DEPARTMENT OF ENERGY OFFICE OF SCIENCE REVIEW OF OPTIONS FOR UNDERGROUND SCIENCE

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Executive Summary

Introduction

The Department of Energy (DOE) Office of Science (SC) High Energy Physics (HEP) and Nuclear Physics (NP) programs are planning investments in underground science to study CP violation in the neutrino sector, the origin of dark matter (DM), and the neutrino mass and mass hierarchy.

In light of the recent decision by the National Science Board to decline a proposal providing further National Science Foundation (NSF) support for development of DUSEL under the existing DOE/NSF stewardship model, Dr. W.F. Brinkman, Director of DOE Office of Science organized and charged a DOE-SC committee to help identify cost effective options for selected underground experiments, as well as setting and staging alternatives for implementing a world-class program of underground science consistent with SC's mission in NP and HEP . The findings of the committee would inform DOE budget planning for FY 2013 and beyond. The charge to the committee is given in *Appendix A – Charge*. Committee membership is listed in *Appendix B – Committee Membership*.

The committee met on April 13-15, 2011 at the SLAC National Accelerator Laboratory to review input solicited by DOE HEP and NP program offices from the Long Baseline Neutrino Experiment; from representative DM and neutrinoless double-beta decay (DBD) experiments which bracket the range of expected costs; from the NSF supported DUSEL project team; from the Sanford Laboratory and the Sudbury Neutrino Observatory (SNOLAB) and to hear presentations from representatives of these activities and from the larger scientific community. *Appendix C – Agenda of Meetings* gives the agenda for the meeting.

Members of the committee also made two site visits—to the Sanford Laboratory at the Homestake mine in South Dakota on April 21, 2011 for a tour of the facilities, both above and underground and for very helpful discussions with local experts; and on May 9, 2011 to the SNOLAB in Sudbury Canada. At SNOLAB committee members were able to view an operating underground laboratory and to engage in discussions with staff. The agendas for those site visits appear in *Appendix C – Agenda of Meetings*.

The committee wishes to commend the presenters and their colleagues for the quality of the information communicated at this meeting as well as the subsequent discussions. It was clear that significant effort had gone into preparation of the material and each presenter was well acquainted with the relevant topics. Presentations were accurately tailored and specific to the DOE charge making it much easier for the committee to do its work.

Based on the input received and additional information provided to the committee, the committee assessed the options, encompassing design, construction, and operations costs, for the scenarios laid out in its charge. With this report the committee provides its major conclusions, and its assessment of the scenarios and options. Summaries of the cost, schedule and other information provided to the committee are provided in section *7.0 Cost and Schedule Summary* of this report.

Major Conclusions

The committee provides here a set of major conclusions that seek to capture the most important findings and results of the committee's evaluation of the extensive input received and reviewed. These conclusions summarize the overall time horizon and scale of investment that would be needed to carry forward a cutting edge program in underground science to study CP violation in the neutrino sector, the origin of DM, and the neutrino mass and mass hierarchy. The committee recognizes the advantages and opportunities in developing a common site for these experiments if the needed infrastructure can be shared in a cost-effective manner.

1. The committee concludes that at the current level of maturity the cost estimates for the 3rd generation DM and ton-scale DBD experiments should be taken as accurate to about 1 significant figure, and the cost estimates for the Long Baseline Neutrino Experiment (LBNE) and associated infrastructure costs, although more mature, are not greater than the conceptual design level.
2. The committee's overall evaluation of the likely Total Project Cost (TPC) including construction and operations, of the three experiments is:
    - LBNE (detectors, beamline, and infrastructure)—approximately $1.2-1.5B in FY11.
    - Each 3rd generation DM experiment—approximately $0.1B in FY11 (infrastructure not included; site dependent- specified in conclusion #3).

- Each ton-scale DBD experiment—approximately $0.2-0.3B in FY11 (infrastructure not included site dependent- specified in conclusion #3).
- The cost of operating the LBNE detector and the Homestake infrastructure with LBNE alone is $18-23M/year. Operating experiments like DM and DBD without LBNE but including the Homestake infrastructure is about $20M/year. With all three experiments operating together the $18-23M assigned to LBNE is roughly the total of operating cost of experiments and infrastructure. The marginal cost of DM and DBD experiments is $2-$3M if LBNE is already established. Operating costs at SNOLab are estimated at ~$2-3M but further work is needed to understand any sharing of facility/infrastructure costs.

3. The additional cost of infrastructure to allow construction of 3rd generation DM and/or ton-scale DBD experiments at the 4850ft level at Homestake, if these costs are not borne by LBNE—are approximately $0.15B in FY11 for the first experiment and $15M for each subsequent experiment if infrastructure is done up front. This cost would exceed the infrastructure costs at SNOLAB for a single DM or DBD experiment by approximately $100M. Adding a second DM or DBD experiment at the Homestake 4850ft level requires infrastructure costs roughly that of SNOLAB.
4. It is not cost effective to consider 3rd generation DM or ton-scale DBD experiments as standalone experiments at Homestake because of infrastructure costs, unless there are three or more of these experiments that would be constructed at the same level so the infrastructure costs could be shared.
5. Constructing the 3rd generation DM or ton-scale DBD experiments at the 7400ft level at Homestake is prohibitively expensive because of infrastructure costs and uncertainties. The DM experiments can likely be accomplished at the 4850ft level with additional shielding. For the DBD experiments, a rigorous assessment of the background and its mitigations, which will determine the feasibility of conducting a ton-scale experiment at the 4850ft level, will not be complete for several years.
6. Significant investments in infrastructure will be necessary to safely construct, commission, and operate a modern underground laboratory at Homestake. Modernizing the Yates and Ross shafts at Homestake is a necessary prerequisite and should not be considered an opportunity for 'value engineering'.

7. Constructing a 3rd generation DM or ton-scale DBD experiment at SNOLAB appears to be the most cost effective option even if a U.S. investment is needed to dig and outfit an additional pit, and provide utilities and other support. This option must be verified by detailed studies.

8. The time needed to carry out the three experiments (LBNE, ton-scale DBD and 3rd generation DM experiments) will extend over two decades or more from now, including about one decade before data taking begins. In each case it is quite likely that there will be upgrades and follow-on experiments that will further extend the time scale of these physics programs.

9. Given the extent of investment needed to carry out these experiments, the long timescales and the likelihood of follow-on experiments in each of these areas of research, the committee recognizes that there are major advantages to developing a common underground site for these experiments. Advantages include:

    - Opportunities to share expensive infrastructure and to coordinate design efforts, construction, management and operations.
    - Significant benefits in training the next and subsequent generations of scientists by having a common facility serve as an intellectual center in these fields of research.

    This facility should include needed underground support facilities for example, low background counting facility, clean machine shop, electroforming, and material storage.

    Locating the facility in the U.S. would help to promote U.S. leadership in these fields for the foreseeable future.

10. The LBNE technology choice (water Cherenkov vs. liquid argon TPC) strongly impacts the strategy for siting 3rd generation DM or ton-scale DBD experiments. If the LBNE choice is a water Cherenkov detector (WCD) at the 4850ft level at Homestake, then the 3rd generation DM and/or ton-scale DBD experiments at the 4850ft level becomes significantly more cost effective. If the LBNE technology is a liquid argon (LAr) detector closer to the surface then this would not be so. *Therefore, the committee emphasizes there is a very significant strategic benefit to making the LBNE technology choice as soon as possible.*

11. The committee notes there are advantages to the "1+1" LBNE option which consists of a WCD at the Homestake 4850ft level and a LAr detector at the 800ft level. The physics reach of the program is increased due to complementary detectors (different systematic uncertainties for neutrino oscillations and sensitivity to different channels in proton decay and supernova detection, get physics started at lower initial cost). Additionally, implementing WCD initially, while continuing with LAr R&D for the possible addition of this capability later would be an option consistent with sharing infrastructure between LBNE, the DBD and DM experiments at the Homestake 4850ft level. The committee notes this is an option for consideration. Further study is necessary for a complete evaluation of this option.

Response to Charge Scenarios

The committee provides here an assessment for each of the specific charge scenarios. This assessment attempts to capture, at a high level, the scientific benefit, technical risks as well as design, construction and operations costs for each of the scenarios.

Charge scenario #1: A LBNE using WCDs located at the 4850ft level near the existing Sanford Laboratory's Davis Campus;

Overall, this option is considered viable and the most cost effective for LBNE physics, given the uncertainties in LAr, if the 1+1 scenario is not included in the discussion.

The physics capability driven by the depth and detector mass (150kt or 200kt) of the Far Detector are considered reasonable to achieve the LBNE physics goals. The 1300 km distance from Fermilab to Homestake is in the optimal "window" for a broad program of accelerator beam physics that includes the mass hierarchy determination and CP violation.

The overall design is considered pre-conceptual (approaching CD-1 design maturity). For the Far Detector at 4850ft level, an LBNE WCD would be a 4th generation device, following the SuperK design. The technology is well understood and technical risk is low in terms of physics capabilities. Given WCD's mature technology preliminary design could begin immediately.

The primary risks (both cost and technical) are the span of the deep underground cavern (65m) and underground construction in general. A cavity for the 200kt detector in the rock appears feasible at the 4850ft level, based on advice from geotechnical experts, but will require detailed geotechnical analysis to determine the best location and shape of such a large cavern. Shafts to the 4850ft level should be upgraded to the baseline level. The Fermilab site boundaries limit the length of the decay pipe to between ~200 and ~250 m, which complicates the beamline design. Two options are:

1. Above grade (shallow), this is cheaper due to less excavation but carries more technical risk due to potential stability and shielding issues.
2. Underground (deep), this is more expensive but offers lower risk for stability and shielding.

Proton beam extraction can occur at either the Main Injector MI-10 or MI-60 straight section. The MI-60 option would require an expensive 48^{o} bend in the proton beam. The Near Detector design should be minimal.

The estimated cost range of 150 to 200kt detectors at 4850ft level is $1127-$1476M, including beamline and infrastructure (as estimated by the DUSEL project team). Further information on contingency assessment and on-going operating costs can be found in *Table 9*. The committee finds this estimate to be credible.

If the LBNE choice is the Water Cherenkov technology the incremental cost to create the Lab Module housing a 3rd generation DM and/or 1-ton $0\nu\beta\beta$ effort and future efforts would be $144 - 159M (as estimated by the DUSEL project team).

Charge scenario #2: A LBNE using LAr detectors located at a shallow campus (800ft level) including the resources need to carry out a program of R&D necessary to prove the scalability of LAr technology to 17 kilotons;

Overall, this option cannot be considered viable until the R&D program is complete. Multi-year R&D is necessary to prove that LAr technology can meet the physics requirements of LBNE.

The primary risk is that the LAr technology may not be workable, or is cost prohibitive. An optimistic date for R&D completion is ~2015. Substantial resources will be needed to meet this deadline.

The early stage of LAr development is a significant factor in assessing cost effectiveness between WCD and LAr, since WCD is 'ready for detailed design' as compared with 'needs 4+ years of R&D'. The 1+1 plan dovetails with the R&D requirements.

Additional uncertainties exist including the lack of characterization at the Homestake 800ft level to the extent of the 4850ft level. While the underground construction risks appear no greater than the 4850ft level a higher level of contingency should be applied to the infrastructure scope given the less mature design.

The use of LAr in an underground cavern entails cryogenic safety concerns. Given the design maturity, a higher level of contingency should be applied to the experimental scope given the necessary safety requirements.

The estimated cost range of LAr at the 800ft level is $977M-$1335M (as estimated by the DUSEL project team). The scope of work at Fermilab for either the WCD or the LAr detector is roughly comparable. Further information on contingency assessment and on-going operating costs can be found in *Table 9*.

If LBNE selects LAr technology at the 800ft level a DM and/or 1-ton $0\nu\beta\beta$ experiment is not viable at this depth due to insufficient shielding, and these experiments would not be cost effective at the 4850ft level without sharing facilities costs with LBNE.

The beamline and Near Detector issues are the same as for the WCD.

Charge scenario #3: A 3rd generation DM experiment located at the 4850ft level;

Overall, this option is considered cost viable if the WCD is chosen at the 4850ft level and LBNE supports the infrastructure costs. A 3rd generation DM experiment is not considered viable at Homestake as a standalone experiment.

Two separate experiments using different targets are considered ideal to confirm detection of the WIMP and measure its mass.

The primary risks are whether additional background at the 4850ft level compared to the 7400ft can be mitigated with additional shielding, and risks from being underground.

The cost range of a DM experiment, exclusive of the underground facility, is $80-100M. The associated facility cost at Homestake is $455M standalone and $144M if the WCD is also at the 4850ft level. Further information on contingency assessment, construction schedules, and on-going operating costs can be found in *Table 9*. In light of there being a number of experimental approaches, the committee finds that to first order, the cost is independent of approach and technology choice. For two experiments, there would be a marginal cost of $15M for additions to the underground facility.

Charge scenario #4: A ton-scale neutrinoless DBD experiment located at the 4850ft level;

Overall, this option is considered viable but only cost effective at Homestake if the WCD is chosen at 4850ft level, and LBNE supports the infrastructure costs. A ton-scale neutrinoless DBD experiment is not considered cost effective at Homestake as a standalone experiment.

The primary risks are; today, a ton-scale experiment is not realistic. Further detector development is needed which is estimated to take 3-4 years and operation of smaller detectors is needed to confirm the path forward. However, rough cost estimates can be derived from the Majorana and EXO collaborations to provide a high level cost assessment. Currently, an extensive R&D program is underway to determine whether additional background at the 4850ft compared to the 7400ft can be mitigated with additional shielding.

The cost range of a ton-scale neutrinoless DBD experiment, exclusive of the underground facility, is $200-300 M. The associated facility cost at Homestake is $455M standalone and $144M if the WCD is also at the 4850ft level. Further information, on contingency assessment and on-going operating costs can be found in *Table 9*.

Charge scenario #5: A 3rd generation DM experiment located at the 7400ft level;

Overall, this option is considered scientifically viable at the 7400ft level. However, an experiment is not considered cost effective at this depth due to the substantial infrastructure costs and additional uncertainties. The DM proposers assert that the higher backgrounds at the 4850ft level can be managed with appropriate shielding.

The primary risk is the water level in the Homestake mine is at approximately the 5500ft level. Assuming the current pumping rate, it is not likely that the condition of the 7400ft level can be accurately assessed before 2015. In addition, the #6 winze needs substantial refurbishment before the 7400ft level can be considered usable for science experiments.

The cost range of a DM experiment, exclusive of the underground facility, is $80-100M. The associated facility costs are $282M if WCD is built at the 4850ft level, $563M if LAr is built at the 800ft level, and $593M standalone.

Charge scenario #6: A ton-scale neutrinoless DBD experiment located at the 7400ft level;

Overall, this option is considered viable at the 7400ft level. However, an experiment is not considered cost effective at this depth due to the substantial infrastructure costs and additional uncertainties. Unlike the 3rd generation DM experiments, it is not known if these experiments could be adequately shielded at the 4850ft level.

The primary risks are the water level in the Homestake mine is approximately at the 5500ft level. Assuming the current pumping rate, it is not likely that the condition of the 7400ft level can be accurately assessed before 2015. In addition, the #6 winze needs substantial refurbishment before the 7400ft level can be considered usable for science experiments. Today, a ton-scale experiment does not exist. Further detector development is needed which is estimated to take 3-4 years and operation of smaller detectors is needed to confirm the path forward.

The cost range of a ton-scale neutrinoless DBD experiment is $200-300M. The associated facility costs are $282M if WCD is built at the 4850ft level, $563M if LAr is built at the 800ft level, and $593M standalone.

Charge scenario #7: A 3rd generation DM experiment located at SNOLAB;

Overall, this option is considered viable at the 6800ft level. This option should also be considered the most cost effective. SNOLAB is currently operating an underground science lab, and has much experience with constructing underground science facilities for example, clean rooms, and cryogens.

Note that no site investigation has been performed to identify a site(s) or cost estimates for a new cavern at SNOLAB. However, it is anticipated that a site adjoining the complex can be identified as suitable for new cavern construction. Additionally, parametric estimate of what a facility might cost can be scaled from existing experiments and facilities.

The primary risks are Canadian cost/liability uncertainties and coordinating with a commercial mining operation. The committee also notes that there are potential benefits to an underground science lab adjacent to a working mine, namely subsidized costs for contractor mobilization, shared infrastructure, experienced on-site mine rescue team, etc.

The cost range of a DM experiment, exclusive of the underground facility, is $80-100M. The associated facility costs at SNOLAB are approximately $30M. Further information, on contingency assessment and on-going operating costs can be found in *Table 9*.

Charge scenario #8: A ton-scale neutrinoless DBD experiment located at the 6800ft level at SNOLAB;

Overall, this option is considered viable at the 6800ft level. This option should also be considered the most cost effective. SNOLAB is currently operating an underground science lab, and has much experience with constructing underground science facilities for example, clean rooms, and cryogens. Note that no site investigation has been performed to identify a site(s) or cost estimates for a new cavern at SNOLAB. However, it is anticipated that a site adjoining the complex can be identified as suitable for new cavern construction. Additionally, parametric estimate of what a facility might cost can be scaled from existing experiments and facilities.

The primary risks are; today, a ton-scale experiment does not exist. Further detector development is needed which is estimated to take 3-4 years and operation of smaller detectors is needed to confirm the path forward. There are also Canadian cost/liability uncertainties, and risks and potential benefits associated with shared operations with a commercial mining operation, similar to the DM experiment scenario. The cost range of a ton-scale neutrinoless DBD experiment is $200-300M. The associated facility costs at SNOLAB are approximately $30M. Further information, on contingency assessment and on-going operating costs can be found in *Table 9*.

Charge scenario #9 (addition): LBNE 1+1 - WCD at the 4850ft level; advancing LAr R&D program to prove scalability; then add LAr detector at the 800ft level (if the technology is viable).

> Overall, this option is considered to be viable, allowing the WCD to move forward today while continuing LAr R&D at a modest cost aimed at adding the LAr detector at a later time. The committee emphasizes that this scenario is for consideration only, and that more study is needed to fully understand its benefits and risks. This scenario is favored by the LBNE Collaboration.
>
> The committee assumes that each detector would be smaller than in single technology scenarios (#1 & #2). Should LAr not prove viable, an additional WCD detector can be added to do the full neutrino physics program. The Fermilab scope of work is comparable with scenarios 1 & 2.
>
> The opportunities of this scenario allow physics to get started at a lower *initial* cost than scenarios 1 and 2, and WCD and LAr detectors provide complementary capabilities- different systematics and sensitivity to different final states. Further, deciding early on WCD at 4850 ft, allows decision to be made for doing DM and DBD at Homestake. Risks are similar to scenarios 1 and 2, however smaller detectors mean smaller caverns, and a reduction in associated construction and large span risks.

1.0 Physics

The experiments being proposed for the deep underground laboratory in South Dakota would address some of the most important scientific questions in high energy and nuclear physics. In 2008, High Energy Physics Advisory committee's (HEPAP) long range planning subpanel, the Particle Physics Project Prioritization committee (P5), developed a vision of elementary particle physics in which the major problems are attacked using the complementary techniques of three frontiers: the energy frontier, the cosmic frontier, and the intensity frontier. The latter, which includes the projects considered in this report, addresses core scientific questions: (1) What is the origin of the matter-antimatter asymmetry we observe in the universe? Such an asymmetry (CP violation) has been seen in the quark sector for almost half a century, but it is far too small to explain the cosmic excess of matter over antimatter. An attractive explanation postulates that CP violation in the lepton sector, specifically in neutrinos, is responsible for the excess. (2) What is the dark matter (DM) that constitutes most of the matter in the universe and is responsible for the large-scale structure we see in the cosmos? (3) What is the comprehensive theory of which the Standard Model is the low energy approximation? Clues to the high energy structure could come from the size and ordering of the tiny masses of the neutrinos, whether neutrinos are their own antiparticles, and whether the proton can decay to lighter particles.

Implicit in the P5 vision is the model of the field that has served the U.S. High Energy Physics community well for over 50 years in which scientists have free access to the facilities around the world in return for each region building and maintaining its share of those facilities. This model represents more than a financial plan it recognizes the importance to a nation's scientific endeavor of having its own facilities in which technological expertise is developed and maintained; undergraduate, graduate, and postdoctoral students are trained under the close tutelage of faculty members; and the nation's citizens are excited and educated by “their” discoveries. Because of these issues in addition to the importance of the science, P5 had the deep underground laboratory and its experiments as a core component of its vision for elementary particle physics in the next 20 years.

The Long Baseline Neutrino Experiment (LBNE) will directly search for CP violation through the detailed study of neutrino oscillations. This is a subtle effect that requires an extremely intense neutrino beam and a massive detector to observe. LBNE could also determine the mass ordering of the neutrino states (mass hierarchy), which would help elucidate the comprehensive theory of the elementary forces and particles. The beam will be provided by Fermilab, initially from its current intensity upgrade and later with the much more powerful beam produced by the Project X accelerator. The detector will have as its active medium tens of kilotons of liquid argon and/or hundreds of kilotons of water. If the detectors are sufficiently deep underground to minimize cosmic ray background, the scientific program is quite broad, including sensitive searches for proton decay and neutrinos from supernovas, both bursts from new supernovas and the cumulative remnant neutrinos from supernovas over the history of the universe.

Observation of neutrinoless double-beta decay (DBD) would unequivocally show that neutrinos are Majorana particles. Both mass hierarchy determination by LBNE and the results of the neutrinoless DBD experiments are necessary to establish that neutrinos have a Dirac nature. This property, which would be unique among the elementary fermions, is an important ingredient in the lepton CP violation explanation for the matter-antimatter asymmetry in the universe. In addition, the neutrinoless DBD rate can determine the absolute neutrino mass scale, important information that is not provided by neutrino oscillation experiments. Neutrinoless double-beta-decay is a rare process with a difficult experimental signature. Consequently backgrounds must be close to zero, requiring that the experiments be located deep underground.

DM experiments directly address the identity and properties of the object that constitutes most of the matter in the universe. From its observed abundance and the physics of the expansion of the universe since the Big Bang, it seems that DM is a massive object that interacts through the Weak Force. If so, the DM that passes through the Earth would scatter in ordinary matter, depositing a very small amount of energy from the nuclear recoil. A number of techniques have been developed in recent years that would enable observation of DM in large detectors. These experiments must also operate deep underground to adequately reduce the cosmic ray background so that the tiny DM signals can be seen.

These three very different sets of experiments are synergistic due to their common need for large sophisticated laboratories deep underground. The neutrino detector's location is largely determined by the required distance from the neutrino source at Fermilab. Sharing the infrastructure could reduce the overall cost of the program by siting the DM and neutrinoless double-beta-decay detectors in the same facility, especially since the needed space does not exist in other underground laboratories in the world.

2.0 Assessment of LBNE Scenarios

2.1 Science Overview

The primary science objectives of the LBNE project are:

1. Top Priority: A search for, and precision measurements of, the parameters that govern muon to electron flavor oscillations including measurement of the third mixing angle θ_{13}, for whose value only an upper bound is currently known, and, if θ_{13} is large enough, measurement of the CP violating phase δ and determination of the mass ordering (sign of Δm_{23}).
2. Precision measurements of Δm^2_{23} and $\sin^2(2\theta_{23})$ in the muon neutrino disappearance channel.
3. Search for proton decay, yielding a significant improvement in current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g. decays to $e\pi^0$ or $K\nu$.
4. Detection and measurement of the neutrino flux from a core collapse supernova within our galaxy, should one occur during the lifetime of LBNE.

The LBNE Collaboration has developed designs for two types of detectors with complementary features that can achieve the scientific goals. These designs offer world-class capability for the top-priority physics goals. *Table 1* provides a summary on science objectives 2 through 4, as well as additional physics which can be accomplished. The table also notes interesting technology transfers that can advance other areas of science. A plan utilizing two modules, with both water Cherenkov detector (WCD) and liquid argon (LAr) designs referred to as the “1+1 scenario” below, was also presented by the collaboration. The 1+1 design is attractive and worthy of consideration.

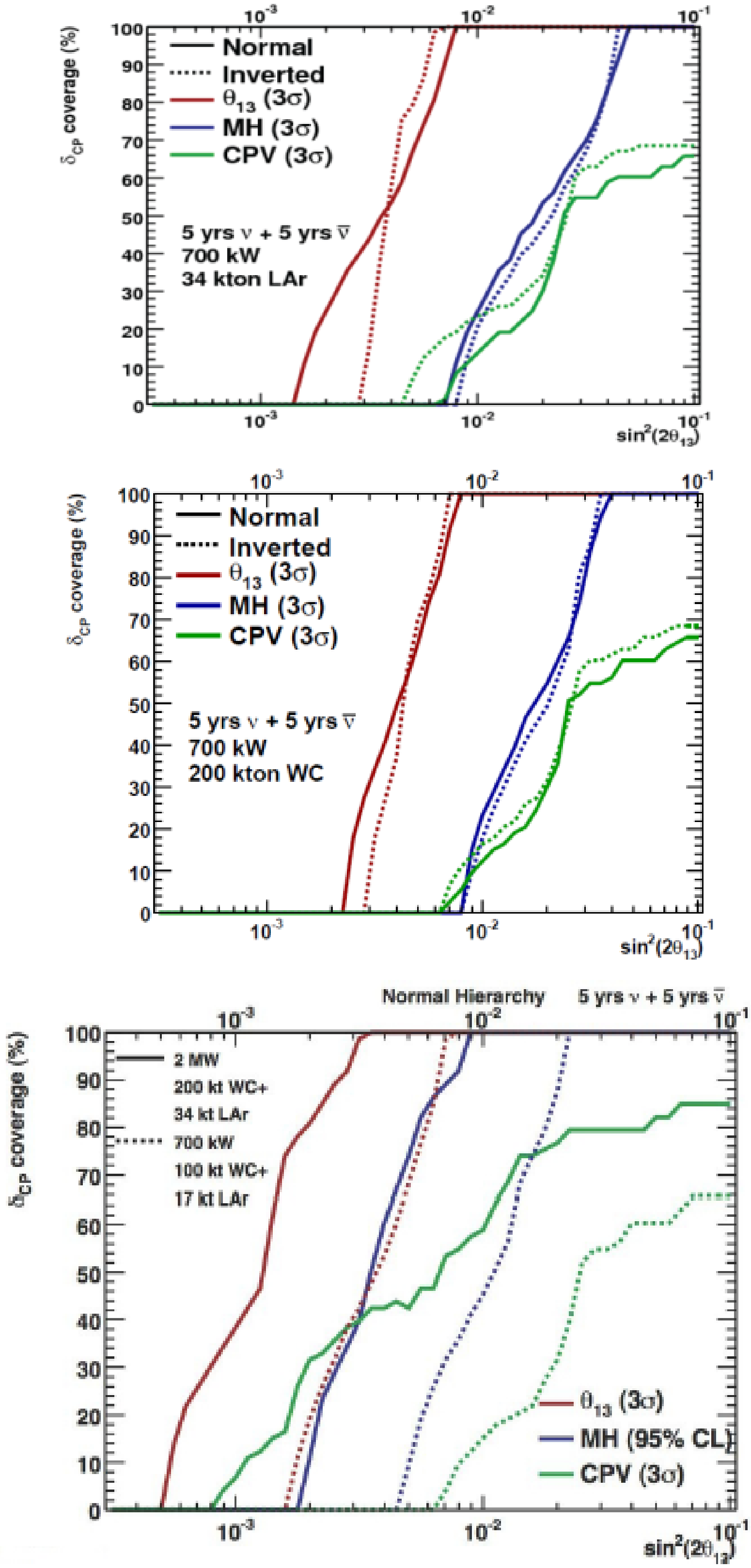

Figure 1: The physics capability of the 34kt LAr detector (left) and 200kt WCD (middle), and a 2-detector system consisting of one 200kt WCD and one 34kt LAr detector (right).

The above figures represent the highest-cost designs for LAr, WCD and 1+1 only. The top and middle figures have comparable fiducial mass, while the figure on the bottom has twice the "effective fiducial mass". As a result, it can be assumed that a factor of 1.41 in improvement comes from the increased mass.

Physics Topic	WCD	LAr
$\nu_\mu \to \nu_e$	**High Discovery Potential** as described in text	**High Discovery Potential** as described in text
ν_μ disappearance ($\nu/\bar{\nu}$)	$\delta(\Delta m^2) : \pm 0.013/0.015$ $\delta(\sin^2 2\theta_{23}) : \pm 0.005/0.007$	$\delta(\Delta m^2) : \pm 0.016/0.025$ $\delta(\sin^2 2\theta_{23}) : \pm 0.006/0.009$
Proton Decay	$P \to e^+\pi^0$ search: $\sim 6 \times 10^{34}$ years $P \to K^+\bar{\nu}$ search: $\sim 1 \times 10^{35}$ years w/ scint. upgrade	$P \to K^+\bar{\nu}$ search: $\sim 3 \times 10^{34}$ years w/o photodetectors $\sim 4 \times 10^{34}$ years w/ photodetector coverage
Supernova Burst at 10 kpc	$\sim 30,000$ evts (primarily $\bar{\nu}$)	~3000 evts (primarly ν) w/ photodetector coverage
Tagged SN Burst	IBD-tagged evts w/ Gd Upgrade	
Supernova Relic Neutrinos	9 to 50 evts/year w/ 40 bkgd ×2 coverage + Gd Upgrade	
Solar Day/Night	0.5% on A_{DN} w/ ×2 coverage Upgrade	
DAEδALUS	Increased δ_{CP} Discovery Potential Cyclotrons +×2 coverage + Gd Upgrade	
Geoneutrinos	>3000 evts/year w/ Scint + coverage upgrade	
Technology Transfer	Improved Photomultiplier Tubes Water-based Gd for neutron dets. Large-Area Fast Photosensors	LAr Technology

Color coding: Purple – under research (no large scale prototypes of needed technology)
Blue – under development (large scale prototypes of technology are running)
Black – Established Technology

Table 1: Summary of the Physics Goals for the Two LBNE Detector Systems for Ten Years of LBNE Operation

The complementary nature of the designs, as seen in *Table 1*, provides the scientific motivation for the 1+1 proposal.

2.2 LBNE systems at Fermilab

2.2.1. The neutrino beamline

The current LBNE beam design is optimized for muon to electron neutrino oscillations, maximizing the number of oscillated electron neutrinos produced at the Far Detector and providing significant flux at the first and second oscillation maxima. The Fermilab site boundaries limit the length of the decay pipe to between ~200m and ~250 m. The possibilities being considered are a beamline either partially above grade or completely underground, and proton extraction either from the MI-60 or MI-10 Main Injector straight sections.

The above grade option (referred to as shallow) potentially has a lower cost than the fully underground option (referred to as deep), but it also carries more risk. The cost savings are recognized by excavating less rock from the shallower depth of the Near Detector Hall, but risk increases because of the stability over time of the beam components, and radiation shielding for the environment.

Proton beam extraction at the Main Injector MI-10 straight section, one of the two possibilities considered has the advantage that the extracted proton beam points (within 7°) towards Homestake minimizing the complexity and cost. There are, however, conflicts with a number of other current and planned uses of the MI-10 straight section. The more conventional option is to extract from MI-60, as was done for the NuMI project, with the beam completely underground. This option would require an expensive 48° bend in the proton beam.

MI-10 extraction limits the decay pipe length to 200m reducing the neutrino flux by about 7% and decreasing (with respect to MI-60) the distance between the beam absorber and the Near Detector Hall from 314m to 200m. The current cost differential between the highest (MI-60, deep) and the cheapest (MI-10, shallow) options is $114M. Thus there is great motivation to optimize this design from the point of view of cost and physics benefit.

The current cost estimate of the LBNE beam has been compared extensively with the NuMI beam costs, and LBNE costs are seen to be much larger, but the causes of the differences are reasonably well understood. The principal reasons for the increases are different methods of accounting, higher current overhead rates, additional shafts and surface buildings in the LBNE design, much higher level of remote handling and better shielding. The last cause is motivated by planning not to foreclose the possibility of a subsequent upgrade in beam power by a factor of 3. An unplanned upgrade after significant radiation exposure would likely be costly and difficult, and so the motivation is sound. Costs for components may be reduced by better use of resources at universities or through outside contracts and the overhead rates may be negotiable. Fermilab is currently engaged in the third round of value engineering.

2.2.2. The Near Detector design

The LBNE Collaboration has been developing separate designs for the two Far Detector options. The requirements for the Near Detector flux measurements and monitoring, however, are rather similar and it seems likely that a single design could be developed which is adequate for both Far Detector options. Even though the Near Detector might be designed to make valuable physics measurements in its own right, the guiding principle, at present, should be strictly limited to support of the Far Detector analysis for the oscillation physics. The design should eliminate all costly Near Detector features that are not absolutely necessary for the main goals.

Consideration of information that might be available in the future should be incorporated in the design process. Some planned capabilities currently utilizing resources may not be important in the future at which point, additional information on neutrino interactions in the LBNE energy range will have come from MINERvA and from the magnetic Near Detector in T2K.

For example, a relatively simple and inexpensive tracking detector followed by an iron magnet (to measure muon charge and energy) may well be able to adequately predict the neutrino spectrum at the Far Detector. Furthermore such a detector might be built by utilizing components from currently running experiments due to be completed several years from now. Examples are scintillator from MINERvA and/or magnets from MINOS. Use of scintillator as the medium in the Near Detector would allow calorimetric measurement of the hadronic energy. Another possibility is reuse of an entire detector like MINERvA or MicroBooNE.

The Near Detector Hall is easily accessible, being located in a radiation free environment, and thus upgrades and modifications during running of the experiment are quite feasible. There is no special urgency to have the ultimate form of this detector decided now and it need not be planned to operate at the beginning of the experiment.

The LBNE Collaboration is currently pursuing several different options for the Near Detector diluting the available resources. Serious thought should be given now to eliminate several possibilities that appear least attractive and costly, based on the work done to date.

The choice of design will eventually require detailed simulations. The LBNE Collaboration is encouraged to concentrate additional emphasis on this line of effort, and apply resources to support such activities at the required funding level.

2.2.3. Beamline construction methods and costs

Deep option sitings are similar to those used for the NuMI beamline with beam extraction and transfer downward, into the bedrock. For these options the major housings (Target Hall, Decay Tunnel, and Absorber Hall) are built as mined excavations in the bedrock. Concrete is used as Decay Pipe shielding. These deep sites would lie in the upper bedrock aquifer, and would be accessed by vertical shaft.

Shallow options provide for beam transfer upward on to a surface berm. For the shallow options the majority of beamline housings would be built as conventional concrete structures, with shielding provided by soil backfill. Soil would also serve as the Decay Pipe shielding. The shallow beamline facilities would lie largely above the bedrock water table and be accessed by a combination of tunnel and vertical shaft.

All the design concepts are under development and subject to on-going internal review. Deep design options were generally considered to be more mature as they have been able to draw upon experience gained in the construction and operation of the NuMI facility. The new “deep” designs notably include enhanced provisions for target handling and groundwater protection. The design of the shallow options were generally considered to be less well developed and the feasibility of some key design features such as the adequacy of the berm stability (lateral and vertical), control of tritiated water flow in unsaturated ground, and the beam extraction geometries are still being assessed.

Although the various design options are at different levels of completeness, all are considered to be consistent with a pre-conceptual level of design definition, and form a reasonable basis for a pre-conceptual level basis of estimate. In developing the shallow options cost minimization has been a driver but the shallow option design is not yet complete, and some technical challenges related to shielding and stability remain.

2.2.4. Near Detector construction methods and costs

Design options presented show the Near Detector facilities as mined excavations sited in the bedrock, below the water table. Various tunnel and shaft access options are under consideration but at least one shaft is likely to be developed to provide access, ventilation and utilities to the cavern site. End-user detector(s) design requirements were not presented in detail.

The design options for the Near Detector Facilities are at a level of completeness consistent with a pre-conceptual level of design and they form a reasonable basis for a pre-conceptual level basis of estimate.

2.3 The Water Cherenkov Detector at 4850ft level

The DUSEL project team presented three WCD options for the Far Detector characterized as “low,” “medium” and “high”, which are described in *Table 2* and the briefing to HEPA presentation *Committee to Evaluate DOE-SC Options for Underground Science*. The “low” cost option would utilize a detector with somewhat reduced mass; 150kt vs. 200kt. The “high” cost option calls for more extensive infrastructure upgrades at Homestake and a more costly neutrino beam than do the other options. The infrastructure upgrades to the shaft can be considered apart from other upgrades in the “high” option, as discussed below.

All WCD designs are based on technology successfully used in past detectors. The proposed detector is often referred to as the “4th generation” of WCDs. The largest and still operating detector (generation 3) is Super Kamiokande (SK), which is about a factor of nine smaller in fiducial mass than the proposed medium and high cost option, and a factor of seven smaller than the low cost option. However, the broad technique is almost identical and the specific technical components are very similar. The designs primarily differ in efforts to take advantage of more cost effective alternatives that have been developed in the fifteen year interim, as well as understanding risks learned from the SK experience including the catastrophic loss of photomultiplier vacuum tubes (PMT) through an implosion in SK. *Appendix E – The Cherenkov Technique and Comparison of LBNE WCD and SK* provides a comparison of various aspects of the proposed detector and the SK detector (*Table 10*) illustrating the similarities and differences, along with a short description of the technique.

As described in the appendix, the large WCD fiducial tonnage is required because of the low efficiency for separating electron neutrinos from background. Because the technique has been in use the efficiencies and backgrounds are well understood, and because the target material is water it is relatively inexpensive – most of the detector cost consists of constructing the large cavern and associated conventional construction to contain and access the water, and of the photodetectors to record the light signals. The photosensitive detectors which are found most cost effective are still PMTs.

The walls of the cavern must simultaneously be made impervious to the contained water and provide provision for mounting photodetectors to detect the Cherenkov radiation. A small number of PMTs are pointed outward to veto charged particles coming from outside, the remainder point inward and for these, the larger the fractional area and photodetection efficiency the better the coverage. The SK detector ran in several different modes providing differing PMT coverage (SK I, II, and III), and so have permitted evaluations of the consequences of different coverage for specific physics issues. These comparisons have permitted reliable estimates of scientific performance in optimizing cost-benefit in the phototube coverage. LBNE Collaboration is investigating methods for different photon detection devices and techniques to gather more light into the detectors. All proposed options assume the same PMT/efficiency coverage.

The walls are planned to be either shotcrete or poured concrete with an impervious polymer membrane separating the water from the sealed walls. In all options, the PMTs will be mounted in a manner similar to a design used in the Irvine-Michigan-Brookhaven (IMB) detector, but the number of PMTs differs between the lowest and other two cost options. Light concentrators are intended to be used in association with the PMTs.

2.3.1. Ongoing research and development efforts

Efforts under way for the three options presented here include:

- Continue geotechnical site investigations for the large cavity excavation to decide cavern siting and to perform the final design.
- Choose photodetection system from:
  - Hamamatsu developments of high quantum efficiency 12-in PMT's with suitable hydrostatic pressure rating.
  - Electron Tubes Limited (ETL) developments of new high quantum efficiency 11-in PMT with suitable hydrostatic pressure rating.
- Investigate vessel designs for protection of the deepest PMT's in the medium and high cost options, where water pressure is somewhat higher.
- Complete LBNE-specific reconstruction code using knowledge gained from SK experience.
- Simulate performances of different light-concentrator options (Winston cones, wave length shifters, etc.) using the new reconstruction code to permit informed choices.
- Test all materials to be used in construction determining the compatibility with ultra-pure water.

These efforts are proceeding well though uncertainties remain. The costs are either included in the proposal costs or committed as part of the NSF S4 process.

For the far future several possible upgrades are being studied which are not included in the initial options including enhanced PMT coverage, dissolving gadolinium compounds in the water to permit tagging inverse beta decay, scintillator contained in an "inner volume" (balloon), and large area picosecond photosensors. These upgrades were presented to show the potential to add science value to the detector in the future (see *Table 1*). The innovative detector development projects are funded separately through programs like the DOE ADR because of applicability to experiments well beyond LBNE. All three of the design options allow for these upgrades with no extra cost to the initial-phase design. Cost and risk for these upgrades must be assessed after future development.

2.3.2. Three options compared - low cost, medium cost, high cost

Option	**Low Cost**	**Medium Cost**	**High Cost**
Parameter	**150kt**	**200kt low range**	**200kt high range**
Fiducial mass (volume)	150kt (150,000 m^3)	200kt (150,000 m^3)	200kt (200,000 m^3)
Height (volume) of excavated cylinder (d = 65 m)	63.1 m (209,000 m^3)	81.3m (270,000 m^3)	81.3m (270,000 m^3)
Dimensions of the active volume	d=63 m h=58 m (180,000 m^3)	d=63 m h=76.6 m (240,000 m^3)	d=63 m h=76.6 m (240,000 m^3)
Number of 12-in PMTs	23,000	29,000	29,000
Water containment strategy	Double layer polymer membrane on shotcrete	Double layer polymer membrane on shotcrete	Concrete vessel with polymer membrane
Shaft strategy	Minimal Yates and Ross shaft upgrades, WRH from Ross, disposal to surface	Minimal Yates and Ross shaft upgrades, WRH from Ross, disposal to surface	Full Yates shaft upgrade, WRH from Yates, disposal to Open Cut

Table 2: Differences among Three Proposed Cost Options Being Considered

The low cost option is identical to the medium cost option except that the detector fiducial mass is 150kt rather than 200kt. The lower fiducial mass reduces the cavern size and associated vessel parameters; the cavern size differs only in height. The number of photodetectors on the reduced surface is also lowered from 29,000 to 23,000, and the rock wall is sealed with shotcrete in the low cost and medium cost options. The collaboration had been studying detectors of 100kt unit size, but has concluded that caverns of larger height are reasonable. The increased pressure on the PMTs at the bottom will require special attention, a concern reflected in the ongoing R&D efforts.

Both medium and high cost options include the indicated larger fiducial mass detector. The principal differences lie in conventional construction, both at the Far Detector site and for the neutrino beamline and Near Detector complex. The last two are discussed in *2.2.2 The Near Detector design*. At the Far Detector site in the medium cost option with the smaller 150kt cavern, only minimal upgrades to both the Ross and Yates shafts are planned. While the shaft upgrades appear only in the high cost option, this can be considered apart from the other upgrades to the medium design.

2.3.3. Cost options compared - large cavity construction

Excavation: Rock conditions at 4850ft level (Yates Amphibolite) are considered to be generally good and there may be opportunities to further optimize the cavern site and reduce the amount of external excavation work based on the results of further site investigation and design work. As recently noted by the Large Cavity Advisory Board (LCAB), there is no technical reason the large cavern excavations of the scale required to house a 200kt detector cannot be built in the rock mass. However, as the span and depth of the opening increase, rock support requirements are likely to become more onerous. Specification for bolt and shotcrete support to be installed before the excavation can advance may result in major increments in time and cost. These increments may not, as yet, have been fully accounted for in the estimated work performed to date. No construction schedule was presented for the 200kt option, but given the infrastructure limitations at the 4850ft level (even with a full upgrade), and the likelihood of an increase in the critical path time devoted to support installation, a significant extension in excavation duration, above that developed from linear extrapolation, may be anticipated.

Watertight Liner: As the design progresses the liner-excavation interface will need special attention to ensure that wall asperities and time-dependent wall movements can be tolerated by the watertight liner, without rupture. The liner will be subject to considerable head and its ability to maintain long-term elongation without rupture is critical to experimental success.

Cost Comments: The design options presented for the large cavity facilities are at a level of completeness consistent with a pre-conceptual level of design and form a reasonable basis for a pre-conceptual level basis of estimate.

2.3.4. LAr detector at 800ft level

The TPC detector options consist of 24 to 34 tons of ultra-pure LAr target in an electric field, instrumented with wire chambers. Charged particles which traverse the detector ionize the argon. The electrons drift to the anode wire plane. Beam timing or scintillation light allows determination of the T0 for the drift, permitting 3-d reconstruction. H. Chen first proposed a LAr tracking detector in proposal FNAL-P496. An extensive program called ICARUS, led by C. Rubbia, has operated in Europe since 1977. The first LAr detector run in a beam in the U.S. is ArgoNeut, which began in 2007.

The parameters for the options presented to the committee are presented in *Table 3*. Substantial R&D remains to be accomplished in order to show that this detector can fulfill its promise. As a consequence, the contingency in this program (see the briefing to HEPA presentation *Committee to Evaluate DOE-SC Options for Underground Science*) is high.

Parameter	24kt	33kt (lower cost)	34kt (higher cost)
Fiducial Mass	24kt	33kt	34kt
TPM configuration per cryostat (w x h x l)	3 x 2 x 13	3 x 2 x 18	4 x 2 x 22
Max drift distance	3.75 m	3.75 m	2.5 m
Wire spacing	5 mm	5 mm	3 mm
Cryostat volume	29,000 m^3	39,100 m^3	41,900 m^3
Photon detection	Yes	Yes	Yes
LAr surface storage tank	No	No	Yes

Table 3: Description of the Three LAr Detector Options

2.3.5. LAr research and development program

The recent results from ongoing R&D were presented to the committee (see *Table 4* for a summary of the full program). The optimistic date for completion of the R&D is 2015. If high priority is placed on performing this R&D, then a cost-effective LAr design might be established within a 5 year timescale. Without these results, it is difficult to assess the most cost-effective LAr option, or to compare this program to the WCD, which is well developed. Costs of the leak tests, the Liquid Argon Purity Detector (LAPD)-30t (a ~30t, un-instrumented module used for purity tests), and LAr 1kt (a ~1kt instrumented module used for tests described in *Table 4*) are on-project because they are LBNE-specific. The costs of ArgoNeut and MicroBooNE are off-project, because these experiments have separate physics goals beyond LBNE R&D.

Topic	Drive by Following Need	Planned to be Addressed by the R&D Experiment	Date R&D Result Available
Establish Automated Event Reconstruction	Obtain better est of efficiencies & backgrounds	ArgoNeut, MicroBooNE	2012, 2014
Construct 125 to 200 kV feedthroughs	Long drift to reduce instrumentation/material	MicroBooNE (2.5 m)	2014, 2015
Demonstrate purity w/o evacuation	Long drift necessitates long e-lifetime	LAPD-35t, MicroBooNE, LAr 1kt	2012, 2014, 2015
Test cold electronics	Req'd S/N after drive & reduced material to ullage to maintain purity	MicroBooNE, LAr1kt	2014, 2015
Construct membrane cryostat	Large volume	Leak test, LAPD -35t, LAr 1kt	2011, 2012, 2015
Design & produce light collection system	Reconstruction of non-beam events ("T0")	MicroBooNE, LAr 1kt	2014, 2015

Table 4: A List of R&D Goals Presented at the Review

The need is listed in column 1. The aspect of the design which leads to this need is described briefly in column 2. The program to address the need is listed in column 3. The earliest dates by which the necessary information will be available is listed in column 4.

The scope of LAr 1kt is not fully determined at this time. Present plans do not include placing LAr in a beam. A careful review of how the LAr detector is used could result in a plan to solidly demonstrate automated reconstruction of LBNE-like events with the required efficiency. Running one of the prototype detectors in a charged particle test beam could provide crucial information. A charged pion beam can produce through charge-exchange neutral pions which quickly decay to gammas. Analysis of data using electrons and charged pions of known energy could be used to demonstrate the e/gamma separation required at the LBNE energies.

The LAr group needs to grow in order to obtain timely results from the R&D program. The effort is largely based at two laboratories, and thought should be given on how to expand the LAr group to better involve universities. The interesting projects now dominated by laboratories could be subdivided and shared. This division may well be more cost-effective since the indirect costs at universities for engineering are often substantially lower than indirect costs at laboratories.

2.3.6. Cost-effectiveness - high versus medium and low options

The important design parameters for the three proposed options are presented in *Table 4* above, while the associated costs are presented in the briefing to HEPA *Committee to Evaluate DOE-SC Options for Underground Science*. Because substantial R&D is still required, at this point it is very difficult to identify the most cost-effective option. The high cost option which minimizes the risk and the required R&D is the one supported by the LBNE Collaboration.

The most important difference between the options is that the low and medium designs employ a substantially longer drift distance for electrons than the high cost design. The two drift lengths considered 2.50 m and 3.75 m, are currently a subject of debate within the LBNE Collaboration and the project team. There is some evidence that the 2.5 m choice would provide a workable solution. On the other hand, the 3.75 m choice would result in significant cost savings. At this time the feasibility of such a long drift distance has not been demonstrated and is a very risky choice. It is prudent to assume for the current design the smaller 2.5 m drift. This issue deserves strong emphasis in the forthcoming R&D program.

There are other advantages to the high cost option includes the largest fiducial volume reducing physics risk. At this point, it is unclear whether the assumed reconstructed signal efficiencies can be achieved and thus whether the full 34kt of the high cost option is required.

On the other hand, the medium and lowest cost options consider wider wire-spacing compared to the high-cost option. This wider wire-spacing could be considered for additional savings in the high-cost option if results from ArgoNeut and MicroBooNE show that wider wire-spacing does not reduce the reconstruction capability.

2.3.7. Conventional construction at the 800ft level

Pending site investigation work, a generic site for LAr caverns has been adopted to support pre-conceptual design work. The caverns would be accessed using a combination of decline tunnel and shaft. The tunnel and shaft structures will likely encounter a range of ground conditions, including faulted and more fractured rock zones, but these openings should be readily mined using industry standard methods and means. Suitable sites for cavern structure(s), away from faulted or more fractured ground, should be identifiable once a modicum of site investigation work has been completed. Though the caverns are relatively large they are not without precedent and could also be readily built using standard excavation and ground support techniques. The design of internal structures includes a cast-in-place concrete with embedded heaters and provisions for evacuation and exhaust systems in the event of LAr release.

The design of the underground LAr facilities is at a level of completeness consistent with a pre-conceptual level of design, and form a reasonable basis for a pre-conceptual level basis of estimate.

2.4 1+1 Scenario

Though not included in the charge, the 1+1 scenario is the first choice of the LBNE Collaboration because the WCD and LAr designs are highly complementary. This scenario utilizes one WCD module at the 4850ft level and one LAr module at the 800ft level, exposed simultaneously to the same neutrino beam.

This design can substantially improve the muon-to-electron flavor oscillation study because the backgrounds for the two modules should be quite different. The other priority physics topics are improved by the two-module design, as can be seen by the complementary signal sensitivities listed in *Table 1*.

The two detectors are also very different in risks and in readiness. The WCD has a modest detector risk with a higher risk for the conventional facility due to the large span. In the case of the LAr detector, the 800ft level is considered less risky (to be confirmed when the specific site and scope are understood) however the LAr technology must still be proven to work at this scale through additional R&D. A 100kt WCD can quickly be designed and understood, while the LAr needs significantly more technical development. A two module plan also allows one detector to be down for maintenance while the other continues to take data (most important for the supernova readiness).

The most cost effective module sizes for a 1+1 design requires further study. This scenario has the additional cost-burden of developing two detectors and two sites, but further review may show that this is warranted by the compelling additional science. A two module design also naturally lends itself to staging, with the WCD going ahead early. An aggressive schedule could help maintain momentum and morale, as well as maintaining U.S. program competitiveness in this science. Having both an early and later detector also allows re-evaluation of the full plan if θ_{13} is found to be small for example, changing the focus to emphasize neutrino astroparticle physics.

While the European program is far behind the U.S. in its plans, a clear feature of their “LAGUNA design” is a multi-detector system. They are pursuing this for all the reasons discussed above so the concept is not new, and is consistent with the thinking of a different neutrino community.

2.5 Conclusions

The LBNE experiment encompasses many options involving broad issues like Far Detector technology, beamline choices, and Near Detector techniques. The presentation of conclusions in this section is divided according to cases that reflect differing broad choices, and clarify which choices are thought to be dependent on others.

2.5.1. Case that Water Cherenkov Detector is the chosen technology

The WCD Far Detector size can be made a separate issue from the shaft upgrades. The shaft upgrades are important for safety and should be included in any plan.

Both 150kt (low cost) and 200kt (medium and high cost) fiducial volumes appear cost effective. In the case of the former, the smaller cavern and detector size implies less risk and cost; however, with 25% less fiducial volume and, up to a 25% reduction in the science reach, depending on the topic. On the other hand, the latter maximizes the science, but with more risk in construction and use due to the larger depth. With future engineering input, these choices can be optimized.

2.5.2. Case that LAr is the chosen technology

The “high cost” LAr option is the design which minimizes risk. However, the technology must be proven by the R&D program. The far LAr detector is autonomous from DM and DBD experiments, as it is positioned at the 800ft level. The conventional facility design is at the pre-conceptual level.

2.5.3. Case that both technologies are chosen in a 1+1 scenario

There are attractive scientific reasons for a 1+1 design, given the complementary capabilities of the two detectors. Understanding the most cost-effective module sizes in a 1+1 option requires further review. Also, further review should be given to the possibility of staging, comparing the “pro” of a smooth funding scenario and ability to respond to the value of θ_{13} with the “con” of extra total costs from developing two sites and two detector designs.

2.5.4. Beam options for cost effectiveness

In general, the beam and Near Detector choices may be decided separately from the far technology, and rely on very different issues. The 'shallow' scheme, included in both low and medium cost options for both far detectors, is clearly more cost effective if it remains feasible and the costs are stable after further study. The 'deep' scheme for the beam, contained in the high cost options, implies less risk. The project may benefit from further effort to bring down beamline component costs. For either far detector, the Near Detector design should be minimal at this stage and the possible use of existing detectors or parts of detectors should be investigated to see if such a strategy would be cost effective and at the same time provide the measurements necessary to adequately understand the flux for LBNE.

3.0 Assessment of 3rd Generation Dark Matter Experiment

3.1 Science Overview

DM is reasonably estimated to comprise 23% of the universe, but little is known about the particle properties of DM. DM searches look for elastic nuclear recoils from weakly interacting massive particles (WIMPs) whose flux through detectors is estimated from cosmological models of the galactic halo. Cross section limits from current experiments are about 10^{-44} cm^2 (spin independent), and 3rd generation experiments are reaching towards (an irreducible neutrino interaction limit) of 10^{-48} cm^2. All of five proposed experiments would operate deep underground to limit cosmogenically produced spallation neutron backgrounds, and use different techniques to separate nuclear from electron recoils. The energy range of the WIMP induced nuclear recoils is in the range of a few keV to a few 10's of keV, leading to somewhat different background reduction strategies from neutrinoless DBD experiments.

3.2 Dark Matter Experiments at 4850ft Level

LZD is a 20 ton liquid xenon two phase Time Projection Chamber (TPC) utilizing direct scintillation and ionization to separate nuclear recoils. It would utilize a water shield and liquid scintillator veto system. LZS, an intermediate step from LUX to LZD, is the next step in its evolution, and will use the Davis cavern in Homestake.

MAX is a two target observatory using 20 tons of depleted Ar in a two phase TPC and 6 tons of xenon (Xe), also in a two phase TPC. It should measure the A dependence of the cross section, measure the WIMP mass by comparison of the recoil spectra in the two targets, and provide an indication of the spin-dependent – spin independent nature of the interaction.

GEODM consists of 300 5.1 Kg Ge detectors. It is derived from CDMS (Soudan) with 16 0.25 Kg detectors and SuperCDMS (Soudan) with 25 0.64 Kg detectors and SuperCDMS (SNOLAB) with 72 1.6 Kg detectors. Separation of background is achieved by comparing ionization and phonon signals.

COUPP is an array of 32 500 Kg bubble chambers utilizing CF3I. It operates at a superheat such that it is insensitive to minI particles but does produce a bubble with nuclear recoil. The COUPP team has demonstrated an acoustic technique for identifying α's. A 4 Kg module is now operating in SNOLAB.

CLEAN is a single phase scintillation detector using 40 tons of LAr or LNe using Pulse Shape Discrimination to distinguish electrons from nuclear recoils. CLEAN is evolving from two lines of experiments: DEAP going through DEAP-3600 which is 3600 Kg LAr at SNOLAB; and CLEAN going through mini-CLEAN 400 Kg LAr or LNe at SNOLAB. The combination of Ar and Ne in CLEAN also allows the measurement of A-dependence. CLEAN expects to also measure the p-p solar neutrino flux.

All of the experiments would utilize more extensive shielding at the Homestake 4850ft level than at either of the deeper locations.

The five 3rd generation concepts have developed a consensus position that they prefer two experiments be supported at the 4850ft level of Homestake. There is a reasonable scientific case that two experiments using different targets are required to estimate the mass of the WIMP as well as confirm detection. Each experiment has developed a cost estimate. The cost estimates are immature and not at CD1 project level, and there was no expectation that the cost estimates would be better than they are. The estimates also do not distinguish among the concepts. A reasonable range is $80-100M. These numbers do not include the experimental area or utilities. While there are many interfaces that are not worked out in detail, these cost contingencies are expected to be relatively small.

The costs for all combinations of one 3rd generation DM experiment, two 3rd generation DM experiments, and one $0\nu2\beta$ experiment are shown in *Table 5*. The first part of the table indicates the laboratory module at the 4850ft and 7400ft levels of Homestake with LBNE at the 4850ft or 800ft level without LBNE, or the SNOLAB facility; the second part is the range of experiment costs; and the third is the estimate of annual experiment operating costs. It is reasonably clear that only one experiment at either level of Homestake is quite expensive.

The cost of the laboratory module at Homestake 4850ft level is for a 20 x 24 x 115 m (100 m available for the experimental program) cavity that could house two experiments, lay down space, and associated utilities. The laboratory at 7400ft level would be 15 x 15 x 75 m, limited by geology.

The DUSEL project team has estimated annual operating costs for the facility during three phases: preliminary design, conceptual design, and operation. They have not analyzed in detail the costs to maintain operation for a single experiment. An estimate (with which Lesko concurs) is that for a singular DM experiment at 4850ft level this amount would be not less than $12M per year. This cost would have to be born from present to the start of the experiment, and then for the duration of the experiment. An estimate is six plus ten years, or approx. $200M.

SNOLAB is located at a depth of the 6800ft level in the Creighton Mine, an operating nickel mine near Sudbury, Ontario. SNOLAB is built as a class 2000 cleanroom. It has 2 MVA installed power underground and is expected to upgrade to 3 MVA. While it is possible that existing laboratory space at SNOLAB might be utilized, the assumption for this report is that these experiments would be placed in new cavities paid for by the U.S. If Utility requirements exceed SNOLAB availability, these would also need to be supplied. SNOLAB was not asked to develop estimates for such cavities. A crude estimate would start from the SNOLAB Cryopit costs of $15M Ca (2004) and roughly double this number to $30M U.S. The committee has also independently estimated these costs in *5.9.3 New Dark Matter or Double-Beta Decay Cavern Facilities at SNOLAB Cost Comments* and gets $27M +$5M contingency.

4.0 Ton-Scale Neutrinoless Double-Beta Decay Experiment

4.1 Science Overview

The goal of these experiments is to observe the neutrinoless DBD of a nucleus in order to determine the fundamental properties of the neutrino. This decay mode is only possible if neutrinos are their own anti-particles, and requires lepton number violation. Once neutrinoless DBD has been established the decay rate can, in principle, be used to establish the mass of the neutrino (in contrast to the mass differences which have been measured to date from interactions of atmospheric, solar and reactor neutrinos). However, extraction of the mass is dependent on unknown nuclear matrix elements and it is likely that additional measurements in different isotopes would be necessary both to remove uncertainties in these matrix elements and to eliminate the possibility of contamination from a very low intensity gamma-ray line at exactly the energy of the neutrinoless DBD.

Practical searches for neutrinoless DBD have been under way for several decades. As with searches for cold DM, successively larger mass detectors have been deployed leading to reduced upper limits on the decay rate, but at the same time requiring ever more stringent reduction in background from natural and cosmogenic radioactivities. Eventually, any experiment will be limited by the irreducible background from DBD accompanied by two neutrinos. Once this limit is reached, the only possibilities to increase sensitivity are to improve the energy resolution of the detector, or to choose isotopes for which the regular process is suppressed.

The current state of this field is that many experiments have set limits, but one experiment (Klapdor et al. Mod. Phys. Lett A21 (2006) 1547) has claimed to observe the process. Thus, the immediate goal of the field is to confirm or refute this claim. A number of experiments in the 100 kg range will have adequate sensitivity to test the Klapdor claim in the next 2-3 years. The optimistic view is that experiments such as GERDA, EXO, CUORE, MJD, SNO+, etc. will each see the effect in the isotope under study, and that by comparing the rates observed, uncertainties arising from nuclear matrix element corrections will be reduced, leading to a model-independent measurement of the neutrino mass. However, it is also quite possible that none of them will see the decay and that a ton-scale experiment will be indicated.

Committees such as the NUSAG (a joint sub-committee of HEPAP and NSAC) have pointed out that a ton-scale experiment will be a major endeavor, that there will likely be only one such experiment, and that the best technology (or isotope) to deploy is not yet known. Realistically, this decision cannot be taken until the present generation of detectors has produced results, perhaps 2-3 years from now. Nevertheless, some general comments can be made on the cost range and technical requirements of a ton-scale experiment.

The committee was presented with two possible experimental approaches one employing germanium-76 (Majorana) and a second using xenon-136 (EXO). These experiments measure extremely slow decay rates with a very small signal, and so will require excellent energy resolution and extremely low background - < 1 count/ton/ year in the region of interest. Each of these collaborations is actively deploying a "prototype" to verify the approach and measure the background. Majorana is working in the Sanford Laboratory at the Homestake mine and plans to have results which would inform the decision for a ton-scale detector by about 2015. (A second collaboration, GERDA is using a quite different Ge background shield and is running now in the Gran Sasso Laboratory in Italy.) EXO-200 is a liquid Xenon experiment just starting to take data in the Waste Isolation Pilot Plant (WIPP) facility. It is the largest DBD experiment in the world – but it is expected that a much larger quantity of xenon will eventually be needed to provide definitive results. There would be a physics benefit in doing at least two experiments with different isotopes at the ton scale, but if there is budget for only one, it will be some years before a technical down-select will be possible.

It should also be mentioned that Ge diodes and liquid Xenon are not the only possible approaches. Bolometry in TeO_2 crystals and high pressure Xenon detectors are also under development for 100kg scale experiments at the Gran Sasso and Canfranc laboratories (CUORE, NEXT).

There is approximately a 20 reduction factor in the cosmic ray muon background from the 4850ft level at Homestake to either the 7400ft level or SNOLAB. Both collaborations agree that there may be too much background at 4850ft level, but mitigating these backgrounds with appropriate shielding is possible. This background measurement will take some time to resolve – perhaps 3 years. If an immediate decision was required it would be conservative to deploy an experiment as deep as possible. However, depending on the site, it may be more cost-effective to invest in shielding and other mitigations than to excavate at greater depth. This increased cost-effectiveness would almost certainly be accompanied by greater technical risk.

4.2 Summary Including Comparison Tables

After receiving detailed presentations from the Majorana and EXO collaborations, the committee can make the following general statements regarding the cost of a ton-scale experiment, at 4850ft level, 7400ft level or SNOLAB, without specifying the isotope or technology:

1. It will be 3-4 years before a technical downselect will be possible based on cost, backgrounds or other factors. The downselect will involve not only a choice of isotope (Xe, Ge …) but of technology (e.g. liquid or gaseous Xe; MJD or GERDA mounting schemes). Because of this, and because of the cost of these experiments, the beneficial occupancy dates of 2018-2019 at 4850ft level and SNOLAB are unlikely to be on the critical paths for the experiments. However, the 2021 date for the 7400ft level might very well be.
2. Either approach will likely cost in the range of $200-300M U.S. in addition to the excavation costs. In either case, procurement of the separated isotope is a significant cost driver.
3. Both collaborations expressed concern that providing a large water shield to mitigate cosmogenic backgrounds at the 4850ft level will also introduce a technical risk.
4. The committee compared facility costs between Homestake 4850ft level and SNOLAB. Homestake has costs associated with the general facility and shafts of several hundred million dollars that have no counterpart costs at SNOLAB. The DUSEL project team has estimated costs, above those that are common with LBNE, for one and two large experiments at 4850ft as $144 and $159M respectively. The cost for a single experiment is dominated by utilities, drifts and ramps for access and egress, shops, refuge, management, and contractors costs (e.g. construction equipment, shaft access, burdens). The incremental cost to excavate a larger hall allowing a second experiment is $15M. It is likely that this incremental cost would be substantially larger if the hall were expanded at a later time.
5. Costs for a variety of options for DBD and DM searches are tabulated in *Table 5* (common for DM and DBD)
6. If a deep site is necessary, the present estimated costs for the 7400ft level option do not appear to be cost effective.

	LBNE Tech Choice = WCD	LBNE Tech. Choice = LAr	Without LBNE	Lab Module Beneficial Occupancy
1 Expt at 4850L	144	425	455	Mar-18
2 Expts at 4850L	159	440	470	Jan-19
1 Expt at 7400L	282	563	593	Mar-21
2 Expts at 7400L	292	573	603	Oct-21
1 Expt at SNOLAB	144	425	455	Jan-18
2 Expts at SNOLAB	159	440	470	Jan-18
3rd Generation Range		80-100	--	--
DBD Range		200-300	--	--
Annual Operations at Homestake		12-20	--	--
DBD Annual Operations		2-3	--	--
3rd Generation DM Operations		2-3	--	--

Table 5: Costs for Double-Beta Decay and Dark Matter Experiments (M FY11$)

The total cost for the DBD and/or DM options is the sum of the infrastructure costs of the option chosen in rows 1-6; the experiment cost from rows 7 or 8; the facility operations cost from row 9; and the experiment operating cost from rows 10 or 11 as seen in *Table 5* above. The facility costs in the first 4 rows are taken from table 2.2 in the white paper *Deep Underground Science and Engineering Laboratory, Hosting Underground Science at the Sanford Laboratory*[1]. The committee has included $77M in the Homestake facility costs for the Yates upgrade for the LBNE=LAr and without LBNE columns. The committee assumes that for LBNE=WCD, the Yates upgrade is costed with the LBNE.

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[1] https://slacspace.slac.stanford.edu/sites/reviews/SC_Apr_2011/Review%20Committee%20Documents/Hosting%20Underground%20Science%20at%20the%20Sanford%20Laboratory_White%20Paper.pdf

5.0 Conventional Facilities - General Conditions

The organizations who contributed presentations and information for this Review are:

- The DUSEL project team at Homestake which prepared an extensive proposal for the NSF to develop a complete research facility at Homestake. This work was recently reviewed and given a favorable report as to the design and cost estimate work completed;
- The LBNE project group based at Fermilab with other organizations contributing, which is in the process of reviewing preliminary design studies for cost effective alternatives; and
- The SNOLAB which is just finishing a major expansion of their facility in Sudbury, Ontario, Canada.

None of these organizations had developed standalone scenarios for any of the eight options proposed by DOE in the Charge Letter. Therefore, each group addressed the specific charge questions based upon information developed under different conditions.

The DUSEL project team identified “common elements” from work previously prepared to support multiple charge options, and then added to those common elements particular items, as used to support individual options. In the course of identifying common elements, the DUSEL project team also chose to downscale some of the infrastructure work stated in the proposal prepared for the NSF. An example is the decision to list as a common element the un-refurbished Yates shaft (counter to the recommendations of their own experts) thereby retaining the wood infrastructure, with only modest maintenance, rather than replacing the wood with steel. Nonetheless, the items listed as common elements had been the subject of rather extensive cost estimate reviews, and substantial planning for utility and access support for facilities at the 4850ft level and 7400ft level were available to support identification of costs for the six options requested by the DOE. The DUSEL project team had used a 100kt WCD as a benchmark in their NSF proposals, which is significantly smaller than the one presented by the LBNE project group. The costs associated with siting and operating the two options at the 7400ft level were substantially higher that at the 4850ft level due to the substantial additional (and even unknown) amount of work associated with finishing the pump down of the water, refurbishing the #6 winze and the drifts, and constructing a new winze access for ventilation and safety.

The LBNE project group reported on three elements; the neutrino production facility at Fermilab, and at Homestake a 200kt WCD at the 4850ft level, and/or a liquid argon detector at the 800ft level. In the sense of "common elements" as discussed above, the neutrino production facility is common to both of these experiment options. The WCD at the 4850ft level uses common facility support elements with other 4850ft level options as developed by the DUSEL project team, but the Liquid Argon detector at the 800ft level is rather independent of any other development at the Homestake site.

The LBNE project group is still studying at least four options for the neutrino production facility at Fermilab, and a significant cost range was reported. These four options are based upon two possible extraction points from the Fermilab Main Injector, MI-60 and MI-10, and for each of the extraction option a "deep" or "shallow" targeting elevation is being studied.

The engineering for support of the liquid argon detector is less advanced than for the 100kt WCD envisioned in the DUSEL proposal (since the detector design is not yet fixed), and the 200kt WCD excavation has risks related to excavating and supporting spans of this width.

The SNOLAB project in Canada has recently completed a major expansion of the facility. Costs associated with the completed work are well known. The facility is extensive but at present does not support the specific dimensions requested by either of the experimental options the DOE included in the charge. The SNOLAB infrastructure is supported by an operating nickel mine making the operating support costs well understood. It is possible, by extrapolation from very recent experience, to make plausible estimates of new excavation and utility support costs.

5.1 General Construction Observations

General observations on the civil construction with respect to underground construction are below.

1. Cost Comparisons, Cost Accuracy: It is difficult to make a direct comparison of the costs presented for the eight options requested by the DOE from a facilities perspective. Hence, the committee agrees there is significant uncertainty in the cost estimates and should be considered accurate to one significant digit. The common impression is that there is considerably more upside (worsening risk) than downside (cost improvements).

2. Design Maturity: The DUSEL Preliminary Design Review (PDR) was recently completed and has undergone a favorable (although internal) review assessment. The DUSEL Plan B (facilities at the 4850ft level) and Plan C (facilities at the 7400ft level) are drawn from some fairly advanced engineering studies.

   The LBNE work is still an effort “in-progress.” Here too cost minimization has been a driver but it is not yet obvious that the less expensive proposals have completed internal project reviews. Again, upward pressure on associated costs is likely. The LAr facility at Homestake, if taken as a standalone facility, will minimally use the rest of the facility envisioned in the DUSEL PDR. This minimal use both suggests the abandonment of much of the recently restored facility, and even brings into question the location at Homestake at all, since almost the only feature in common with the rest of the Homestake facility envisioned for the NSF proposal is the distance from Fermilab for the long baseline.

   No detailed engineering to support the two experiments at SNOLAB envisioned in the DOE charge to this committee has been performed. Extrapolated costs from past experience probably have about the same level of accuracy (or better) than the six options at Homestake.

3. Market Conditions: Prevailing market conditions in the mining/underground construction industry will influence the number of bidders and the competiveness of the bids. The committee estimates market conditions can influence award pricing from -10% to +10%. Further, SNOLAB construction will be sensitive to demands of the mining cycle.

4. Differing site conditions are a fact of life underground. Given the recent experience mining smaller openings at SUSEL in the same Yates rock mass (rock support increments, overbreak volumes), and NuMI DSC’s encountered in the glacial till and upper bedrock at Fermilab a significant allowance for geo-variability is deemed appropriate.

5. Any standalone experiment at Homestake without LBNE as a partner does not appear feasible from a cost/benefit comparison.

6. The location of a Liquid Argon experiment at Homestake does not require or preserve much, if any, of the Homestake infrastructure.

7. Considerably more engineering to bring these options to the level of the DUSEL proposal for NSF is advisable to make further standalone choices.

5.2 LBNE WCD 200kt Construction Observations

1. Complete and Reasonable Design: The committee considers that the designs are at a level of completeness consistent with a pre-conceptual level of design. The committee considers that the designs form a reasonable basis for a pre-conceptual level basis of estimate.
2. Geotechnical Uncertainties: Rock conditions at 4850ft level (Yates Amphibolite) are considered to be generally good. There may be an opportunity to optimize the cavern site based on further site investigation work that has yet to be performed. Soil and rock conditions are relatively well defined across the Fermilab site.
3. Design of Key Structures: The recent proposal to double the detector volume may result in increased requirements for rock support and monitoring. A larger cavity span may also allow for a reduction in the amount of drift excavation external to the cavity volume. As the design progresses the liner-excavation interface will need special attention to ensure that load conditions and time-dependent rock wall (shotcrete)-liner differential movements can be tolerated by the selected plastic membrane material (a similar membrane system was used on the IMB experiment). At Fermilab, an elevated beamline options was presented. If acceptable, this option could allow for substantial cost reduction relative to deep-based options. However, the technical feasibility/acceptability of this option is still under review.
4. Estimating Methods: The 100kt facility costs were developed using bottoms-up estimating methods. Linear extrapolations were used to cost 150 and 200kt options. At Fermilab cost estimates were developed by in-house staff and outside consultants.
5. Schedule: A schedule for construction of the 200kt has not yet been fully developed (change only recently implemented). This schedule will be needed to ensure that parallel excavation activities on 4850ft level and below do not result in activity interference or ventilation and/or muck bound operation.
6. Given the longer duration of the excavation work for a 200kt cavity there is an increased possibility that ventilation and waste rock removal capacities may constrain production rates.

5.3 LBNE LAr 34kt Construction Observations

1. Complete and Reasonable Design: The committee considers that the designs are at a level of completeness consistent with a pre-conceptual level of design. The committee considers that the designs form a reasonable basis for a pre-conceptual level basis of estimate.
2. Geotechnical Uncertainties: The LAr cavern site has not been investigated. Faulting has been mapped in the vicinity, but there may be an opportunity to optimize siting based on investigation work. Soil and rock conditions are relatively well defined across the Fermilab site.
3. Design of Key Structures: The cavern required to house the LAr detectors is large and the impact of stiffness contrasts between the concrete veto drifts and rock material will need to be studied in detail once an appropriate site is selected. At Fermilab, an elevated beamline options was presented. If acceptable, this option could allow for substantial cost reduction relative to deep-based options. However, the technical feasibility/acceptability of this option is still under review.
4. The site is accessed from the hill side. Some delays and construction costs could be incurred mitigating community concerns.

5.4 Common Preliminary Design “Surface to 4850ft Level”

1. Complete and Reasonable Design: The committee considers that the designs are generally at a level of completeness consistent with a preliminary level of design. The committee considers that the designs form a reasonable basis for preliminary basis of estimate. Headframe and shaft structures have been studied in detail and rehabilitation scopes-of-work for the two shaft frame structures, to depth, are well defined
2. Geotechnical Uncertainties: Ground conditions in the shafts are not well known. Visual assessments are rendered difficult by the presence of lacing. Zones of broken rock/rubble are present and a section of the Ross Shaft Pillar is subject to on-going deformation.
3. Design of Key Structures: Headframe and guide design work is well advanced in both shafts. The scope for ground support replacement is less well defined. Additional effort will be needed to collect as-builts that can support a more accurate quantification of support replacement needs (to meet OSHA design standards), including in the Ross Pillar area.

4. Value Engineering: The committee feels that opportunities for value engineering will emerge during the final design process and encourages continued interaction between members of the IAB, DUSEL and SUSEL staff.
5. Significant levels of recurring cost may be associated with support and alignment work to limit and compensate for the deformation of the Ross Pillar, and replacement costs on big ticket items (e.g. hoist rope/crusher liners/conveyor belting/etc. replacement). These items may be covered in the operating costs section.
6. Oro Hondo Ventilation Shaft: The shaft walls are progressively failing. The shaft may become partially or totally blocked during the life of the facility. A contingency plan is being developed to ensure ventilation continuity should the shaft become blocked at height.
7. Added Contingency: Pending the collection of additional as-built information on the state of ground supports in the shafts (Yates, Ross, Oro Hondo) contingency is needed to account for uncertainty in the estimate for example, % of rubble removal, scaling and ground support work.
8. The amount of rubble rock and deteriorated support work that will need removal and replacement to meet OSHA standards as part of both the Yates and Ross rehabilitation work has been estimated without the benefit of shaft ground support as-builts. The new ground support design will need to be sufficiently robust to provide for shaft stability for the targeted period of operation.
9. The level of rehabilitation and ground support work needed to provide adequate long-term shaft stability in the Ross Pillar area (reduced rate of convergence/squeeze) is also difficult to estimate without further study.

Summary: The contingency spread (-25 to +50%) is a simple addition of best case and worst case contingencies. These may be considered to represent extreme values, but are considered to be a reasonable contingency range for these major underground works, prior to collecting additional information on the needed amounts of ground support replacement and Ross Pillar conditions.

5.5 LBNE at Fermilab Construction Observation

1. The committee considers that the designs are at a level of completeness consistent with a pre-conceptual level of design. The committee considers that the designs form a reasonable basis for a pre-conceptual level basis of estimate.
2. Soil and rock conditions are relatively well defined across the Fermilab site.

5.6 Double-Beta Decay and Dark Matter/3rd Generation Construction Observations at 4850ft Level

1. Complete and Reasonable Design: The committee considers that the designs are generally at a level of completeness consistent with a preliminary level of design. The committee considers that the designs form a reasonable basis for a preliminary basis of estimate.
2. Geotechnical Uncertainties: The module location has been recently realigned. A small tunnel exists along this new alignment. This tunnel provides key information on expected rock conditions. Some additional borehole work may be required to investigate arch conditions but confidence in the site-specific rock conditions is already high.
3. Design of Key Structures: It is considered that caverns of a span of between 15m and 20m at the proposed site can be effectively stabilized using the conventional mining techniques identified by the designer. Some local geotechnical issues requiring mitigation may be expected.
4. Scope Growth and Increased Design Specification: As the designs progress and become more detailed the subcommittee thinks it will be difficult to avoid scope growth and the addition of some tough specifications, as required to meet the end-user needs.
5. Value Engineering: The committee feels that some opportunities for value engineering will emerge during the design process and encourages continued interaction between members of the Collaborations, IAB, DUSEL and SUSEL staff.
6. Given the longer duration of other excavation work that may be undertaken at the 4850ft level (e.g. LBNE WCD 150 or 200kt) and below there is an increased possibility that the site’s limited ventilation and waste rock removal capacities may constrain excavation productivities.

5.7 Homestake Common Conceptual Designs “4850ft to 7400ft Level” Construction Observations

1. Complete and Reasonable Design: The committee considers that the designs are generally at a level of completeness consistent with a conceptual level of design. The committee considers that the designs form a reasonable basis for a conceptual basis of estimate.
2. Geotechnical Uncertainties: The site is currently under water and no site specific site investigation has yet been performed. Assessments of ground conditions and support needs at depth are based on Homestake records and the technical input of former Homestake mine personnel. Local zones of adverse geotechnical conditions (geo-structural planes of weakness and high stress) are anticipated at depth. However, there may be opportunities to minimize the impact of adverse ground by optimization of the facility layout based on the results of a comprehensive site investigation program (site investigation will be a critical element that will inform the design work).
3. Design of Key Structures: The scope of work for the #6 winze rehabilitation has been developed based on down-shaft camera inspection. No major stability issues were identified. The new suite of common structures (shafts and access tunnels) at depth will likely be subject to local instability (stress/fracture-driven). Site investigation will be required prior to developing site-specific mitigation plans.
4. Value Engineering: The committee feels that opportunities for value engineering will emerge during the design process and encourages continued interaction between design team members and outside consultants.
5. Some adverse conditions were encountered and are anticipated at the lower levels of the Homestake Mine. Design mitigation measures, based on the results of a good site investigation, should prove adequate in most cases, but some provision for construction contingency is necessary. This contingency should be increased significantly if the site investigation is minimized.

6. Given the longer duration of other excavation work that may be undertaken at the 4850ft level (e.g. LBNE WCD 150 or 200kt) and below there is an increased possibility that the site's limited ventilation and waste rock removal capacities may constrain excavation productivities.

5.8 Double-Beta Decay and Dark Matter/3rd Generation Conceptual Designs at the Homestake 7400ft Level

This judgment-based contingency category assesses the design stage of the conventional construction elements of the project.

1. Complete and Reasonable Design: The committee considers that the designs are generally at a level of completeness consistent with a conceptual level of design. The committee considers that the designs form a reasonable basis for a conceptual basis of estimate.
2. Geotechnical Uncertainties: The site is currently under water and no site-specific site investigation has yet been performed. Assessments of ground conditions and support needs at depth are based on Homestake records and the technical input of former Homestake mine personnel. Local zones of adverse geotechnical conditions (geo-structural planes of weakness and high stress) are anticipated at depth. However, there may be opportunities to minimize the impact of adverse ground by optimization of the facility layout based on the results of a comprehensive site investigation program (site investigation will be a critical element that will inform the design work).
3. Design of Key Structures: The laboratory module structures at depth will likely be subject to local instability (stress and/or fracture-driven). Site investigation will be required prior to developing site-specific mitigation plans, but it is considered that caverns of a span of between 15 and 20m can be effectively stabilized using the conventional deep mining techniques identified by the designer.
4. Scope Growth and Increased Design Specification: The conventional designs of the modules represent a basic level of fit-out. As the designs progress and become more detailed the committee thinks it will be difficult to avoid scope growth and the addition of some tough specifications needed to meet the end-user needs of this challenging facility.

5. Value Engineering: The committee feels that opportunities for value engineering will emerge during the design process and encourages continued interaction between members of the Collaborations, IAB, DUSEL and SUSEL staff.
6. Some adverse conditions were encountered and are anticipated at the lower levels of the Homestake Mine. Design mitigation measures, based on the results of a good site investigation, should prove adequate in most cases, but some provision for construction contingency is necessary. This contingency should be increased significantly if the site investigation level of effort is minimized.
7. Given the longer duration of other excavation work that may be undertaken at the 4850ft level (e.g. LBNE WCD 150 or 200kt) and below there is an increased possibility that the site's limited ventilation and waste rock removal capacities may constrain excavation productivities. .

5.9 SNOLAB

5.9.1. Construction description - dark matter or double-beta decay experiments housed in existing cavern facilities

Proposing collaborations should be encouraged to develop SNOLAB-specific designs that minimize or eliminate the need for space creation, and requirements for new or upgraded infrastructure. The cost-effectiveness of experiment deployment at SNOLAB can be increased significantly and the time-to-physics reduced, if experiments can be designed to be built and operated within SNOLAB's existing space under the facilities' established installation and operational constraints. Resources required to make significant modifications to existing SNOLAB space and infrastructure capacities will likely be non-negligible.

No site investigation has been performed to identify a site(s) for a new cavern at SNOLAB. However, it is anticipated that a site, adjoining the complex can be identified that is suitable for new cavern construction. Away from the mine workings, the Norite hanging wall has already proven itself to be a good host rock material for the major SNO excavation and other SNOLAB facilities.

Pending the acquisition of site-specific data it is reasonable to assume that cavern spans in the range required to house DM and DBD experiments (15-25m) can be effectively mined and stabilized using similar construction and design methods to those employed on SNO and SNOLAB. New site investigation work will be needed to confirm these assumptions and investigate rock conditions prior to selecting a site and developing a site-specific design for a new cavern facility.

5.9.2. Cost comments - new dark matter or double-beta decay cavern facilities

Pending the development of a site specific design, a screening-level estimate of duration and cost was developed with the help of the SNOLAB Team. The design and construction duration was estimated at three years. The basis for the $30M estimate is derived from actual costs of the SNOLAB cryopit, excavation completed 2008. The size of the cryopit cavern is 15m dia x 20m ht (~4,000 m3). A pit of this size is seen as roughly sufficient to support a 3rd generation DM experiment. Total actual historical costs for the cryopit project (management, design, underground construction and some infrastructure) was CA$15M. Including 20% markup for design and project management, 50% contingency/escalation and an assumption that the full utilities and infrastructure would require another $5M, brings the total to approximately $30M. A conceptual design and supporting cost estimate is necessary to validate this rough estimate.

The cost advantages for construction at SNOLAB versus Homestake are primarily due to the presence of a commercial mining operation on the SNOLAB site as well as new excavations only need to support the marginal costs of excavation and specific infrastructure. Most general infrastructure costs at SNOLAB (mobilization, power, water, ventilation, shafts, emergency support, etc.) are already in place whereas Homestake requires substantial infrastructure investment to support a functional underground science facility.

6.0 Operations Considerations

Homestake's current on-site operations and maintenance staff of 102 FTEs are an experienced core group who has the capability to oversee the Homestake site. Their vast, shared knowledge of the facility enable them to move forward with the maintenance and rehabilitation of the shafts, conveyances and other hoist equipment. Their approach to work safety including new infrastructure improvements like redundant communication feeds, modern monitoring equipment, proper operating procedures and training all contribute to safely operating the site and maintaining control of the hoist while overseeing contractors doing the civil construction and outfitting.

Understanding operation costs was difficult to confirm and compare. In Value Engineering (VE) measures, large pieces of the base project have been removed from the more detailed Preliminary Design Report. The operations shown in the PDR are based on all in-house work and range from $70-$121M per year which includes complete rehabilitation of the shafts and all excavations done with in-house staff. These operations had a staff ranging from 180-230 FTEs.

The new cost model places the experiment excavation as part of their cost instead of the facility. While it helps to understand each experiment cost it makes it more difficult to understand the common costs that are shared with so many different variables.

The estimate for FY12 including Sanford contribution is ~$18M with a staff of ~85 FTE's.

- DUSEL Plans B/C uses a reduced staff of 112-132 FTE's $18-23M/year.
- Standalone WCD shows a reduced staff of ~55 FTE's and a $9-13M/year operating cost but assumes that some portion of the maintenance is done via outside contractor, plus assumes complete shaft rebuilds.
- Standalone LAr at the 800ft level shows a reduces staff of ~32 and a $8-11M/year costs with outside maintenance help and no rebuild of the Yates Shaft and the Ross shaft down to 1500ft level.

Most of the operations estimates shown during the review ranged around $15M. This did not include any contingency. 30-40% should be added to this total since the scope is not clearly defined. A range of $18-23M/year as shown with the plan B/C options would be more appropriate.

6.1 Construction and Cost - Shaft Upgrades

It is critical to the success of the Homestake site that the shaft structures provide reliable service to the underground facilities. The Yates and Ross shafts were built over 75 years ago and the furnishings and surrounding rock structures have been subject to many of the deterioration mechanisms commonly encountered in operating mine shafts (rock wall loosening and deformation, corrosion, mechanical and fatigue damage, and wear). For the shafts to provide the long-term reliability essential to support both construction and laboratory activities a full upgrade of the Yates and Ross shafts is required. The upgrade scope should be consistent with the recommendations of the Infrastructure Advisory Board (IAB). Notably, the waste rock handling capacity should be maintained at the 3000 tpd level. In addition, to ensure the maintenance of adequate long-term ventilation, one of the two up-cast shafts (Oro Hondo or Number 5) should be sufficiently cleared and stabilized to guarantee a minimum level of air flow.

Cost Comments: As noted above, for the shafts to provide a reliable level of service a full upgrade of both shafts is considered essential. The design associated with headframe, in-shaft framing and guide work is well advanced (probably beyond a preliminary level of design) for both shafts. However, the design of the new ground supports in the shafts is less well defined. Although there are opportunities for cost reduction as the scope of the ground support work is better defined, there is also significant potential for cost growth.

From both a safety and a schedule risk standpoint, a complete rehabilitation of both shafts is required. While both shafts operate with a sprinkler system to reduce fire damage, the fuel load is high in the timber lined Yates Shaft. One of the VE suggestions was to remove redundant power and communication feeds. With working staffs of over 200 FTE's underground and sensitive detectors relying on these utilities infrastructures having redundant feeds for maintenance purposes is critical because of the large number of non-miners employed underground.

Operating a deep underground laboratory with a decade of civil construction (200kt WCD) while operating multiple facilities would be very difficult if the shaft maintenance plans suggested in Plan B are in effect. Plan B/C models use a module of assigning a shift per day for shaft upkeep and maintenance. Because the shafts have not been rehabilitated this greatly reduces the payload and the conveyance speeds as shown the chart below.

	FURNISHING REPLACEMENT	GROUND SUPPORT	CAGE	CAGE CAPACITY	SKIPPING CAPACITY
Yates Shaft					
Plan B/C	50% timber	Timber	Existing	5 tons, 800fpm	N/A
Baseline	100% Concrete/Steel	Bolts/ shotcrete	supercage	20 tons, 1500 fpm	N/A
Ross Shaft					
Plan B/C	20% steel	Bolts/ shotcrete	Existing	4 tons, 800fpm	1500 tpd
Baseline	50% steel	Bolts/shotcrete	Existing	6 tons, 1600 fpm	3300 tpd

Table 6: Yates Shaft and Ross Shaft Payload and Conveyance Speeds

Studies done in the PDR baseline showed that hoist usage spiked to full capacity with the smaller 100kt WCD. With the reduced loads and speeds, plus increased maintenance construction schedules would have to increase.

The removal of Super Cage design in the Yates shaft also increases the number of hoist trips required for detector assembly. Reduction in the size and weight of the payload to build the large detectors also potentially increases installation costs by the increased labor required underground. Again this increases the detector construction period.

6.2 Safety Considerations - Shaft Upgrades

General observations on the civil construction with respect to safety are below:

1. Over the past year, Homestake has experienced a serious injury underground, a major dropped load, a fire, and an incident in the shaft. These incidents are not acceptable for an underground science facility. On the positive side, the staff has gradually become aware of DOE safety expectations for modern research facilities. The infrastructure improvements necessary to bring Homestake up to an acceptable level of performance have been identified, and resource-loaded schedules that would accomplish the upgrades exist. To date, significant improvements have been made to the Homestake mine and shaft support facilities to support research. However, prior to moving into underground scientific activities, the probability of a significant accident must be low.

2. Homestake has improved their safety program over the last few years as concluded by a committee site visit on April 21, 2011. Emergency response, training and the core group overseeing the safety program are impressive and support a continuously improving safe environment. It is important to continue supporting safety measures like removing fire load in the Yates shaft to reduce the potential life safety risk.
3. The shafts at Homestake must be brought to current requirements before significant scientific activities can be initiated. A number of studies on the shafts and lifts have been conducted, and all identify major structural issues with both shafts. Canadian experts stated they would rehab the shafts and lifts underground including; refitting the shafts, replacing the motors, controls, and cables, and rework the headstock, within 1-2 years, and felt waiting for years to perform the repairs was absurd.
4. Homestake's ventilation system was never designed to handle quantities of cryogenic gases underground. The large detectors proposed, plus the supporting equipment will place heretofore unimagined (at Homestake) gases underground, and a release will threaten all those above and below the release level. The alternative locations have some experience with cryogens in research applications, but will require an analysis of the maximum credible releases, and an evaluation of the ability of the system to detect releases and maintain acceptable levels of oxygen where staff may be present. Again, heavier-than-air gases threaten those at lower levels (including evacuation routes), while lighter-than-air gases threaten higher levels and evacuation routes. Reliance on rough ventilation shafts and routing if gas through walkways simply will not support the research envisioned over the coming decades.
5. Homestake has significant fire hazards already underground (motor control centers, pump stations, cabling) but no fire detection or suppression system that would pass muster at any modern research facility. Modern fire detection and suppression systems must be installed and while this effort is not a large it requires careful consideration as activities increase.
6. The electrical distribution system is at best suitable for mining activities. The flexibility of the system, back-up and UPS requirements, and NFPA/National Electrical Code standards must be considered now so that when research begins the infrastructure support will be ready.

7.0 Cost and Schedule Summary

A summary of cost ranges and rough schedule durations for each scenario evaluated by the committee in response to the charge for the review is provided in *Table 9*. Included in the table are several additional scenarios that reflect opportunity for the various experimental programs to share facility, infrastructure, and common costs if implemented together at one facility.

The cost and schedule values in the summary table are derived from the data submitted to the agency by the various collaborations, provided in papers and presentations to the committee at the review, and referenced in earlier sections of this report. In the majority of cases the committee found the collaborations' estimates to be reasonable and consistent with the facility or experiment project design phase.

The cost and schedule estimates contained in *Table 9* have bases of estimates that vary from pre-conceptual (many of the experiments) to fairly advanced design (the DUSEL PDR for Homestake). The estimate ranges for experiments and facilities are based primarily on alternate scopes of work (e.g., different sizes of detectors, alternate detector technologies, alternate facility sizes and depth).

Facility costs are driven by the cost of safely accessing spaces deep underground; creating large, stable, long-lived excavations at depth; and fabricating, testing, installing, and operating sensitive detectors in this unique environment over long periods of time. Most proposed experimental programs are pushing the state of detector art, using expensive liquids, gases, and crystals requiring significant design efforts, costly experimental apparatus, and unique supporting infrastructure to ensure a successful deployment and safe, reliable long term operation.

Much has been learned from the actual construction and operation of existing underground facilities and detailed planning for new facilities, nevertheless, significant risks and uncertainties will accompany any chosen future scenario. Many risks and uncertainties have been described in previous sections of this report.

Table 7 summarizes major internal and external risks and uncertainties that will influence the cost and duration of any underground project(s) undertaken. The majority of risks are related to facility design and construction, but many risk elements are also relevant for the various experimental programs envisioned.

Internal Risk and Uncertainty	External Risk and Uncertainty
Design Maturity	Funding - Availability and Timing
Size and Depth of Excavations	Stakeholder Support
Underground Infrastructure Requirements	National Environmental Protection Act / National Historical Preservation Act Compliance
Design Criteria/Codes and Standards (DOE vs. Industry)	Management Organization
Safety Requirements and Performance	Construction, Installation, Operations Contracts
Integration of Multiple Experiments	Market Conditions
Escalation	

Table 7: Major Risks and Uncertainties Influencing Cost and Duration of Underground Projects

Key internal project risks and uncertainty (stemming from technical or scope-related concerns and generally within the control of the project owner) include the ultimate size and depth of required excavations to house and service selected experiments; the codes and standards governing all aspects of facility design needed to meet statutory and agency requirements; and all safety related systems needed to protect workers and experimenters during design, construction and operation phases.

External risks arise from programmatic or political concerns, often originate in organizational or contractual relationships, and while they may be influenced they are not controlled by project owners. The amount and timing of available funds is the primary external risk, but strong support from the science community and the public will be needed to drive the overall schedule of a very complex, costly, and long duration portfolio of activities. Market conditions at the time of construction start will have a significant influence on amount of competition for the proposed work as well as cost of materials and supplies. Establishing and supporting an appropriate management organization for overseeing activities at locations distant from DOE facilities will also be a consideration.

After discussion among the committee about the data contained in *Table 10*, the committee decided to adjust the estimates to reflect higher levels of contingency suggested by committee members. Also, the cost of stripping and reequipping the Yates Shaft was added to virtually every scenario. *Table 8* provides the general relationships among project design maturity, level of scope definition, and typical amounts of contingency used for projects at each design phase. The scope definition and contingency entries in the table reflect historical experience in SC.

Design Maturity	Scope Definition	Contingency Range
Pre-Conceptual	1% to 15%	> 50%
Conceptual	10% to 40%	40% to 50%
Preliminary Design	30% to 70%	30% to 40%

Table 8: General Relationships

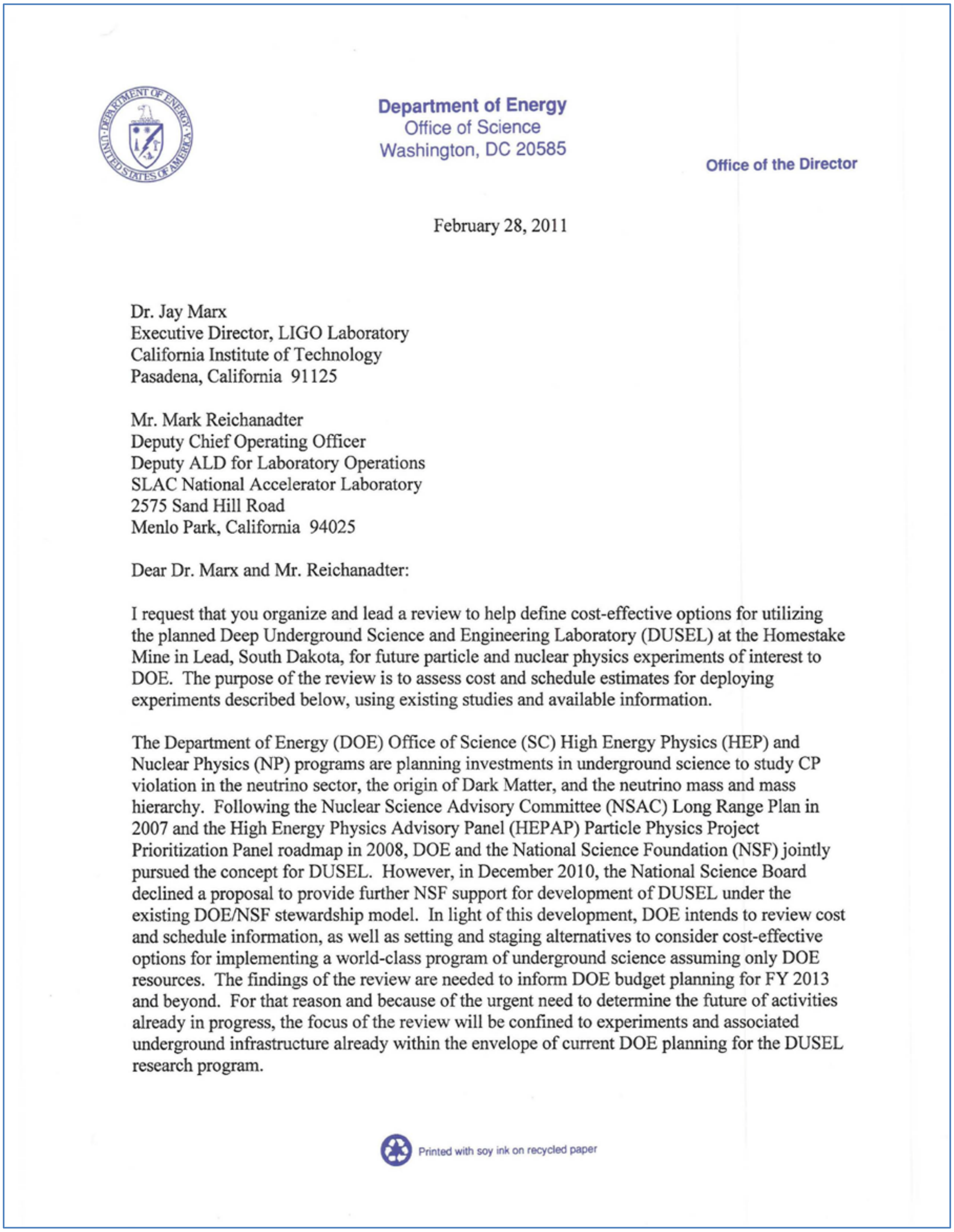
The level of design maturity and associated contingency range was used by the committee to adjust the amounts of contingency included in the facility or experiment estimates.

Experiment	Location	Depth	Experiment Cost Range (2011 $M)		Facility Cost Range (2011 $M)		TPC Range (2011 $M)		Committee Adjusted TPC Range (2011 $M)		Schedule Duration (Years)	Annual Operating Cost (avg.) (2011 $M)*
			Low	High	Low	High	Low	High	Low	High		
	Scenarios Requested in Review Charge											
LBNE w/WCD	Homestake	4850	414.8 (150kt)	517.1 (200kt)	712.5 (150kt)	959.2 (200kt)	1127.3	1476.3	**1200**	**1500**	10-12	18-23
LBNE w/LAr	Homestake	800	498.6 (24kt)	698.4 (34kt)	478.9 (24kt)	637.0 (34kt)	977.5	1335.4	**1000**	**1400**	10-12	18-23
DM	Homestake	4850	80	100	140	380	220	480	**300**	**800**	8-10	20
DBD	Homestake	4850	200	300	140	380	340	680	**400**	**800**	8-10	20
DM	Homestake	7400	80	100	280	520	360	620	**450**	**700**	8-10	20
DBD	Homestake	7400	200	300	280	520	480	820	**600**	**950**	8-10	20
DM	SNOLAB	6400	80	100	30	30	110	130	**100**	**150**	8-10	n/a
DBD	SNOLAB	6400	200	300	30	30	230	330	**230**	**400**	8-10	n/a
	Scenarios that Leverage Potential for Shared Facility, Infrastructure, and other Common Costs											
DM+DBD	Homestake	4850	280	400	160	390	440	790	**560**	**930**	8-10	20
DM+DBD	Homestake	7400	280	400	290	530	570	930	**700**	**1100**	8-10	20
DM+DBD	SNOLAB	6400	280	400	60	60	340	460	**400**	**550**	8-10	n/a
LBNE w/WCD+DM+DBD	Homestake	4850/4850	694.8	917.1	872.5	1119.2	1567.3	2036.3	**1600**	**2100**	10-12	18-23
LBNE w/LAr+DM+DBD	Homestake	800/4850	778.6	1098.4	838.9	997	1617.5	2095.4	**1700**	**2300**	10-12	18-23
LBNE w/WCD+DM+DBD	Homestake	4850/7400	694.8	917.1	1002.5	1249.2	1697.3	2166.3	**1800**	**2300**	10-12	18-23
LBNE w/LAr+DM+DBD	Homestake	800/7400	778.6	1098.4	978.9	1137	1757.5	2235.4	**1900**	**2400**	10-12	18-23
Legend – Color Coding for Overall Experiment and Facility Design Maturity in Above Scenarios												
Pre-Conceptual			**Conceptual**				**Preliminary Design**					

* LBNE annual operating cost for Fermilab Near Detector and beamline are not included.

Table 9: Summary of Cost Ranges and Rough Schedule Durations

Appendix A – Charge



Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

February 28, 2011

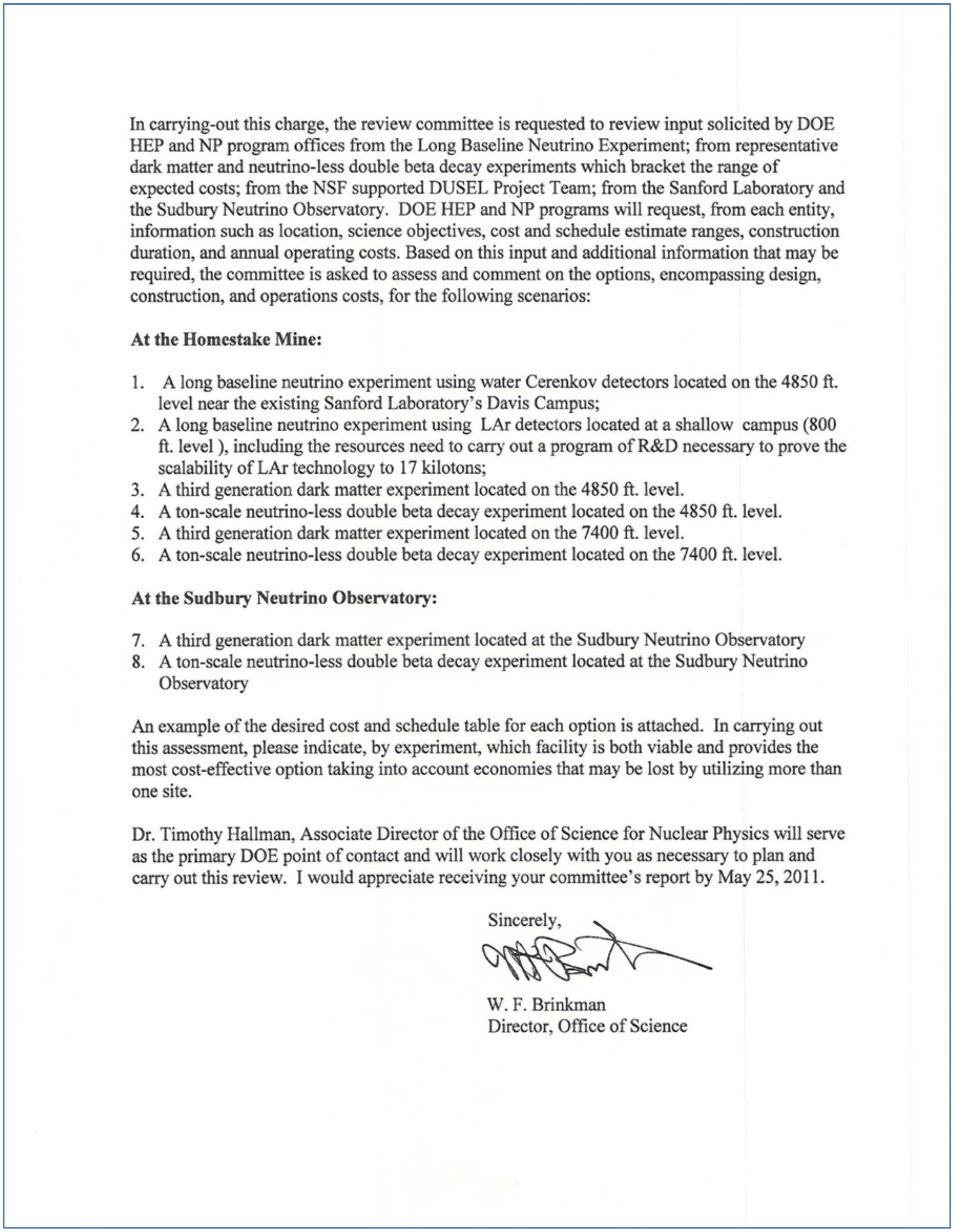
Dr. Jay Marx
Executive Director, LIGO Laboratory
California Institute of Technology
Pasadena, California 91125

Mr. Mark Reichanadter
Deputy Chief Operating Officer
Deputy ALD for Laboratory Operations
SLAC National Accelerator Laboratory
2575 Sand Hill Road
Menlo Park, California 94025

Dear Dr. Marx and Mr. Reichanadter:

I request that you organize and lead a review to help define cost-effective options for utilizing the planned Deep Underground Science and Engineering Laboratory (DUSEL) at the Homestake Mine in Lead, South Dakota, for future particle and nuclear physics experiments of interest to DOE. The purpose of the review is to assess cost and schedule estimates for deploying experiments described below, using existing studies and available information.

The Department of Energy (DOE) Office of Science (SC) High Energy Physics (HEP) and Nuclear Physics (NP) programs are planning investments in underground science to study CP violation in the neutrino sector, the origin of Dark Matter, and the neutrino mass and mass hierarchy. Following the Nuclear Science Advisory Committee (NSAC) Long Range Plan in 2007 and the High Energy Physics Advisory Panel (HEPAP) Particle Physics Project Prioritization Panel roadmap in 2008, DOE and the National Science Foundation (NSF) jointly pursued the concept for DUSEL. However, in December 2010, the National Science Board declined a proposal to provide further NSF support for development of DUSEL under the existing DOE/NSF stewardship model. In light of this development, DOE intends to review cost and schedule information, as well as setting and staging alternatives to consider cost-effective options for implementing a world-class program of underground science assuming only DOE resources. The findings of the review are needed to inform DOE budget planning for FY 2013 and beyond. For that reason and because of the urgent need to determine the future of activities already in progress, the focus of the review will be confined to experiments and associated underground infrastructure already within the envelope of current DOE planning for the DUSEL research program.



In carrying-out this charge, the review committee is requested to review input solicited by DOE HEP and NP program offices from the Long Baseline Neutrino Experiment; from representative dark matter and neutrino-less double beta decay experiments which bracket the range of expected costs; from the NSF supported DUSEL Project Team; from the Sanford Laboratory and the Sudbury Neutrino Observatory. DOE HEP and NP programs will request, from each entity, information such as location, science objectives, cost and schedule estimate ranges, construction duration, and annual operating costs. Based on this input and additional information that may be required, the committee is asked to assess and comment on the options, encompassing design, construction, and operations costs, for the following scenarios:

At the Homestake Mine:

1. A long baseline neutrino experiment using water Cerenkov detectors located on the 4850 ft. level near the existing Sanford Laboratory's Davis Campus;
2. A long baseline neutrino experiment using LAr detectors located at a shallow campus (800 ft. level), including the resources need to carry out a program of R&D necessary to prove the scalability of LAr technology to 17 kilotons;
3. A third generation dark matter experiment located on the 4850 ft. level.
4. A ton-scale neutrino-less double beta decay experiment located on the 4850 ft. level.
5. A third generation dark matter experiment located on the 7400 ft. level.
6. A ton-scale neutrino-less double beta decay experiment located on the 7400 ft. level.

At the Sudbury Neutrino Observatory:

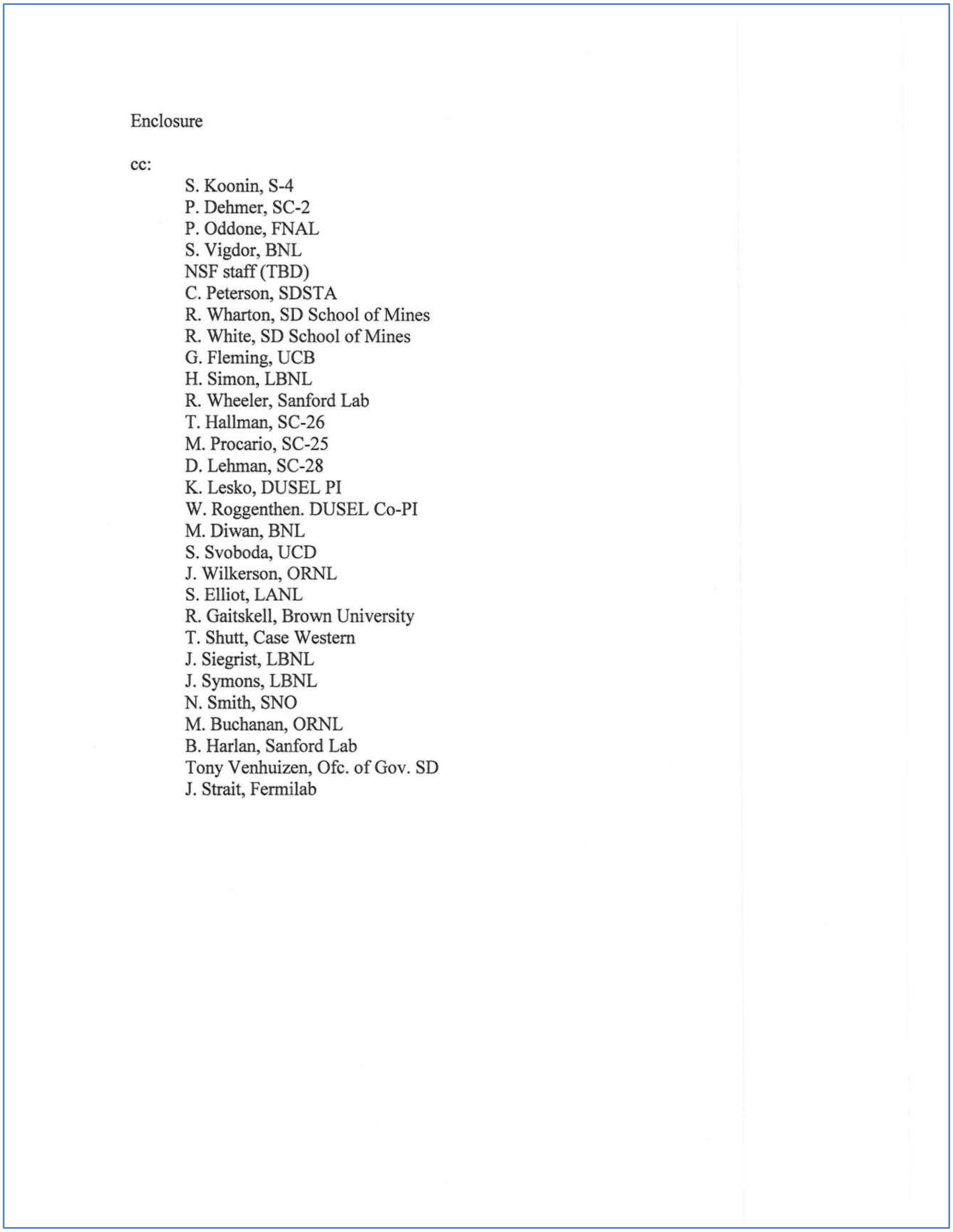
7. A third generation dark matter experiment located at the Sudbury Neutrino Observatory
8. A ton-scale neutrino-less double beta decay experiment located at the Sudbury Neutrino Observatory

An example of the desired cost and schedule table for each option is attached. In carrying out this assessment, please indicate, by experiment, which facility is both viable and provides the most cost-effective option taking into account economies that may be lost by utilizing more than one site.

Dr. Timothy Hallman, Associate Director of the Office of Science for Nuclear Physics will serve as the primary DOE point of contact and will work closely with you as necessary to plan and carry out this review. I would appreciate receiving your committee's report by May 25, 2011.

Sincerely,

W. F. Brinkman
Director, Office of Science



Enclosure

cc:

S. Koonin, S-4
P. Dehmer, SC-2
P. Oddone, FNAL
S. Vigdor, BNL
NSF staff (TBD)
C. Peterson, SDSTA
R. Wharton, SD School of Mines
R. White, SD School of Mines
G. Fleming, UCB
H. Simon, LBNL
R. Wheeler, Sanford Lab
T. Hallman, SC-26
M. Procario, SC-25
D. Lehman, SC-28
K. Lesko, DUSEL PI
W. Roggenthen. DUSEL Co-PI
M. Diwan, BNL
S. Svoboda, UCD
J. Wilkerson, ORNL
S. Elliot, LANL
R. Gaitskell, Brown University
T. Shutt, Case Western
J. Siegrist, LBNL
J. Symons, LBNL
N. Smith, SNO
M. Buchanan, ORNL
B. Harlan, Sanford Lab
Tony Venhuizen, Ofc. of Gov. SD
J. Strait, Fermilab

Appendix B – Committee Membership

Review Team Co-Chairs

Marx, Jay	LIGO
Reichanadter, Mark	SLAC

Overview of Science Alternatives

Shochet, Melvyn J *	University of Chicago
Henderson, Stuart	FNAL

3rd Generation Dark Matter Experiment

Breidenbach, Marty *	SLAC
Seestrom, Susan	LANL

Double-Beta Decay Experiment

Symons, James *	LBNL
Gordon, Howard A.	BNL

Neutrino Physics Experiment

Conrad, Janet *	MIT
Sciulli, Frank	Columbia
Wojcicki, Stan	Stanford

Conventional/Underground Facilities

Bogert, Dixon *	FNAL
Kornegay, Frank	ORNL
Laughton, Chris	Consultant
Miller, William	Soudan Underground
Wightman, Toby	Wightman Associates

Cost and Schedule

Herron, Suzanne *	ORNL
Lutha, Ronald	DOE
Meador, Steve	DOE/SC

* Subcommittee Chair

Appendix C – Agenda of Meetings

DOE Office of Science Independent Review Of Options for Underground Science

April 13-15, 2011

Wednesday, April 13

Plenary, Kavli Auditorium, Building 51, Room 102

8:00 am	Executive Session	J. Marx, M. Reichanadter
8:45	Welcome	P. Drell
9:00	Underground Science Requirements and Experimental Capability Drivers	R. Svoboda, H. Nelson, E. Beier
10:30	Break	
10:45	Long Baseline Neutrino Experiment	J. Strait
12:15 pm	Lunch	
1:30	3rd Generation Dark Matter Experiment	H. Sobel
3:00	Break	
3:15	Neutrinoless DBD Experiment	J. Wilkerson, G. Gratta
5:00	Executive Session	Executive Committee
7:00	Adjourn	

Thursday, April 14

Plenary, Cypress Conference Room Building 40, Room 147

8:00 am	Input from DUSEL PDR	K. Lesko, J. Yeck, R. Wheeler
10:30	Break	
10:45	SNO Infrastructure Capability Assessment	N. Smith
11:30	Individual Breakouts (see following pages)	

Thursday, April 14

SESSION 1 – 3rd Generation Dark Matter Experiment Redwood Conference Room, Building 48, Room 112A

11:30am	DM Consensus Positions	B. Sadoulet
12:30 pm	Lunch	
1:30	LZ	T. Shutt, R. Gaitskell
1:45	MAX	C. Galbiati, E. Aprile
2:00	GEODM	S. Golwala, B. Cabrera
2:15	COUPP	J. Collar, A. Sonnenschein
2:30	CLEAN	D. McKinsey, A.Hime
2:45	Discussion	Group
3:00	Break	
3:15	Joint Session w0v2β with Nigel Smith	Group
3:45	Joint Session continued	Group
4:15	Continued discussion as needed	Group
5:00	Executive Session	Executive Committee
7:00	Adjourn	

Thursday, April 14

SESSION 2 – Double-Beta Decay Experiment, Redwood Conference Building 48, Room 112B

11:30am	EXO Follow-up	G. Gratta
12:15 pm	Lunch	
1:30	Majorana Follow-up	S. Elliott
2:15	Discussion of Backgrounds	J. Wilkerson
3:00	Break	
3:30	Joint Discussion with Dark Matter Group	Group
4:15	Joint Discussion with Dark Matter Group with Nigel Smith	Group Group
4:30	Final Discussion	Executive Committee
5:00	Executive Session	
7:00	Adjourn	

Thursday, April 14

SESSION 3 – Neutrino Physics Experiment, Redwood Conference Building 48, Room 112C

11:30am	Introduction	M. Diwan, R. Wilson
12:15 pm	Lunch	
12:45	Executive Session	Neutrino Committee
1:15	Liquid Argon: Science Technology Strengths, Risks and Issues Related to Cost and Schedule	J. Urheim, M. Soderberg, B. Baller, S. Pordes, C. Thorn, B. Fleming
3:30	Executive Session	Neutrino Committee
4:05	Beam Design/ Components – Science/Technology Strengths, Risks and Issues Related to Cost and Schedule	M. Bishai, G. Rameika
4:45	Executive Session	Neutrino Committee
5:00	Executive Session	Executive Committee

Thursday, April 14

SESSION 4 – Conventional/Underground Facilities, Cypress Conference Room, Building 40, Room 147

11:30am	Options 1-6 Common Systems	M. Headley, J. Willhite
12:15 pm	Lunch	
1:30	LBNE Conventional Facilities for WCD – Option 1	E. McCluskey
2:00	LBNE Conventional Facilities for LAr – Option 2	T. Lundin
2:30	SNO Conventional Facilities for Dark Matter	N. Smith
3:00	Break	
3:15	LBNE Conventional Facilities for Beam and Near Detector at Fermilab	T. Lundin
4:00	DUSEL Plan B continued	M. Headley, J. Willhite
5:00	Executive Session	Executive Committee
7:00	Adjourn	

Thursday, April 14

SESSION 5 – Cost and Schedule, Redwood Conference Building 48, Room 112D

11:30am	SNOLAB Operation Costs	N. Smith
12:30 pm	Lunch	
1:30	Homestake Facility Design	M. Headley, S. DeVries, D. Vardiman, R. Wheeler
2:00	LBNE Water Cherenkov	J. Stewart, J. Strait
2:30	LBNE Option	E. McCluskey, T. Lundin, J. Strait
2:50	LBNE LAr	B. Baller, J. Strait
3:10	Break	
3:30	Dark Matter Gas Based Experiments	T. Shutt, C. Galbiati
3:50	Dark Matter Ge-Based Experiments	S. Golwala
4:10	DBD EXO	G. Grata
4:30	DBD Majorana	J. Wilkerson, S. Elliott
5:00	Executive Session	Executive Committee
7:00	Adjourn	

Friday, April 15

Executive Session, Redwood Conference Room Building 48, Room 112

8:00 am	Session 4 Continuation: H20 – Science/Technology Strengths, Risks and Issues Related to Cost and Schedule	E. Kearns, C. Walter, J. Maricic, M. Sanchez, M. Vagins
10:00	Executive Session	Session 4 Committee
10:30	Break	
10:45	Executive Session	Executive Committee
1:30 pm	Adjourn	

DOE Site Visit Agenda, Homestake on April 21, 2011

April 20, 2011	Travel to Deadwood, South Dakota (fly to Rapid City)
April 21, 2011	Administration Building @ Sanford Lab, Lead, SD
8:00 am	Coffee and introductions (Ron Wheeler)
8:30	Overview of the Sanford Laboratory
9:30	To Ross Dry for safety training
10:00	Underground tour of 4850 level. (limit 12 people)
12:00pm	Brief tour of LUX surface Lab.
12:30	Lunch and discussion of ongoing costs. Operation and life cycle costs. Risks and Mitigations past, present and future. Above ground civil construction, shaft safety upgrades.
2:00 pm	Surface tour of Hoist room and Water Treatment plant
Adjourn	

DOE Site Visit Agenda, SNOLAB on May 9, 2011

6:30am	Meet at SNOLAB: Safety and PPE	N. Smith
7:30	Descend to 6800ft level	
9:00	Transition to clean room quality SNOLAB	
9:30	Tour of Ladder Labs, Cube Hall, Cryopit, and SNO+, tour of services such as electrical substations, chillers, communications and safety systems	
3:00pm	Lunch and discussion of options for future discussions	

Appendix D – References to Key Documentation and Other Input

ID	Session/Topic	Title	Presenter(s)
1	Plenary	Executive Session	DOE, J. Marx, M. Reichanadter
2	Plenary	Underground Science Requirements and Experimental Capability: LBNE Underground Science Requirements and Capability Drivers	R. Svoboda
3	Plenary	Underground Science Requirements and Experimental Capability: Direct Dark Matter Orientation	H. Nelson
4	Plenary	Underground Science Requirements and Experimental Capability Drivers: Neutrinoless Double-Beta Decay	E. Beier
5	Plenary	Long Baseline Neutrino Experiment	J. Strait, E. McCluskey
6	Plenary	3rd Generation Dark Matter Experiment	H. Sobel
7	Plenary	1TGe: Ton-Scale Ge-Based Neutrinoless Double-Beta Decay Experiment	J. Wilkerson
8	Plenary	EXO	G. Gratta
9	Plenary	Input from DUSEL PDR Team - Physics Roadmap at Homestake	K. Lesko
10	Plenary	Input from DUSEL PDR Team - South Dakota Contributions	R. Wheeler
11	Plenary	Input from DUSEL PDR Team - DUSEL Preliminary Design	M. Headley
12	Plenary	Input from DUSEL PDR Team - Project Alternatives	J. Willhite
13	Plenary	SNO Infrastructure Capability Assessment	N. Smith
14	3rd Gen Dark Matter	DM Consensus Positions	B. Sadoulet
15	3rd Gen Dark Matter	LZ	T. Shutt, R. Gaitskell
16	3rd Gen Dark Matter	MAX	C. Galbiati, E. Aprile
17	3rd Gen Dark Matter	GEODM Breakout	S. Golwala, B. Cabrera
18	3rd Gen Dark Matter	COUPP-16T	J. Collar, A. Sonnenschein
19	3rd Gen Dark Matter	CLEAN	D. McKinsey, A.Hime
20	Double-Beta Decay	EXO Follow-up	J. Ku, M. Swift
21	Neutrino Physics	Introduction - Collaboration Overview	M. Diwan
22	Neutrino Physics	Introduction - LBNE Collaboration Science Overview	R. Williams
23	Neutrino Physics	Liquid Argon: Physics Program with a Liquid Argonne Detector	J. Urheim

ID	Session/Topic	Title	Presenter(s)
24	Neutrino Physics	Liquid Argon: Event Reconstruction and Simulation	M. Soderberg
25	Neutrino Physics	Liquid Argon Science : Membrane Cryostat Challenges and Benefits	B. Baller
26	Neutrino Physics	Liquid Argon Science: Progress in Purity	S. Pordes
27	Neutrino Physics	Liquid Argon Science: LArTPC for LBNETPC, Electronics and DAQ	C. Thorn
28	Neutrino Physics	Liquid Argon: Plans for R&D Experiments for the Future	B. Fleming
29	Neutrino Physics	Beam Design/ Components The Physics of the Beam Design Choices	M. Bishai
30	Neutrino Physics	Beam Design/ Components - NuMI to LBNE Cost Comparisons	G. Ramieka
31	Conventional/Underground Facilities	Options 1-6 Common Systems	S. De Vries
32	Conventional/Underground Facilities	DUSEL Plan B continued	S. De Vries
33	Conventional/Underground Facilities	LBNE Conventional Facilities for WCD - Option 1	E. McCluskey
34	Conventional/Underground Facilities	LBNE Conventional Facilities for LAr- Option 2	T. Lundin
35	Conventional/Underground Facilities	LBNE Conventional Facilities for Beam and Near Detector at Fermilab	T. Lundin
36	Cost and Schedule	Homestake Facility Design - Facility Cost and Schedule	M. Headley, S. DeVries, D. Vardiman, R. Wheeler
37	Cost and Schedule	Homestake Facility Design - DUSEL Operations Plans and Costs	M. Headley, S. DeVries, D. Vardiman, R. Wheeler
38	Cost and Schedule	LBNE Water Cherenkov	J. Stewart, J. Strait
39	Cost and Schedule	LBNE Option	E. McCluskey, T. Lundin, J. Strait
40	Cost and Schedule	LBNE LAr	B. Baller, J. Strait
41	Cost and Schedule	LZ Budget and Schedule	T. Shutt/R. Gaitskell
42	Cost and Schedule	MAX Cost and Schedule	C. Galbiati
43	Cost and Schedule	GEODM Cost/Schedule Breakout	S. Golwala

Appendix E – The Cherenkov Technique and Comparison of LBNE WCD and SK

The WCD technique involves a large volume of pure water, re-circulated to maintain purity and transparency, in a sealed cavern located at the 4850ft level of Homestake. This water acts as a target for the muon neutrinos produced at the accelerator source; because of the weakness of the neutrino interaction in water, only a tiny fraction of the neutrinos interact as they pass through the detector. One important figure of merit is the mass of water target, which together with the intensity of the neutrino source, determines the number of interactions produced in the water. The neutrino interactions in the detector almost always produce charged particles (e.g., electrons, muons, pions) some of which are travelling at relativistic speeds. Those travelling faster than the speed of light in water produce Cherenkov radiation in a well-defined cone around the particle's direction of travel. Different particles have different characteristic behaviors in the water and so produce different characteristic patterns of light at the walls. These light patterns permit unraveling the specifics of the interaction, often permitting characterization of whether the final state contained a high energy electron (from an electron neutrino) or a high energy muon (from a muon neutrino). The ability to distinguish electron neutrino interactions from other interactions is critical to the science of LBNE. Since the technique is only sensitive to relativistic particles and to conversions of multiple photons produced in high energy neutrino collisions, this technique has low efficiency (~15%) and finite backgrounds (~25%). The large fiducial tonnage is required because of the low efficiency.

Table 10 enumerates the characteristic parameters for the proposed WCD for LBNE and the SK detector, presently being used for the long baseline T2K experiment in Japan using neutrinos produced from the J-PARC accelerator.

Parameter	WCD	SK	Comments
diameter (m)	65	39	
height (m)	81	41	
total volume (ktons)	270	50	
instrumented diameter (m)	63	33.8	
instrumented height (m)	79	36.2	
instrumented detector mass (ktons)	240	32	
water buffer (m)	0.8	2.5	
fiducial volume cut (m)	2.0	2.0	
fiducial mass (ktons)	200	22	

Parameter	WCD	SK	Comments
depth (mwe)	4290	2700	
S/V ratio (m^{-1})	0.08623	0.15018	Surface to volume ratio
recirc rate (m^3/min)	2.87878	0.94697	Water recirculation rate
turnover time (days)	65.1315	36.6667	
(S/V ratio)*turnover time (days/m)	5.61628	5.50672	
water transparency @ 400 nm	100 m	100 m	Mean attenuation length at typical wavelength for PMTs
radon mBq/m^3	2	2	
PMT type	12" HQE	20" R3600	Diameter –Type Photomultiplier
relative PC efficiency	1.6	1.0	Relative photocathode efficiency for detecting photons
number pointing inward	29,000	11,146	
geometrical coverage	9%	40%	
PMT effective coverage	15%	40%	
Light collector factor	1.3	1	
total effective coverage	19%	40%	
ave. photoelectrons/MeV	3.0	6.0	LBNE is SK-II like(reduced coverage)
muon rate (s^{-1})	0.2	1.9	
number veto PMTs	2400	1885	
veto efficiency	99%	99.99%	
excavation started	2015	1991	
detector operational	2021	1996	

Table 10: Comparison between Parameters of the Proposed LBNE WCD Option and the SK Detector

Note that the technique is essentially identical. Though coverage by PMTs is less than nominal SK, it is very similar to SK-II, the period when that detector ran with reduced coverage.

Sources: R. Svoboda and http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html