersymmetric models with detector masses of 100-1,000 kg and ultalow radioactivity • Directional sensitivity useful • Potentially useful for ββ decay	• Depths ≥4,000 mwe • Volume of 700 – 4,500 m^3 • Clean room environment • Low radon levels • Ability to safely handle cryogens • Special shielding from terrestrial radioactivity	• Nature of lightest supersymmetric particle • Existence of weakly interacting massive particles (WIMPS) • Possible relevance to models of extra dimensions, string theories and quintessence • Insight into unification of gravity
Soudan NUSEL will provide both the extreme depth and clean environment required to facilitate these experiments. CDMS 2 can be improved and moved to a deeper location to increase experimental sensitivity.			

Scientific and Technological Questions	Detector Requirements, Capabilities	Lab Requirements	Discovery Potential
Nuclear Astrophysics			
• Do we understand the low-energy nuclear physics reactions that power stars? • What is the influence of nuclear structure and reactions on the evolution, energy generations, and time scales in stars and stellar explosions? • What is the origin of elements that make up the present day Universe?	• High intensity, low energy heavy ion accelerator to do inverse kinematics experiments (located underground to reduce backgrounds for extremely low rate measurements)	• Depth ≥ 4,000 mwe • Volume of 6,000 m • Must be isolated from experiments sensitive to radioactivity • Maintain safe environment for accelerator operation	• More precise understanding of important and low rate p-p and CNO stellar processes • Understanding of nuclei far from stability • Understanding of heavy element nucleosynthesis
This research requires installation of an accelerator, likely in a location remote from other detectors. The Soudan NUSEL decline tunnel will facilitate access to a suitable remote location and bringing large accelerator components into the underground accelerator hall.			
Geoscience			
• How do liquids and gases move through geologic structures? • How can hydrogeology be better understood when only surface and borehole data are available? • What are stress-strain relationships for real rock formations? • What kinds of geochemical reactions dominate in various rock formations? • What are effects of rock heating and cooling?	• As much three dimensional exposure of rock as possible • Ability to drill bore halls from underground access tunnels • Variety of seismic, magnetic, gravity, rheology, compression strength, pH and other geophysical and geochemical measurements • Ability to heat and cool rock structures	• Access to as extensive and geologically diverse locations as possible • Range of depths	• New models for environmental control and pollution remediation • New understanding of effects of earthquakes and other seismic events, such as underground nuclear tests • New understanding of effects of storage of high-level radioactive wastes deep underground • New understanding of underground construction methodology
The Soudan NUSEL decline provides extraordinary access to a large volume of rock for geoscience investigations. The "passing" areas distributed along the decline will facilitate drilling and geophysical measurements at a variety of locations. The decline will be equipped with a communications system for experiment control and data acquisition.			
Extremobiology (Geomicrobiology)			
• How do organisms survive in harsh, non-traditional environments? • What level of bioactivity are possible in extreme environments? • Are microbes in deep underground fluid inclusions different from microbes embedded in rock strata?	• Ability to drill and recover cores from bore holes without killing or contaminating micro-organisms • Ability to characterize stress, physics and chemistry of a variety of locations	• Access to as extensive and geologically diverse locations as possible • Range of depths • Volume of 1200 m • Sterile and non-lethal bore holes • Environmental monitoring system • Chemistry and biology lab facilities	• Insight into life in extreme environments, such as deep sea locations and outer space • Possible discovery of life forms decoupled from evolution on Earth's surface • Understanding of relationship between microbial life forms and their environment
The Soudan NUSEL decline provides extraordinary access to a large volume of rock for extremophile searches and other geomicrobiological studies. These studies can use the "passing" areas distributed around the decline as bases to investigate geomicrobiology at a number of locations. These locations will have easy access and good communications.			

<table>
<tr><th>Scientific and Technological Questions</th><th>Detector Requirements, Capabilities</th><th>Lab Requirements</th><th>Discovery Potential</th></tr>
<tr><td colspan="4">Mineralization</td></tr>
<tr><td>• Understanding how minerals have been concentrated by sub-surface fluid flows
• Better understanding of how to identify areas of mineralization from geophysical, geochemical and other data
• Understanding of effects of mining discharges</td><td>• As much three dimensional exposure of rock as possible
• Ability to drill bore halls from underground access tunnels
• Variety of seismic, magnetic, gravity, rheology, compression strength, pH and other geophysical and geochemical measurements</td><td>• Access to as extensive and geologically diverse locations as possible
• Range of depths
• Extensive geological, geophysical and geochemical characterization of entire nearby rock volume</td><td>• Better understanding of how to characterize mineralization from surface and bore hole data
• Better understanding of environmental remediation for mining activities</td></tr>
<tr><td colspan="4">Driving the Soudan NUSEL decline will unique data about mineralization in a large volume of rock. The “passing” distributed around the decline will permit core drilling to supplement the information learned from the construction of the decline itself.</td></tr>
<tr><td colspan="4">Geoengineering</td></tr>
<tr><td>• Rock stress and strain not currently well understood over large volumes
• Need to correlate 3d stress-strain with interferometric synthetic aperture radar and GPS data
• Better understand methods for excavation and rock support of underground structures</td><td>• As much three dimensional exposure of rock as possible
• Ability to drill bore halls from underground access tunnels
• Variety of seismic, magnetic, gravity, rheology, compression strength, pH and other geophysical and geochemical measurements</td><td>• Access to as extensive and geologically diverse locations as possible
• Range of depths
• Extensive geological, geophysical and geochemical characterization of entire nearby rock volume</td><td>• New non-invasive techniques for evaluating sites for underground structures
• New techniques for excavating and supporting underground structures</td></tr>
<tr><td colspan="4">The Soudan NUSEL decline will provide access to a large volume of rock. Designing and building the decline, the megatonne detector cavity and the possible pumped hydro energy storage facility are challenging geoengineering projects, which may facilitate development of innovative engineering and construction methods.</td></tr>
<tr><td colspan="4">Precision Radioassay</td></tr>
<tr><td>• What sensitivity levels can be reached in counting low-background materials?
• Can cleaner materials be found and utilized in next generation science experiments?
• Can more sensitive radioassay techniques be developed for environmental studies and nuclear nonproliferation?</td><td>• Low background germanium counting systems
• Whole body scintillation counter
• Dedicated systems for specialized purposes</td><td>• Depths ≥4,000 mwe (can start at 2,000 mwe)
• Volume 4,000 m
• Low radon levels
• Clean room environment
• Special water shield to reduce terrestrial radioactivity</td><td>• Facilitate construction of next generation low background detectors for □□ decay, dark matter and solar neutrinos
• Verification of nuclear testing treaties
• Investigations of environmental impacts of smokestack gases, chemical discharges, etc.</td></tr>
<tr><td colspan="4">Soudan NUSEL will immediately establish a clean, low background counting laboratory at the 710 m level. As the 1,450μ and 2,500 m levels are developed, these facilities can be moved to deeper locations that will even further enhance precision radioassay capabilities at Soudan NUSEL.</td></tr>
</table>

Scientific and Technological Questions	Detector Requirements, Capabilities	Lab Requirements	Discovery Potential
Materials Development			
• To what effect do radioactive trace elements affect performance of semiconductors for electronics, medical imaging, etc.? • Can ultraradiopure materials be fabricated deep underground?	• Low background germanium counting systems • Whole body scintillation counter • Dedicated systems for specialized purposes	• Depths ≥4,000 mwe (can start at 2,000 mwe) • Volume 4,000 m • Low radon levels • Clean room environment • Special water shield to reduce terrestrial radioactivity • Equipment for crystal growing, distillation and other purification processes	• New ultrasensitive detectors for medical imaging, etc. • New ultraradiopure semiconductor electronics • Production of ultraradiopure materials for users
Soudan NUSEL will have clean, low background facilities immediately at 710 m and later at deeper depths. Materials development at Soudan NUSEL can start right away and develop as facilities improve.			
Deep Pumped Hydroelectric Energy Storage			
• Is deep underground pumped hydroelectric storage economically feasible? • What are the load following capabilities of high-head hydro? • Are special turbines and pumps useful for high head applications?	• Process control instrumentation and software	• Large volume deep underground for lower reservoir • Dedicated shaft for penstock • Intermediate pumping and turbine stations	• Increased ability to make renewable energy sources (wind, solar, etc.) dispatchable • Reduced dependence on turbine peaking plants
Soudan NUSEL has abundant supplies of water and good access to the Midwest power grid. Wind farms in southwestern Minnesota generate renewable energy that requires storage capacity for most efficient utilization.			
Low Background Counting Facility			
• Facility to support detector development, materials development and precision radioassay	• Low background germanium counting systems • Whole body scintillation counter • Dedicated systems for specialized purposes	• Depths ≥4,000 mwe (can start at 2,000 mwe) • Volume 4,000 m • Low radon levels • Clean room environment • Special water shield to reduce terrestrial radioactivity	• Next generation detectors • Outcomes for materials development and precision radioassay
The Soudan NUSEL low background counting facility can be implemented quickly at the 710 m level. The facility can be moved or expanded to lower levels as needs increase and thresholds become lower with ongoing experience.			

3.0 Conceptual Design

3.1 Design Process: The successful construction and operation of a successful underground science and engineering laboratory is a challenging project. We present here the results of the first stage of the design process, a conceptual design with cost estimates based on unit costs for standard rock conditions. This phase of the design process has benefited from consultation with three engineering firms and other experts— Charles Nelson and Lee Petersen of CNA Engineers, Chuck Michael and Dan Hestetune of Short Elliott Hendrickson, Jarmo Roinisto and Mikael Takala of Kalliosuunnittelu Oy (Rockplan Ltd.), Timo Maki of Inmet Mining and Juha Peltoniemi of Oulu University. On April 21, 2003, we began work on the next stage of the design process, namely detailed geological mapping of the proposed site based on surface rock outcroppings and an examination of the 27th level east drift of the Soudan Mine, which extends ~800 m east of the No. 8 shaft. Dr. Dean Peterson of the University of Minnesota Duluth Natural Resources Research Institute is the leader of the field mapping team. On the basis of the detailed geological mapping, we expect to develop a specific site layout and acquire options for the required land. The next stages of the design process will require a serious commitment of resources, particularly for core drilling, core logging and interpretation, rock testing and geophysical measurements. These data will then inform a detailed design process, including a value engineering of the entire design, with special attention to the excavation methods and sequence for the decline access tunnel.

3.2 Design Criteria: The design criteria for Soudan NUSEL begin with the three frontiers of underground laboratories discussed in Section 1.4. Soudan NUSEL must exceed or at least equal the best in the world in depth, size of cavities and access and ability to safely utilize difficult detector materials. Additional design criteria are discussed below:

(a) *Life safety:* The Soudan NUSEL design must include all reasonable measures to protect life safety for underground populations of several hundred people of all ages and physical conditions at any given time. Life safety design measures include multiple egresses from all points, automatic and manual fire suppression systems, completely reversible ventilation systems, smoke propagation control, seismic monitoring as necessary, evacuation chambers and monitoring systems for location of people underground. Of course, life safety depends on not just physical design, but also procedures, training, inspections, assessments, drills and rescue equipment. These life safety procedures are currently in use at the Soudan Laboratory and will be reviewed and upgraded as necessary for Soudan NUSEL.

(b) *Cleanliness and radioactivity:* The Soudan NUSEL design must facilitate reaching levels of cleanliness and low MeV-energy radioactivity background as required by the most sensitive experiments, such as dark matter searches and solar neutrino p-p measurements. Cleanliness requires careful attention to dust control and facilities for both progressive decontamination of people and equipment as they move from the mine environment to the clean room environment and feasible clean equipment transport in sealed containers from the surface directly to the clean room areas. Low MeV-energy radioactivity requires control of radon by both ventilation and epoxy sealing of rock surfaces, the feasible installation of water and other shielding around sensitive detectors and the possible use of active shielding to provide a time-dependent veto when background radioactivity is detected in the vicinity of a sensitive detector.

(c) *Efficiency:* The Soudan NUSEL design must be efficient both for construction and operation. Construction efficiency includes cost-effective excavation and muck removal methods, steady progress with a minimum of mobilization and de-mobilization, minimal changes in crew size and careful scheduling of available ventilation and muck removal resources. Operating efficiency includes rapid and easy 24/7 access between the surface and underground laboratory sites, efficient means for moving both large and small equipment underground, minimal production of hazardous waste, heat exchangers to minimize heating and cooling of intake ventilation air and water control to reduce underground pumping costs.

(d) *Education and outreach:* Education and outreach are an integral part of the Soudan NUSEL mission. Soudan with its mezzanine visitor observation facility is currently the only underground laboratory in the world with physical facilities specifically designed for education and outreach. The Soudan NUSEL design should facilitate the ability of the general public and special groups such as K-12 school children to directly interact with the deep underground science and engineering activities. The Soudan Laboratory is currently ADA (Americans With Disabilities Act) compliant with respect to visitors and accessibility for all people should be maintained in the Soudan NUSEL design.

(e) *Schedule:* Soudan NUSEL would start with an ongoing science program including the MINOS Far Detector and CDMS 2. The Soudan NUSEL design should facilitate a balanced program with concurrent advances in science and engineering research and capital construction. Soudan NUSEL should be able to commence some new research activities, in addition to the ongoing MINOS and CDMS 2, within its first year of operation. By its third year, Soudan NUSEL should be capable of research at a level significantly deeper than the currently 710 m. Soudan NUSEL should support research at a world-class depth of 2,500 m within five years of commencement of NUSEL construction.

3.3 Site Description: The Soudan Laboratory is located in St. Louis County, Minnesota (47.82° N. latitude, 92.24° W. longitude) about 150 km north of Duluth MN and ~300 km north of Minneapolis-St. Paul. Soudan is reachable by all-weather, mostly four-lane divided highways from airports at Hibbing (HIB—about 1 h), Duluth (DLH—about 1.5 h) and Minneapolis-St. Paul (MSP—about 4 h). The current laboratory is located adjacent to the lowest level (710 m underground) of the No. 8 shaft of the Soudan Mine, a natural ore, hematite mine in which mining began in 1884 and ended in 1962. The mine and about 1,200 acres of surrounding property are owned by the State of Minnesota and administered by the Department of Natural Resources, Division of State Parks as the Soudan Underground Mine State Park. About 40,000 people per year participate in underground tours at the Park. Ore processing did not occur at Soudan. After 40 years without mining, there are essentially no remaining environmental consequences of the mining operations. In addition to a few historic buildings, the mining legacy is limited to a few relatively shallow surface pits and some stable, overgrown piles of waste rock.

Science activities at Soudan began in 1980 on the 23rd level of the mine in an existing drift. The Soudan 2 Detector Hall was constructed from 1984 to 1986. The MINOS Detector Hall was constructed from 1999 to 2001. Both of these halls are located on the 27th and currently deepest level of the mine.

Past environmental assessments of science activities at Soudan have identified only three areas of possible concern: (1) possible leaching of some low pH water from waste rock piles remaining from laboratory construction, (2) possible disturbance of hibernating little brown bats locating mostly at the 12th to 15th level of the mine by construction and other activities, (3) possible visual impact of construction or other activities on a registered national historic site. These concerns were all satisfactorily addressed during the MINOS Hall construction following the preparation of an Environmental Assessment Worksheet (EAW). Acid leaching was mitigated by segregating a fraction of the waste rock for treatment with lime and deposition as aggregate under an asphalt surface for a parking lot. Impact on brown bats was mitigated by scheduling of the start of blasting relative to the bat hibernation season. Mitigating the visual impact on a historic site required minor cosmetic changes in the design of the laboratory access.

The overall geology of northeastern Minnesota is typical of locations in the Canadian Shield. The rock is old (~1 billion years or more), cool and relatively low in radioactivity because its age. The most prominent economic feature of the area is three "ranges" of iron—both hematite and magnetite. The ranges have a length of tens or even hundreds of kilometers and widths ranging from essentially zero to hundreds of meters and depths to at least a kilometer. The long axes of the ranges lie generally east northeast to west southwest, although there is local folding in some areas. Soudan is located in the Vermilion Range, the northernmost of the three. The lenses of iron oxide in these ranges are generally embedded in a hard, dense iron-bearing rock, locally known as jasper. Jasper is considered hard to drill and thus difficult to mine. Surrounding the iron and jasper formations is a softer, metamorphic rock known locally as greenstone. The current Soudan laboratories are located in greenstone, because it is relatively easy to drill, homogenous and impermeable to water. The compressive strength of greenstone, however, is only "fair" and deep laboratories in greenstone would likely require considerable rock support.

The Minnesota Geological Survey (MGS) and the University of Minnesota Duluth Natural Resources Research Institute (NRRI) has done extensive field mapping, magnetometer surveys and measurements of *g* in the general area of the Soudan Mine. MGS and NRRI geologists have interpreted these data using models to identify type, size and shape of rock masses. Two areas of basalt, which has higher compressive strength than greenstone are of interest for this proposal. Both sites are located east of the Soudan Mine. The site north of Minnesota Highway 169, about 1.5 km east of the Soudan No. 8 shaft, is of primary interest, because it can be reached from the existing laboratories without crossing a shear zone. The site south of Highway 169 and Jasper Peak is currently a secondary location. A geological map of the Soudan area is shown[3] in Fig. 1.

The USGS 1:24000 topographic map for the same area is shown in Fig. 2. This area is Sections 26, 27, 34 and 35 of Township 62 North, Range 15 West, Saint Louis County, Minnesota (Township of Breitung). The northern site in Sections 26 and 27 consists of low hills with a maximal elevation change of ~30 m (contour line separation is 10 feet). The southern site in Sections 34 and 35 is flatter and is traversed by the abandoned roadbed of the Duluth Missabe and Iron Range Railroad. The plat map for this same area is shown in Fig. 3. The northern site is primarily owned by United States Steel Corporation. The southern site is currently owned by the State of Minnesota, the Township of Breitung and several private individuals. Fig. 4 shows aerial photography of the site. Soudan is located in the left-center of the photograph. The area is clearly traversed by three east-west corridors. The northernmost one is a power line; the middle one is Minnesota Highway 169 and the southern corridor is the DM&IR railroad right-of-way. Both expansion sites are forested with essentially no existing development. The northern expansion site is adjacent to the power line corridor; the southern expansion site is adjacent to the railroad corridor. The estimated value of non-lakeshore property in northern St. Louis County is $1,000 to $2,000 per acre plus the value of any standing timber. Our current estimate is that NUSEL will require ~100 acres of land, mostly for excavated rock stockpiles. Since timber would be harvested in the stockpile area, the value of timber is mostly irrelevant. If the Soudan NUSEL proposal is funded, the University of Minnesota will provide funding to acquire the necessary land.

3.4 Development Plan: The overall development plan for the Soudan NUSEL Laboratory expansion includes three overlapping phases. Phase 1 is the re-use of existing, utility-equipped laboratory space at a depth of 710 m in both the Soudan 2 and MINOS labs. A portion of this space would be equipped as a clean, low background counting facility, particularly intended for prototype studies and to qualify materials for future detectors. Phase 2 is an improvement and extension of the underground access at Soudan to provide both semi-trailer capable decline access and 20 tonne capacity shaft access to laboratories at depth of 710 m, 1,450 m and 2,500 m. Phase 3 is the construction of new laboratories, particularly at depths of 1,450 m and 2,500 m. We expect to locate a megatonne-class neutrino and proton decay detector at the 1,450 m level. Phase 3 also includes a modest expansion of the surface facilities at Soudan. A new education and outreach facility would likely be constructed and operated in partnership with Minnesota State Parks. We also plan a surface facility for hosting visiting scientists and providing space for laboratory support staff.

3.5 Cost Estimating: In the text that follows, we describe the three-phase development plan and provide budgetary cost and time estimates. Budgetary estimates are based on unit quantities such as cubic meters of laboratory space, square meters of conventional building floor space and linear meters of drifts and tunnels. The costs per unit quantity are based on actual costs of the MINOS Far Detector Laboratory construction, inflated to current levels, cost estimating data published in estimating manuals by Western Mine Engineering, Inc., cost data reported in mining journals and on websites and costs determined from the experience of our engineering consultants. Time

[3] All figures are located in Appendix 1.

estimates are again based on the MINOS Laboratory experience and on the recommendations of our consultants.

It is important to emphasize the limitations of budgetary cost estimates. These estimates assume "average" rock, with no consideration of factors such as RQD, hardness, compressive strength, jointing, etc. Budgetary estimates do not consider the sequence of work, crew size, mobilization and de-mobilization, the required investment in capital construction equipment and similar factors. These estimates also assume "average" muck haulage distance. Clearly, muck haulage is a major expense in the construction of the decline tunnel and careful value engineering will be required to determine the most efficient and effective methods for the excavation of the decline. Because of all of these limitations, we believe that a 50% contingency is warranted at this stage of the proposal. However, for purposes of comparison of costs with other proposals, we also provide cost estimates with 25% contingency.

Our cost estimates include a 15% surcharge for Engineering, Design, Inspection and Administration (EDIA), in addition to a direct cost item described in the next section for Preliminary Design and Engineering. The 15% estimate is based on the MINOS Laboratory experience (13%, including a 1.5% fee for University construction administration) with an additional 2% for the increased complexity of the NUSEL project. Our experience with underground construction is that the Owner and the Owner's Engineers need to participate at a higher than usual level in the underground construction process, especially if the bidding process selects a general civil works contractor as compared to a specialized mining contractor such as Thyssen or Redpath. The prime contractors for both the Soudan 2 and MINOS Laboratories were civil works contractors with no deep mining experience.

The cost and time estimates for Soudan NUSEL are shown in Table 2. Unit prices for construction below 1,450 m is increased to account for additional rock support and hoisting distance.

3.6 Preliminary Design and Engineering: The next stage in the development of Soudan NUSEL is a preliminary design and feasibility study leading to a Technical Design Report and Review. The University of Minnesota recently began work on this phase with a detailed geological mapping of bedrock outcroppings in Sections 26 and 27 of T62N, R15W. In addition to outcrop mapping, the three field geologists working at Soudan will map east drifts at several levels underground to test their understanding of the three-dimensional geology. The geological mapping report is expected deliverable at the end of June, 2003. As funding permits, the University then expects to contract for the design of a preliminary layout of the NUSEL Laboratory based on the geological data. This layout will be used to determine boundaries for acquisition of land or options to acquire land and to develop a core drilling and geophysical testing plan for the site. An optimal funding schedule would enable core drilling between November 2003 and March 2004, when the land is sufficiently frozen to provide easy access for core drilling rigs through swamp areas. The data from the core drilling and geophysical measurements will then inform the Soudan NUSEL design, which will be documented in a Technical Design Report.

The Preliminary Design and Engineering work will also include the preparation of an Environmental Assessment Worksheet for Soudan NUSEL. We expect that the major environmental concern will be the establishment of a rock stockpile on the NUSEL site. The design effort will thus likely include development of mitigation procedures to minimize possible acidic and/or heavy metal leaching from the rock stockpile, as well as methods to promote rapid re-vegetation of the stockpile. Depending on the NUSEL design, some wetland preservation or re-arrangement may also be required. Because very little of the Soudan NUSEL construction will take place in the historic area of the Soudan Mine, we expect minimal mitigation will be necessary to protect the hibernating brown bat population and minimize visual impact on the historic site.

"The cost of a detailed or 'bankable' feasibility study is typically in the range of 2% to 5% of the project, if the costs of additional drilling, assaying, metallurgical testing, geotechnical investigations, environmental scrutiny, etc. are added to the direct and indirect costs of the study itself." (McIntosh Redpath Engineering *Hard Rock Miners' Handbook*, Chapter 6) As indicated in Table 2, we estimate the cost of the Preliminary Design and Feasibility stage at $5 million or approximately 2 1/2% of the project capital cost. The deliverable of this work is a Technical Design Report, capable of informing an intensive review and including realistic cost estimates with a reliability of ±15%-20% and appropriate contingency factors for each substantial aspect of the project. The Technical Design Report will define all of the substantive parameters required to complete the design and produce bid packages for construction. It will also include an Environmental Assessment Worksheet. The significant cost elements of this stage are engineering and other consultant fees and core drilling and geophysical testing. Core drilling is particular expensive because of the necessity of extending at least one hole to >2,500 m. At this depth, just the time required to retrieve a core becomes very expensive.

3.7 Phase 1—Re-use of Existing, Utility Equipped Laboratory Space: Plan and cross-section views of the existing Soudan 2 and MINOS Laboratories are shown in Figs. X-x. Approximately 30% of the floor space in the existing laboratories has been used for MINOS Far Detector assembly and installation. Since completion of MINOS installation is expected in the next month or so, much of this space will be available for re-assignment beginning in Summer 2003. The largest and most readily available space is the MINOS assembly area located northwest of the MINOS Detector in the MINOS Laboratory. This area has bridge crane coverage. The next two largest areas suitable for re-use are the MINOS Upstream area, located southeast of the MINOS Detector in the MINOS Laboratory and the MINOS Scintillator Testing Area, located west of CDMS 2 in the Soudan 2 Laboratory. Access to the MINOS Upstream area for large equipment is limited by the presence of the MINOS Detector. A portion of the Scintillator Testing Area is equipped with a steel mezzanine deck, which may be of use for certain new detectors. Possibly available at some future time is the Soudan 2 Detector area. This area is the southern third of the Soudan 2 Laboratory, that is, the area in the Soudan 2 Laboratory south of the CDMS 2 Detector. This area has both bridge crane coverage and an enclosing aluminum proportional tube shield, which might be on interest as an active shield for a new detector.

In addition to proposal-driven installation of new detectors, we expect to re-use some of the available space as a clean room for detector prototype assembly and as a clean, low background counting facility. The "White Paper" by J. Nico, A. Piepke and T. Shutt (see Appendix 4) describes both the motivations and possible implementations of the low background counting facility. The uses for such a facility include detector prototyping and testing, qualification of materials for new detectors, fabrication of ultrapure materials for commercial purposes, monitoring of trace elements in the environment, monitoring of the environment by use of radioactive tracers, measuring radioactivity activity in materials for semiconductors and measuring trace isotopes for homeland security applications. The implementation of this facility would likely include extensive water shielding, clean room environments, special fabrication areas, cryogenic facilities and both germanium and liquid scintillator ionization detectors. Further discussion of these topics is included in Appendix 4. Specification of the design of the clean, low background counting facility will be a task in the preliminary design process.

3.8 Phase 2—Providing and Improving Access to 710 m, 1,450 m and 2,500 m: Access to the existing laboratories at Soudan to the No. 8 shaft of the Soudan Mine. No. 8 is a three compartment, rectangular concrete and steel-braced shaft inclined at 78° to the horizontal. Two of the compartments are used for hoisting. The third compartment is used as a manway and for utilities.

The No. 8 shaft has a two skip, drum hoist with a normal capacity of 6 tonnes. Routine production capacity is 300-500 tonnes per day. The hoist is driven by a 600 hp electric motor with a diesel backup drive. The cages are both double-decked and can be readily disassembled to carry large equipment. The maximum size that can be hoisted is approximately 1.3 m by 2 m by nearly 10 m in height. Despite its limitations, the No. 8 shaft has been used to remove ~80,000 tonnes of rock and to install ~8,000 tonnes of instrumentation.

Despite its features, the No. 8 shaft is inadequate for the requirements of NUSEL. A major component of this proposal is to provide world-class access to the existing laboratories at 710 m and to new laboratories at 1,450 m and 2,500 m. Our access design is a combination of a modern, circular, concrete-lined shaft, raise bored and slashed to a diameter of 5 m and a 1:7 decline with a cross-sectional area of 20 m^2 laid out in a racetrack cross-section helix from the surface to the 2,500 m level. The shaft will provide quick access for personnel and "small" equipment (up to 3 m by 3 m by 10 m in height by 20 tonnes in weight) and hoisting capacity for up to 5,000 tonnes per day in routine rock production. The decline will provide the initial access to depth, access for large and heavy instrumentation and production equipment, an emergency egress and access for people who absolutely insist on driving. The decline also has important programmatic value, as previously indicated in Table 1. In addition to the shaft and the decline, Soudan NUSEL will have one or more ventilation raises. During the Preliminary Design Study, we will consider the utility and feasibility of installing Alimak-style emergency escape lifts in ventilation raises.

In the conceptual design, the hoisting shaft and one or more ventilation shafts will be constructed by raise boring, which is relatively inexpensive but dependent on having an independent access to the shaft bottom. In this technique, a pilot hole is drilled, usually 20 cm to 30 cm in diameter. A high strength drill pipe, typically in ~2 m sections with male threads at one end and female threads at the other, is inserted into the pilot hole. A reaming head is brought to the bottom of the shaft and attached to the drill pipe. The raise drilling rig, located at the top of the shaft, then pulls and turns the drill pipe, thus cutting a cylindrical shaft in the rock with the reaming head. When the reaming heads reaches the bottom of the raise bore rig, this stage of the process is complete. The excavated rock chips drop through slots in the reaming head to the bottom of the shaft, where they can be picked up with a loader and hauled away. It is possible to raise bore a shaft >5 m in diameter and up to 1,000 m in length. More commonly, shafts are raise bored to smaller diameters and then slashed back down to their final diameter. For example, the new Timo Shaft at Pyhäsalmi was raise bored to 2.8 m diameter and slashed to 5 m diameter from the top down. Slashing, as a final step before installing the concrete lining, relieves the ring stress in the surface rock surrounding the shaft.

The conceptual design for the hoisting shaft is for a 5 m diameter, concrete lined shaft with an enclosed concrete or steel headframe and a friction (Koepe) hoist located in the headframe directly above the shaft. This location eliminates transverse loading and thus the requirement for extensive bracing on the headframe. Our preliminary choice of a Koepe hoist is based on the advantages of multiple hoist ropes and thus higher weight capacity and the ability to use cheaper and smoother rope rather than fixed guides. The hoist shaft will be offset at the 1,450 m level and a second Keope hoist installed above a transfer station. A value engineering study might suggest a smaller diameter shaft with a smaller capacity hoist for the lift from 2,500 m to 1,450 m, because programmatically we expect to install the largest detectors at the 1,450 m level. At this stage of analysis, we believe a two-stage shaft provides an optimal approach because most of the lab activity will be focused at the 1,450 m level. These conclusions will be more rigorously tested during preliminary engineering.

The location of the new hoisting shaft will be 1-2 km east of the Soudan No. 8 shaft tangent to the "race track" decline helix. The exact position of the hoisting shaft with respect to the "race track," will depend on rock conditions and an optimized lab layout at the 1,450 m and 2,500 m levels. The shaft will have a shaft station at each point where it touches the decline helix, although only the stations at 710 m, 1,450 m (shaft and transfer station) and 2,500 m will be fully developed. The other shaft stations (at 350 m, 1,080 m, 1,800 m and 2,150 m) will be used only for raise boring, muck removal and emergency egress. Vent shafts will also be located at tangent points to the decline helix. The primary vent will likely be across the "race track" from the hoisting shaft. The exact layout will be determined during preliminary engineering.

The decline will have a cross-section of 20 m^2, beginning at the surface and extending downward to the 2,500 m level. The decline will drop ~350 m per revolution, thus requiring 7 revolutions to reach the lowest level. The conceptual design is that each revolution will be 2,450 m in length, with two straight sections of 597 m each and two 180° curved sections, each of length 540 m. The radius of curvature is 200 m. The cross-section of this layout is ~800 m, approximately east-west and ~400 m, approximately north-south. The area of the circumscribed rectangle is ~320,000 m^2 or ~80 acres. These parameters will be value engineered during the preliminary design phase of this project. The decline will have a gravel roadway and will be illuminated solely by vehicle-mounted lights. The anticipated speed limit for the decline is 35 km/hr in the straight sections with lower speeds required in the curves and for heavily loaded vehicles. The travel time from the top to the bottom will be ~1/2 hour for a personnel vehicle and about twice as long for a semi-trailer. This design is modeled on the decline in the Pyhäsalmi Mine, which is easy drivable in a standard, highway-qualified diesel Toyota Land Cruiser, although four-wheel drive is not actually required. It is justified because unlike Gran Sasso or the planned access at Mt. San Jacinto, at Soudan NUSEL, the shaft is the primary access, especially for routine entrance and exit by scientists and visitors.

The decline will have a number yet to be determined of vehicle passing stations and gravel, water-filled polyethylene barrel traps for runaway vehicles. The vehicle passing stations will also have notches perpendicular to the roadway, so they can be used as temporary locations for core drilling rigs. The nearly one cubic kilometer of rock both inside and outside the decline helix easily reachable with core drilling will thus provide a unique laboratory for geoscience, geoengineering, mineral geology and geomicrobiology. We know of no other location in the world that provides similar access for detailed studies of a similar-sized rock volume. During preliminary design, we expect to value engineer the installation of a communications system for the decline using leaky coax in the curved sections and either leaky coax or microwaves in the straight sections. The communications system would be used for emergency communications, traffic control and programmatic instrument control and data acquisition.

Both the shaft and the decline will be equipped with security, personnel access control and appropriate life safety systems. The shaft will be normally downdraft, but it will be equipped with sufficient fan capacity to fully reverse the airflow. The decline will be normally ventilation neutral and will be equipped with automatic smoke damper doors, including a door at the surface to minimize condensation-producing air flow. The decline portal will be designed to minimize the entrance of surface water into the underground areas.

The construction sequencing of the access will depend on whether the decline is excavated by mechanical techniques (tunnel boring machine or TBM) or drill and blast. The slope of the decline may be too large for a TBM, but further study is required on this point. TBM excavation of the decline, if feasible, would clearly begin at the surface and proceed downward. The connection to the 27th level east drift and the widening of that drift could be completed any time after the TBM reached the 710 m level.

The sequencing is different if the decline is driven by drill and blast. Then, the decline clearly becomes the critical path and it is important to begin the decline as soon as possible from the 710 m level downward. The decline would be initially accessed and mucked through the No. 8 shaft and the 27th level east drift until the new hoisting shaft could be raise bored from the 710 m level to the surface. The raise bore would also be mucked through the No. 8 shaft. As the decline proceeds downward, the hoisting shaft would be raise bored in ~350 m sections each time the decline came around to the shaft area. Muck haulage back up the decline would be for a maximum distance of just over one turn before the muck could be loaded into a skip and raised to the surface for disposal. If drill and blast is the chosen excavation method, the portion of the decline between the surface and 710 m could be driven either just from the surface or using two headings from both the surface and the 710 m level. The commencement of the heading from 710 m upward would probably await completion of the new hoisting shaft between surface and 710 m. The issues concerning construction sequencing will be thoroughly examined during preliminary engineering.

3.9 Phase 3—Constructing and Equipping New Laboratories: The construction of new laboratories at Soudan NUSEL will primarily be proposal-driven. That is, we expect to initially construct 20,000 m^3 of general purpose space at the 1,450 m (for example, a room 16 m wide by 16 m high by 80 m in length, similar in size to the MINOS Far Detector Laboratory). The budget then includes sufficient funds to construct 1.5 times the general purpose volume (that is, 30,000 m^3) of special purpose detector space. The layout of special purpose labs would be optimized for the detectors that they will contain. For example, rooms with liquid detectors would have accesses at the top and rooms with difficult material detectors would have isolation barriers and isolated vents. At 2,500 m, we propose to construct 10,000 m^3 of general purpose space (for example, a room 15 m wide by 15 m high by 45 m in length (about 2/3 of the existing Soudan 2 Laboratory). The budget again provides funding for 1.5 times this quantity of special purpose laboratory space (that is, an additional 15,000 m^3) at a depth of 2,500 m.

The Soudan experience with both the Soudan 2 Laboratory and the MINOS Laboratory is that the cost of excavating, rock bolting, shotcreting and installing a poured concrete floor represents about half of the final construction cost. An approximately equal amount of money is required to fund the "outfitting" of the laboratory, that is, the electrical system, the HVAC, the communications network, the life safety systems, the materials handling systems and some minimal support structure for detectors or partitions for isolating work spaces. The budgets in this section are based on this experience and provide equal funding for "construction" and "outfitting" of the laboratory volumes.

After the completion of all construction funded in this budget, the total laboratory volume at Soudan will be 112,350 m^3, roughly equal to the volume of the three principal laboratories at Gran Sasso. (The total Gran Sasso volume of 180,000 m^3 includes smaller tunnels for access and some instrumentation.) This total includes 37,350 m^3 at the 710 m level, 50,000 m^3 at the 1,450 m level and 25,000 m at the 2,500 m level. The volume of the access decline is 350,000 m^3, the volume of the two raise bores is 98,125 m^3 and the volume of the access drifts and the decline passing/instrumentation areas is 54,000 m^3. Thus, the construction of Soudan NUSEL will produce approximately 1.65 million tonnes of rock.

The Soudan NUSEL design will allocate space at the 1,450 m level but not fund the megatonne-class neutrino and proton decay detector. Soudan NUSEL will have the flexibility to house this detector regardless of whether the chosen technology is water Cherenkov, liquid scintillator or liquid argon. The maximum assumed gross volume for this detector will be 1.25 million m^3. Although many discussions of the shape of this volume assume the "rural mailbox" or circular vault cross-section, we note that underground petroleum storage facilities in Finland have not used this shape for many years. The more recently constructed use either a parabolic vault, a horseshoe or a trapezoidal cross-section. The trapezoidal cross-section is used in the largest of these facilities, which has a volume of 750,000 m^3. Soudan NUSEL will develop designs for the cavity for megatonne class detector for each of the three detector technologies when more is known about the rock and the rock stresses at the 1,450 m level.

3.10 Other Costs: The three categories of expense listed as "Other Costs" are site-wide utilities, surface facilities and "Scientific and Technical Project Administration." The allocation for site-wide utilities is intended to cover the costs of bringing electricity, communications, domestic water and sewage facilities to the site and distributing them as necessary across the site. This item also includes site-wide security systems and systems for monitoring specific location of personnel on the site. With regard to surface facilities, Soudan NUSEL will take over use and assume the lease of the existing 640 m^2 Soudan Surface Building, which is primarily a receiving facility and warehouse, constructed for the laboratory by the Township of Breitung. The funding in this item will provide for new construction of 2,000 gross m^2 for scientific visitors and laboratory administration and 2,000 gross m^2 for education and outreach. We will propose that the State of Minnesota funds an additional 2,000 gross m^2 of education and outreach space and the use of the space is shared between Soudan NUSEL and Minnesota State Parks. An important feature of the new education and outreach facility will be support for "science camp-ins" for school groups, similar to those sponsored by the Adler Planetarium in Chicago. Low cost overnight facilities at Soudan will greatly increase the number of school groups who can afford to visit the laboratory.

The third type of cost in this item is intended to cover the cost of the Director, the Project Manager and their staffs for effort and expenses related to management of the construction of Soudan NUSEL, as differentiated from the cost of operation of Soudan NUSEL, which is discussed in Section 3.12. The size of these staffs is intentionally modest. Soudan NUSEL intends to take advantage of the existing University of Minnesota infrastructure to the maximum extent possible. Soudan NUSEL will not attempt to duplicate for itself University services such as human resources, payroll, general counsel, purchasing, contract administration, environmental health and safety, general network support and real estate acquisition and management. However, some staff will be required to coordinate and direct these services for NUSEL.

3.11: Total Project Cost: The total project cost is $275,973,800. An important component of this cost is our assumption of 50% contingency, which we believe is appropriate for underground construction at this stage in the design process. We expect that the Preliminary Design phase will considerably reduce the size of the contingency allowance, although it may or may not reduce the total project cost. We note that some other proposals have used a 25% contingency allowance. Although we believe such an allow is inadequate, we show a "Total for Comparison" of $229,978,200, so that Soudan NUSEL may be compared with other NUSEL proposals on a more equal basis. Although this latter cost provides a better basis for comparison, it still does not reflect the value of existing facilities at Soudan, the value of Soudan as an ongoing operation and, most of all, the value of the Fermilab-to-Soudan neutrino beam. We believe that such a beam is essential component of a NUSEL and should be included as a cost for other sites at a level in excess of $100 million.

3.12 Lab Operations Costs: One advantage of Soudan NUSEL is that its scientific and engineering program starts on "day one." Thus, in contrast to a laboratory that requires several years of construction before any operations, Soudan NUSEL will require an operating budget from its inception. However, we expect initial operations funding to come primarily from the funding sources that are currently supporting MINOS and CDMS 2. Thus, the need for additional operating funds will grow slowly as new facilities come on line. Our observation is that operating funding for national laboratories is of order 10% of the total capital investment in the laboratory per year. This level of funding supports both effort and expendables to operate the laboratory and some amount of depreciation reflected as investments in upgrading facilities and equipment. Thus, our expectation is that the operating funding needs for Soudan NUSEL would grow from a few hundred thousand dollars in the first year to perhaps $25 million in the sixth year. Over six years, a reasonable estimate of aggregate operating needs is of order $75 million. Producing an operating budget request ("business" plan) will be an important task in the Soudan NUSEL Preliminary Design process.

5.0 Broader Impacts

5.1 Science and Technology Impacts: The proposed Soudan NUSEL is explicitly broad and impactful in its scope and goals. NUSEL addresses some of the most fundamental questions in basic research, such as the mechanism for the baryon antibaryon asymmetry in the Universe. However, NUSEL also addresses clearly applied questions such as "Is someone testing nuclear weapons somewhere on Earth?" NUSEL thus seems an excellent venue to explore the relationship between basic science and impactful technology. This relationship can be either direct—for example, GPS satellites use general relativistic timing corrections—or it can be through technique—for example, documentation requirements for complex, multi-institution particle physics experiments led to the World Wide Web. The connections through technique are generally easier, because they seem to require less time to mature. In underground science, for example, Ray Davis's radioassay techniques developed for solar neutrino studies have been applied to environmental remediation analyses. Techniques for holding large volumes of water underground to search for proton decay may be feasible for storage of energy from renewable sources. The Soudan NUSEL program will seek ways to use the advantages of assembling people from multiple disciplines in science and engineering in a compact and geographically remote location to facilitate connections between science and technology and thus catalyze both direct and indirect broad impacts.

Table 2: Budgetary Estimates for Soudan NUSEL

Item	Units	Unit Cost	Unit Time	Cost (FY03 $) (No Escalation)	Time (mos.)
Preliminary Design and Engineering					
Engineering Consultant Fees and Expenses				$2,000,000	
Core Drilling and Geophysical Testing				$1,500,000	
Environmental and Permitting				$250,000	
Other Costs				$250,000	
Sub-Total				$4,000,000	
Contingency (50%)				$2,000,000	
Total				$6,000,000	18
Phase 1: Re-Use Existing Laboratory Space					
Reuse existing lab space for new detectors				$500,000	
Clean, low background counting facility (LBCF)				$1,500,000	
Sub-Total				$2,000,000	
EDIA (15%)				$300,000	
Sub-Total				$2,300,000	
Contingency (50%)				$1,150,000	
Total				$3,450,000	
Phase 2: Improve and Extend Access					
Widen existing east drift at 710 m	900 m	$1,000	0.002	$900,000	2
Extend east drift	500 m	$3,000	0.004	$1,500,000	2
Raise bore new hoist shaft: surface to 1,450 m	1,450 m	$3,000	0.005	$4,350,000	8
Raise bore new hoist shaft: 1,450 m to 2,500 m	1,050 m	$4,000	0.004	$4,200,000	5
Raise bore new vent shaft: surface to 1,450 m	1,450 m	$3,000	0.005	$4,350,000	8
Raise bore new vent shaft: 1,450 m to 2,500 m	1,050 m	$4,000	0.004	$4,200,000	5
New headframe				$2,000,000	6
Friction hoist at surface and hoist/guide ropes to 1,450				$3,000,000	
Ventilation Equipment				$2,000,000	
Hoist room at 1,450, friction hoist, ropes from 1,450 to 2,500				$4,000,000	
Decline portal				$1,000,000	
Construct decline from surface to 710 m	4,970 m	$3,000	0.004	$14,910,000	20
Construct decline from 710 m to 1,450 m	5,180 m	$3,000	0.004	$15,540,000	21
Construct decline from 1,450 m to 2,500 m	7,350 m	$4,000	0.004	$29,400,000	30
Construct 20 passing areas of length 25 m each	500 m	$3,000	0.002	$1,500,000	2
Construct access drifts at 1,450 m level	500 m	$3,000	0.004	$1,500,000	2
Construct access drifts at 2,500 m level	300 m	$4,000	0.004	$1,200,000	2
Life safety and communications equipment for access				$1,000,000	
Sub-Total				$96,550,000	
EDIA (15%)				$14,482,500	
Sub-Total				$111,032,500	
Contingency (50%)				$55,516,300	
Total				$166,548,800	
Phase 3: Construct and Equip Laboratories					
Construct new labs at 1,450 m	50,000 m^3	$200	0.0004	$10,000,000	
Equip new labs at 1,450 m				$10,000,000	
Construct new labs at 2,500 m	25,000 m^3	$300	0.0004	$7,500,000	
Equip new labs at 2,500 m				$7,500,000	
Sub-Total				$35,000,000	
EDIA (15%)				$5,250,000	
Sub-Total				$40,250,000	
Contingency (50%)				$20,125,000	
Total				$60,375,000	

Other Costs					
Site-wide utilities				$8,000,000	
Surface facilities for outreach/education and scientific visitors	4000 m^2	$2,000		$8,000,000	
Sub-Total				$16,000,000	
EDIA (15%)				$2,400,000	
Scientific and Technical Project Administration for 6 years				$8,000,000	
Sub-Total				$26,400,000	
Contingency (50%)				$13,200,000	
Total				$39,600,000	
Total				$275,973,800	
Total Contingency				$91,991,300	
Total for Comparison (25% Contingency)				$229,978,200	

5.2 Education and Outreach: Soudan has a long history of successful and growing education and outreach programming. From its beginning in 1980, the Soudan Lab has hosted visits by organized groups, primarily high school and college student groups. The laboratory has also hosted informal, adult education weekend programs sponsored by the University of Minnesota's *Compleat Scholar* program. The Soudan Laboratory has also worked with the mass media to help the public understand both the content and excitement of underground science. Television programs about Soudan have appeared on local newscasts in both Minneapolis-St. Paul and Duluth, on National Geographic Today, on the Independent Television Network in the United Kingdom and the Australian Broadcasting network. Radio coverage on activities at Soudan include several science shows on National Public Radio and, in July 2002, a two hour live program with call-ins from listeners from the Soudan Laboratory broadcast on all the stations of the Minnesota Public Radio (MPR) network. The full two hour audio and supporting materials are available on the MPR website at **http://news.mpr.org/features/200207/26_mainstreet_soudan-m/** Stories about Soudan have appeared in a variety of print media, including newspapers such as *The New York Times* and the *Wall Street Journal* and magazines, such as *National Geographic* and *Discover*.

The design of the MINOS Far Detector Laboratory specifically includes features to enable general public tours of the deep underground location. The Minnesota *Legislative Commission on Minnesota Resources* provided $400,000 towards laboratory construction to enable installation of a mezzanine-level visitor observation desk and an elevator for ADA accessibility. Minnesota State Parks also modified a cage in the No. 8 shaft for ADA compliance. During 2002, Minnesota State Parks provided science tours to more than 6,000 visitors to the Soudan Laboratory. Tours are available to the general public, seven days a week May through September, for $7 for adults and $5 for children. A $2 discount is given to people who take both the historic tour and the science tour.

Soudan NUSEL expects to significantly increase the scope and intensity of the current Soudan education and outreach program. Northeastern Minnesota is similar to many other frontier areas of America with few perceived opportunities and shrinking population. Soudan NUSEL hopes to provide a local population magnet, as well as to provide enrichment opportunities for both school children and adults through the area. A particular goal of Soudan NUSEL will be to provide opportunities to younger members of Minnesota's 12 Native American tribes, particular the Bois Forte tribe, whose reservation is located near Soudan, and the Fond du Lac tribe, which operates a tribal college at Cloquet, ~150 km south of Soudan.

6.0 Management

6.1 General Considerations: Successful NUSEL management requires a combination of broad involvement of the American and international scientific and technical communities and clear accountability for the expenditure of resources and supervision of personnel. For the Soudan NUSEL, we propose the Regents of the University of Minnesota as the sponsoring and accountable institution. The University of Minnesota intends to partner with the regional, national and international scientific communities in a manner to be determined later in consultation with the National Science Foundation. Section 5.4 below discusses preliminary ideas about such partnerships.

6.2 Regents of the University of Minnesota: The Regents of the University of Minnesota is a constitutional corporation chartered by the Legislature of the Territory of Minnesota in 1851 and confirmed by the Constitution of the State of Minnesota in 1858. The University is essentially a fourth branch of the State government and the Regents have the sole authority to govern the University, including collecting, disbursing and borrowing money, hiring employees and determining the University curriculum. Of particular relevance to Soudan NUSEL, the University also has the powers of a municipality with respect to University property. The Regents can enact laws and ordinances including building codes that are enforceable in court, determine zoning requirements, authorize issuance of building permits, authorize building inspections and initiate eminent domain proceedings to acquire land and structures for public purposes. With respect to University property, the University's codes and regulations take precedence over those of the normal municipality in which the property is located. University permitting and inspections have supervised nearly $100 million of construction and capital equipment invested at the Soudan Laboratory since 1984.

The budget of the University of Minnesota is just over $2 billion per year. Sponsored research expenditures are currently ~$550 million per year. In recent years, the University typically has $200 million of civil construction projects in progress at any given time. Any foreseeable level of capital or operating expenditures at Soudan NUSEL thus represent only a relatively small increment on the University's current level of activities.

The University of Minnesota is insured for all risks by RUMINCO, Ltd., a captive insurance company with assets of ~$xx million. RUMINCO re-insures the University's risks above a deductible to insure coverage in case of catastrophic loss.

6.3 Project Management for Soudan NUSEL: We propose a clear chain of responsibility for Soudan NUSEL from the Regents to the President of the University to the Vice-President for Research to the Principal Investigator and Director of Soudan NUSEL. The initial Principal Investigator and Director of Soudan NUSEL will be Morse Alumni Distinguished Professor Marvin L. Marshak. Professor Marshak was the initiator of the Soudan Laboratory in 1980 and the initial spokesperson for the Soudan 2 Detector. Professor Marshak directed the construction of the Soudan 2 Laboratory from 1984 to 1986. His administrative experience includes an interim appointment as the University's No. 2 administrator, the Senior Vice-President for Academic Affairs, during 1996 and 1997, ten years' service as Head of Physics and Astronomy (1986 to 1996), four years' work as Faculty Legislative Liaison (lobbyist) (1997 through 2001 and again in 2003), and five years' experience on the executive committee of the University Senate. The University's management team for Soudan NUSEL will also include as co-Principal Investigators Professor Priscilla Cushman, Morse Alumni Distinguished Professor Kenneth Heller, Assistant Professor Jeffrey Nelson and Professor Earl Peterson and as Laboratory Operations Managers Mr. William Miller and Mr. Jerry Meier. All of these individuals have past and ongoing experience in underground science. Professors Hellers, Nelson and Peterson are active in the MINOS Collaboration.

Professor Cushman participates in the CDMS 2 Collaboration. Professor Peterson has worked on underground experiments at Soudan since 1980. He is the current Director of the Soudan Laboratory and is the person most responsible for planning and supervising the construction of the MINOS Far Detector Laboratory at Soudan between 1999 and 2001. Mr. Miller, the current Soudan Laboratory manager, has nearly 20 years experience at Soudan, including laboratory construction and detector installation and operation for both the Soudan 2 and MINOS Detectors. Mr. Meier is Mr. Miller's deputy. He has more than 15 years' experience at Soudan and specializes in electronics, communications and data systems. In the aggregate, the proposed management has more than 75 years experience in underground science and management of underground laboratories and has managed underground capital investments of nearly $100 million in civil construction and scientific equipment. The biographical section of this proposal includes more complete information about the Principal and Co-Principal Investigators.

6.4 Partnering With the Scientific and Engineering Communities: The University of Minnesota is enthusiastic about partnering in the scientific and technological management of Soudan NUSEL, while maintaining its legal and fiscal responsibility for project management. The premiere topics for shared governance are strategic planning, program and proposal approval and intellectual reviews and audits of NUSEL's effectiveness. The University is open to discussion of the most effective partnership structure. The partnership could be on the basis of institutional arrangements in which certain institutions designate individuals for service on governance, planning and review boards. Another possibility is that distinguished individuals from the national and international scientific and engineering communities are recruited in some yet-to-be-defined way to serve on governance, planning and review boards, independently of their institutional affiliations.

The University of Minnesota has existing regional and national affiliations that might serve as a basis for NUSEL governance partnerships. For example, the University is a member of Universities Research Association (URA) and the Committee on Institutional Cooperation (CIC: the "Big 10" plus the University of Chicago). The University has resident tuition reciprocity relationships with the States of Wisconsin, South Dakota and North Dakota and the Province of Manitoba. The University has numerous relationships with the Minnesota State College and Universities (MNSCU), including the Fond du Lac Tribal College in Cloquet MN and Vermillion Community College in Ely MN. The University expects that consultations regarding governance will be part of the NUSEL pre-design and review process.

7.0 Comparisons Between Soudan and Other Possible NUSEL Sites

7.1 General Comparisons: Both the early NUSEL initiatives in the 1980's and the increased activity during the past two years suggest that it is not possible to identify a single underground site that is ideal for all aspects of NUSEL. Underground science is too broad and the requirements of detectors too diverse for one location to be universally considered as absolute best for all purposes. Thus, the selection of a NUSEL site requires balancing many considerations. Because of different perspectives and thus different weightings of the various factors, reasonable people may reach different conclusions about the "best" NUSEL site. Indeed, NUSEL might well have more than one site—a primary site for most activities and one or more other sites for detectors with special requirements, such as the ultralow uranium-thorium activity and low humidity found in a salt environment. These diverse sites would likely be co-located with other facilities in order to minimize overhead and operating expense. Despite these complexities, we believe this proposal demonstrates that Soudan is an outstanding site for most NUSEL purposes.

7.2 Soudan vs. Homestake: The Homestake Mine in Lead SD has received the most attention as the possible NUSEL site since the announcement of the mine's closing in Fall 2000. Homestake's most obvious strength is the possibility of nearly immediate access to a depth of 2,440 m. In March 2001, the Bahcall Committee made a preliminary designation of Homestake as the preferred NUSEL site. The Committee set two conditions for its endorsement of Homestake, both of which were expected to be satisfied within a period of a few months. The Committee wrote “The Homestake pre-proposal at present is not complete. First, the indemnification problem must be solved. Second, a representative, national group of underground scientists must be involved in the preparation of a formal proposal that describes a detailed science program and a complete cost estimate for the laboratory. Given the imminent closure of the Homestake mine, these two issues must be solved in a timely fashion, or the advantages which lead us to favor the Homestake site will be significantly reduced.” It is not yet clear that either of these conditions has been met. In addition, lay-offs and mine closure operations by the current owner, Barrick Gold, have removed the Davis solar neutrino detector and reduced the capabilities of the Homestake infrastructure.

Even if Homestake solves its immediate problems, we believe that this proposal for the Soudan Laboratory offers significant advantages. In our opinion, the science and engineering opportunities and the depth and the rock quality at Soudan and Homestake are roughly comparable. The stated cost of NUSEL at Soudan and Homestake are also roughly equal, at least within the accuracy of cost estimates produced so far. Insurance premiums for past and future environmental and general liability, a potentially significant direct cost factor at Homestake, are not yet defined. At Soudan, the University of Minnesota will fund these costs from its general research indirect cost base. In the end, Homestake may turn out slightly less expensive than Soudan if the NUMI beam is not counted and considerably more expensive than Soudan if the NUMI beam is considered. What is really different between the two proposals is that a Soudan NUSEL will have

- a modern infrastructure,
- essentially no remnant mining liabilities,
- low operating expense,
- “drive-in” access for semi-trailers to all levels,
- existing equipped laboratory space,
- an ongoing scientific program,
- an experienced staff,
- a history of successful project management experience,
- an ongoing outreach and education program, and
- a sponsoring organization with the interest and financial capacity required to operate a successful laboratory.

7.3 Soudan vs. Mt. San Jacinto: The University of California’s proposal for NUSEL at Mt. San Jacinto near Palm Springs CA has several attractive features. Perhaps most obvious is the ability to drive into the deep underground laboratory area via a nearly horizontal highway-style tunnel. The San Jacinto location, nearby to downtown Palm Springs and easily accessible to the 15 million people in the Los Angeles basin, is also very attractive. In addition, the interest, project management experience and significant financial capacity of the University of California are major assets for the Mt. San Jacinto proposal.

The major advantages of Soudan relative to Mt. San Jacinto are the NUMI neutrino beam, the ongoing Soudan scientific program and the immediate availability of equipped lab space at Soudan at a depth of 710 m. The Soudan site, with its access to multiple vertical levels, including the surface over the laboratory, is able to use shorter, vertical ventilation raises rather than the much longer horizontal ducts required for San Jacinto. The cool rock and air temperatures at Soudan provide an easier environment for that lab’s HVAC systems. The Mt. San Jacinto site also presents potential difficulties that are less significant or non-existent at Soudan. These include possible land use controversies, significant California environmental regulations and high Davis-Bacon wages. As a mountain in the Southwest, Mt. San Jacinto is also subject to possible Native American claims, similar to those that have complicated telescope projects on Mt. Graham. Finally, although Mt. San Jacinto appears to be a granite monolith, significant seismic faults on either side of the mountain may cause difficulties with respect to life safety systems in the event of an earthquake.

7.4 Soudan vs. WIPP: The Waste Isolation Pilot Plant (WIPP) is a low-level, transuranic waste disposal facility located in deep salt beds ~40 km east of Carlsbad, NM. The principal attraction of WIPP as a NUSEL site is the availability of a superb infrastructure and an experienced operating staff. The location of proposed NUSEL laboratories in salt has both advantages and disadvantages. Salt is easy to mine, has extremely low levels of uranium and thorium and is very dry. Disadvantages of salt include plastic deformation, low density and therefore less effective shielding and corrosion due to salt dust of instrumentation removed from the underground location.

The chief advantage of Soudan vs. WIPP is depth. Although the current labs at Soudan and WIPP have approximately equal depth, because of the lower salt density, WIPP is at 1,600 mwe, compared to 2,100 mwe for the current labs at Soudan. More importantly, a downward expansion of WIPP is limited to ~3,000 mwe because of the location of hydrocarbon deposits beneath the salt layer. While WIPP may be suitable for some detectors, it can never satisfy the most stringent requirements for low cosmic ray background.

Another advantage of Soudan is that science is clearly a secondary priority for the overall WIPP site. While a dedicated access for science might address some issues, the possibility for mission conflict is higher at WIPP than Soudan. A conceivable example is access restrictions for non-U.S. scientists due to homeland security requirements.

7.5 Soudan vs. Henderson: The Phelps Dodge Henderson Molybdenum Mine is located about 15 km north of Empire CO and just over 100 km from the Denver Airport. Henderson is a relatively modern block-caving operation, capable of producing ~10^7 tonnes per year. In block caving, a large volume of rock is sufficiently undercut that it collapses from its own weight and self-crushes by gravitational force. The block caving operation at Henderson has visibly reduced the height of the mountain peak over the mine.

The principal attractions of the Henderson site for NUSEL were reportedly the cessation of mining operations within the next few years so that a Henderson NUSEL could operate without interference from mining and the ability to drive into the mine via a nearly horizontal access. A group of scientists visited Henderson in March 2003 to assess the site. No one at Henderson confirmed the near term availability of the mine for science. Indeed, it was stated that the mine had ore reserves for at least 20 years and that mining was expected to continue indefinitely. Henderson does indeed have a nearly horizontal access that extends for more than 15 km under the Continental Divide. However, most of that tunnel is used for a conveyor belt for ore extraction. The remainder of the tunnel is occupied by a single, mine-gauge rail track. Drive-in access to Henderson is not possible as long as mining operations continue. In comparison with Soudan, Henderson presents all of the problems of working with a mining company in an existing mine.

8.0 Summary

Underground science in the United States has prospered in a dozen locations over the past four decades, whetting the appetites of researchers in many fields. They have embraced the concept of a National Underground Science and Engineering Laboratory that will provide a dedicated infrastructure for the wide range of basic and applied research opportunities offered by the deep-underground environment. We believe that our proposal for Soudan NUSEL offers the most direct route to that goal. Soudan has a working scientific laboratory already in operation. There are no uncertainties in the proprietorship, with the state of Minnesota acting as a strong and stable partner in current and future research endeavors. We have a proven management team backed by the University of Minnesota, one of the nation's leading research universities. There are no known environmental challenges, and the citizens and leaders of St. Louis County and Minnesota support and take pride in the science that they host. Soudan has a significant head-start on the scientific infrastructure for NUSEL. Fermilab's long-baseline neutrino beam represents a major Department of Energy investment, and Soudan NUSEL would facilitate its continuing exploitation into the next decade. We believe that all of these factors make Soudan an ideal site for NUSEL. We look forward to participating in the detailed studies that will establish the best national strategy to achieve the scientific and technological benefit that NUSEL can provide to America and the world.