LBNE Reconfiguration
Engineering/Cost Working Group
Final Report

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Contents

Acronyms, Abbreviations, and Definitions

APA	Anode Plane Assembly
CF	Conventional Facilities
CFFS	Conventional Facilities at the Far Site
CPA	Cathode Plane Assembly
(G)DAQ	(Global) Data Acquisition System
Homestake	Former Homestake gold mine, now the Sanford Laboratory in Lead, South Dakota
OHEP	DOE Office of High Energy Physics
LAr	Liquid argon
NDC	Near Detector Complex
OTR	Optical Transition Radiation
SURF	Sanford Underground Research Facility
TPC	Time Project Chamber or Total Project Cost, depending on context
UGI	Underground Infrastructure
27L	The 27th level in the Soudan Mine, at a depth of 2340 feet (~2100 meters water equivalent)
4850L	A level in the Homestake mine at a depth of 4850 feet (~4300 meters water equivalent)

1 Introduction

1.1 Executive Summary

The Long-Baseline Neutrino Experiment (LBNE) is in the Conceptual Design stage, approaching CD-1 readiness. A complete Conceptual Design and corresponding project plan has been developed and thoroughly reviewed in preparation for a planned DOE CD-1 review. However, it was judged that the cost of LBNE as planned was not sustainable, and on March 19, William Brinkman, Director of the DOE Office of Science asked Fermilab to lead the development of an affordable and phased approach to LBNE, including alternate configurations, that will enable important science results at each phase. He noted that this decision is not a negative judgment about the importance of the science, but rather it is a recognition that the peak cost of the project cannot be accommodated in the current budget climate or that projected for the next decade. To develop the response to this charge, Pier Oddone, Director of Fermilab, formed a Steering Committee, a Physics Working Group, and an Engineering/Cost Working Group. This is the final report from the Engineering/Cost Working Group.

The primary goals of LBNE are to determine if there is CP-violation in the lepton sector, determine the ordering of the neutrino mass states, make other precision neutrino oscillation measurements, search for proton decay, and measure supernova neutrinos. LBNE would employ a 700 kW beam from Fermilab and a large liquid argon time-projection chamber (LAr TPC) at the Sanford Underground Research Facility (SURF) in the Homestake mine in South Dakota, 1,300 km away. With the 1,300 km baseline, a broad-band neutrino beam designed specifically for this purpose, and the highly capable detector, LBNE would measure many of the oscillation parameters to high precision and, in a single experiment, test the internal consistency of the three-neutrino oscillation model. The neutrino beam can utilize the full beam power of Project X, which would further extend its reach. Placing the detector underground enables the proton decay and astrophysical neutrino measurements.

The Steering Committee considered reduced scope versions of LBNE with the 1,300 km baseline as candidates for the first phase of LBNE. These have the advantage of providing a clear path through subsequent phase(s) to achieve all the goals of LBNE. However, they require significant investment in the new beamline, limiting the mass of the far detector within the budget guideline for the first phase. The Steering Committee also considered alternatives utilizing the existing NuMI beamline, with detectors placed either at the Soudan Lab or the Ash River site in Minnesota, with baselines of 735 km or 810 km respectively. These have the advantage of not requiring construction of a new beamline, permitting larger detectors to be built in the first phase. But at the shorter baseline, there are fundamental ambiguities between matter effect and CP-violating asymmetries that could be very difficult to resolve, limiting their capabilities for the main oscillation physics.

The Engineering/Cost Working Group investigated the engineering feasibility and estimated the costs of a large number of options for the far detector, the neutrino beam, and the near detector. These included

LAr TPC detectors of 5, 17 and 34 kt fiducial mass, located deep underground at Homestake or at Soudan or on the surface at Homestake, Soudan or Ash River. For the beamline, many value engineering proposals were considered which would either lower the cost of the LBNE beamline design with minimal if any impact on functionality, or would result in some compromises in the first phase which could be restored in a subsequent phase of the project, e.g. limiting the beam power handling capability to 700 kW or accepting a less than optimal beam spectrum below the first oscillation maximum. In addition, an evaluation was done of the limitations and risks related to operation of the NuMI beamline for an extended period of 10 or more years beyond the currently planned NOvA running. Near detector options studied included possible first-phase near detectors in the LBNE beamline which could be fit in a much smaller space than the originally planned near detector hall, and adaptations of the LBNE near detector designs to fit into the near detector halls in the NuMI beamline.

Based on the cost information developed by the Engineering/Cost Working Group and the evaluation of scientific capabilities of the different configurations done by the Physics Working Group, the Steering Committee identified three phase one options that would provide significant scientific results and are consistent with the budget guideline that the first phase cost should be limited to \$700M - \$800M, including contingency and escalation. These three options and their estimated costs are:

Option	Estimated Total Project Cost
30 kton surface detector at Ash River (NuMI low energy beam, 810 km baseline)	\$684M
15 kton underground (2340 ft) detector at Soudan (NuMI low energy beam, 735 km baseline)	\$675M
10 kton surface detector at Homestake (new beamline, 1,300 km baseline)	\$789M

The pros and cons of each are summarized in the Steering Committee Report. While each of these first-phase options has some advantages over the others, the Steering Committee in its discussions strongly favored the option to build a new beamline to Homestake with an initial 10 kton LAr-TPC detector on the surface. The physics reach of this first phase is very strong and balanced for neutrino physics. This option is seen by the Steering Committee as a start of a long-term world-leading program that would achieve the full goals of LBNE in time and allow probing the Standard Model most incisively beyond its current state. Ultimately this option would exploit the full power provided by Project X. For an additional investment of ~\$135M, the detector could be placed underground, rather than on the surface.

1.2 Plan of the Report

The report begins with a discussion in Chapter 2 of the status of the LBNE design and project plan prior to the decision that a phased or alternative program needed to be developed, the reasons for developing a phased plan, and the constraints and assumptions under which the cost estimates for the phased program options were developed. Chapter 3 presents the different technical options considered, organized according to LBNE subproject: Far Detector, Conventional Facilities at the Far Site, Neutrino Beamline and its Conventional Facilities, and the Near Detector and its Conventional Facilities. The main phase 1 scenarios are presented in Chapter 4, together with sketches of possible phase 2 options for each. The cost estimates for different far detector locations and sizes are presented in Chapter 5, including discussion of subproject-specific cost estimating methodology, and contingency, escalation and cost range estimations. Chapter 6 presents the conclusions.

2 Context

The Long-Baseline Neutrino Experiment (LBNE) Project worked in conjunction with the LBNE Collaboration for more than two years to produce a Conceptual Design for a world-class facility that would enable the scientific community to carry out a compelling research program in neutrino physics. The ultimate goal in the operation of the facility and experimental program is to measure fundamental physical parameters, explore physics beyond the Standard Model, and better elucidate the nature of matter and antimatter. During this pre-conceptual stage, major alternates were studied and choices were made regarding a far detector technology and siting, as well an innovative beamline design to reduce risk. Thorough cost estimates and schedules were developed, including assessments for risk, and when those costs were documented for a CD-1 Director's Review, it became apparent that the Project could not be supported as originally conceived in the current budget climate in the U.S. The DOE Office of Science directed development of an affordable and phased approach to LBNE that produces important science at each step, in time to inform the next round of budget planning [1].

2.1 Reference LBNE Conceptual Design, Cost, and Schedule

The six-volume LBNE Conceptual Design Report [2] documents a reference design configuration of the LBNE Beam, Near Detector, Far Detector, and Near and Far Site Conventional Facilities for which total project cost and schedule were compiled. The reference LBNE Conceptual Design consists of a primary proton beam extracted from Fermilab's Main Injector. The proton beam strikes a target to generate neutrinos through a 200m decay pipe. Also, within the Fermilab site, an on-axis Near Detector Complex provides beam monitoring and characterization of the neutrino spectrum transmitted to the LBNE Far Detector. The LBNE beam is aimed at a 33 kt Liquid Argon (LAr) Far Detector located deep underground at the 4850 foot level (4850L) in the Sanford Underground Research Facility (SURF) in the former Homestake mine in Lead, SD. Many details of the technical systems and conventional facilities of the Near Site at Fermilab, and the Far Site at Homestake, can be found in the LBNE Conceptual Design Report.

The CD-1 project cost and schedule were developed for the Director's Independent Conceptual Design and CD-1 Readiness Review of LBNE conducted on March 26-30, 2012, and were found to be in an advanced stage at that review. The review website [3] provides links to documents describing cost range development [4], estimate uncertainty [5], cost book and basis of estimate navigation aids [6], and other documents that assist in study of the LBNE cost and schedule.

The LBNE Cost Summary Report [7] documents the Total Project Cost (TPC) and provides details of costs for all of LBNE project management and subprojects. Various methodologies, tailored to the type of estimate, were used. Expert scientists and engineers developed technical systems costs using past similar projects. In some cases experienced private companies were tasked with generating full estimates from engineering design through installation as was done in the case of the LAr Far Detector cryostat and cryogenics systems. The Conventional Facilities subproject also used experienced private companies to estimate design and construction costs for both Near and Far Site. LBNE technical systems' scientists and engineers provided detailed requirements where private companies developed the costs.

The LBNE schedule [8] was developed using Primavera P6 software and COBRA analysis tools. The schedule as of the March 26-30, 2012 Director's Independent Review reflects an effort to conform to a funding profile discussed with the Department of Energy. Resource level-loading was not entirely accomplished prior to the review; therefore, details of the schedule presented at the Review retained artificial peaks. The schedule of installation of the Far Detector was influenced by external conditions, including the need to rehabilitate the existing shafts at Sanford Laboratory. The schedule for construction of Near Site Conventional Facilities, Beamline and Near Detector Complex was influenced by the need to delay as long as possible to avoid interference with NOvA experiment running.

The LBNE cost and schedule referred to in this report reflects the status of development of the conceptual reference design at the time of the LBNE Director's Independent Conceptual Design and CD-1 Readiness Review.

2.2 Need to Phase the Program or Find Alternatives

Just prior to the LBNE Director's Review in March 2012, Office of Science Director Bill Brinkman sent a letter to Fermilab Director Pier Oddone indicating the ~ $1.5B unescalated cost of LBNE was unaffordable as a single project [1]. Dr. Brinkman charged Fermilab with finding a path forward to reach the scientific goals of the Long-Baseline Neutrino Experiment in a phased approach. A Steering Group was formed by Fermilab to study phased approaches and alternative experimental configurations. Two working groups were formed to support the work of the committee – Physics and Engineering/Cost. Under consideration are phased programs based on the original LBNE design, with a new beamline and a far detector at Homestake; and alternatives utilizing the existing NuMI beamline at Fermilab and a far detector either at the Soudan Underground Laboratory in Minnesota, the site of the MINOS experiment, or at Ash River, the site where the NOvA experiment is under construction.

2.3 Constraints and Assumptions at each Phase

There are several constraints and assumptions that control the design and the estimating for options under consideration. These include (in no particular order):

- Estimate basis: To the extent possible, estimates are based on the LBNE reference design as presented at the LBNE CD-1 Director's Review in March 2012.
- Maximum cost for each phase: Based on guidance from DOE OHEP, the cost of each phase of LBNE should be no more than $700-800M. This amount is not absolute, but is a strong guideline.
- Cost range: DOE OHEP has strongly suggested that the Phase 1 CD-1 cost range should stay within the LBNE CD-0 cost range of $660M-$940M. The upper end of the cost range for the reference design is about 15% above the point estimate; this implies that the point estimates should stay below about $800M.

- Annual available funding: DOE OHEP and Fermilab Management have provided guidance that annual expenditures for LBNE should not exceed about $120M/year.
- Science capabilities: Per Dr. Brinkman's letter, each phase must produce important science on its own.
- Accelerator-based oscillation physics has higher priority and should be addressed in Phase 1.
- The Sanford Underground Research Facility will be operated independently of LBNE for the Early Science Program and potentially for other subsequent experiments. The Soudan Underground Laboratory and the Ash River sites will be operated independently of LBNE for the existing neutrino experiments and potentially other subsequent experiments. The operating costs of these facilities will not be the responsibility of the LBNE Project during its construction.

3 System Options Considered

This section describes the technical systems and the conventional facilities options that can be combined into various configurations. The starting basis for all work is the LBNE reference design and this section will describe the evolution of or relationship to the systems from that design. Along with the description of the scope of each system option, evaluation of the quality and maturity of the engineering designs for the various options is included. The options considered for this exercise and for which costs were developed (see Chapter 5) include:

- Liquid Argon Far Detectors of 5 kt, 17 kt and 34 kt fiducial mass. Note that for this exercise, the largest mass detector (34 kt) is slightly more massive than the one in the reference design (33 kt). The cost of other detector masses are estimated by interpolation.

- Conventional facilities (CF) to support the Far Detector construction and operation for all three detector sizes at the Sanford Underground Research Facility at Homestake at the 4850L or on the surface; at the Soudan Underground Laboratory at the 27L (2340 foot depth) or on the surface; and at the Ash River facility on the surface. The cost of CF for other detector sizes are estimated by interpolation.

- The LBNE neutrino beamline, modified from the original design according to a set of value engineering proposals that have been evaluated since the Director's Review.

- Required investments in the existing NuMI beamline to allow it to operate in the low-energy configuration at 700 kW for at least 10 years beyond the end of the NOvA run.

- Near Detector configurations for use in either the LBNE or NuMI beamlines, based on the reference design of a magnetized liquid argon TPC or the alternative magnetized straw-tube tracker design, as well as several simplified designs that could be part of a phase 1 implementation. The option of constructing no near neutrino detector in phase 1 for the Homestake options was also considered. In this case the beam would be monitored by muon detectors downstream of the absorber until a neutrino detector cold be constructed in phase 2. For the NuMI options, the possibility of utilizing the existing MINERvA, MINOS and NOvA near detectors in phase 1 was also considered.

3.1 Far Detector

The far detector is a Liquid Argon Time Projection Chamber (TPC). The construction of the basic TPC components, anode plane assemblies (APA) and cathode plane assemblies (CPA), are the same for all options. The modular detector is constructed in a rectangular array of double-sided drift cells, each consisting of a central APA and two CPAs. The options differ in the number of components and their relative spacing. The APA/CPA spacing is the maximum drift distance over which ionization electrons must travel and has been set in the range of 3.6 – 3.9 meters for underground options and in the range of 2.3 – 2.4 meters for surface options. The selection of drift distance for the underground options reflects the need to limit the cavern span to a reasonable size (~30 m) while minimizing the number of TPC components. [9] The shorter drift distance for surface options was chosen to mitigate the effects of space charge build-up due to cosmic rays [10] [11]. The detector would ideally be constructed as a cube to minimize the surface area, and therefore the cost, of the cryostat and to maximize self-shielding from external background sources. The chosen options reflect this general principle.

The options shown in Table 1 are characterized by five parameters: 1) the number of detector modules, 2) the number of drift cells high, 3) the number of drift cells wide, 4) the number of longitudinal drift cells along the beam direction and 5) the drift distance. The applicability of each of the options to a specific depth and location are shown. All options include a cryogenic refrigeration plant sized for each cryostat and a standby refrigeration plant.

Table 1: Far Detector Options

Option	**Fid Mass (kt)**	**Level**	**Drift (m)**	**Cryo Plants**	**Location**
1x2Hx3Wx10L	5	0	2.3	2 x 45 kW	Homestake, Ash River, Soudan
1x2Hx2Wx9L	5	27L	3.65	2 x 60 kW	Soudan
1x2Hx2Wx9L	5	4850L	3.65	2 x 60 kW	Homestake
2x2Hx4Wx12L	17	0	2.38	3 x 50 kW	Homestake, Ash River, Soudan
2x2Hx3Wx10L	17	27L	3.63	3 x 70 kW	Soudan
2x2Hx3Wx10L	17	4850L	3.63	3 x 70 kW	Homestake
2x2Hx4Wx23L	34	0	2.42	3 x 75 kW	Homestake, Ash River, Soudan
2x2Hx3Wx18L	34	27L	3.89	3 x 100 kW	Soudan
2x2Hx3Wx18L	34	4850L	3.89	3 x 100 kW	Homestake

The quality of the TPC design for these options is the same as for the reference design. The options differ primarily in the number of components constructed and installed. The options for the 17 kt and 34 kt options include a 1 kt engineering prototype. These large-detector options are constructed in two cryostats, allowing both cryostats and both detector modules to be qualified before final filling of the second cryostat.

A 5 kt detector is considered too small to devote such a significant level of prototyping resources as well as being too small to break into two cryostats. This loss of flexibility has been compensated for to some extent by including a liquid argon surface storage tank. Additional prototyping activities, e.g., installing a TPC in the 35 ton membrane cryostat prototype, could reduce risk for the smaller detector.

3.2 Conventional Facilities at the Far Site (CFFS)

The conceptual design of the LBNE project has evolved over the last several years culminating in the reference design for a 33 kt far detector that was the subject of a Director's Independent Conceptual Design and CD-1 Readiness Review of LBNE in March 2012. As part of the project reconfiguration exercise the reference design has undergone a re-scoping process that included consideration of constructing far site detector facilities at either the former Homestake mine in Lead, South Dakota (the reference design location), the former Soudan Mine in Soudan, Minnesota, or the Ash River site in northern Minnesota. Scope and cost models of 5, 17, and 34 kt detector sizes were developed for deep underground locations at Homestake (4850 foot depth) and Soudan (2340 foot depth) and for surface configurations for all three sites.

For all options considered, the following modifications to the scope of the reference design have been incorporated into the Conventional Facility (CF) scope and cost models.

- Cryogens will be delivered to the underground detector enclosure as a gas instead of a liquid. This eliminates the need for pressure reducing stations previously required every ~800 feet down the shaft, and reduces the amount of power delivered to the detector enclosure and also reduces the heat load rejected to air.
- The "muffin top" has been omitted from all detector enclosure options.
- Redundant UGI systems for cyber infrastructure and power delivery systems have been omitted.
- Surface detector options include the LAr pit excavated into the earth with the top of the pit placed near existing grade. The septum area and the highbay portion of the cavern that houses equipment are located in a surface structure for the surface detector option.
- Surface detector options have omitted emergency and standby electrical power distribution systems. The small amount of equipment that requires electrical power will be connected to uninterruptible power supplies.
- Layouts of all options were discussed with the LBNE ES&H manager to validate that emergency egress and ventilation system requirements were met.

3.2.1 CFFS at Homestake

Detector options evaluated at the Homestake site include detectors sited below grade at the 4850L and at the surface. Details of the scope of the 4850L and surface detector options at Homestake are described below.

3.2.1.1 Siting at the 4850L

Designs are based on the reference design with the scope scaled to reduced detector requirements. The 5-kt and 17 kt excavation scope applied to Homestake are not as mature as the 34 kt design. For the 5, 17, and 34 kt detector sizes located at the 4850L, the following additional assumptions are included in the scope and cost models.

- UGI systems outside the cavern required for fire/life safety or for early science at Homestake have been omitted from the LBNE scope and have become a SURF responsibility, as they are necessary to support the on-going early science program.

- Ross and Yates shaft rehabilitation scope and costs are separated from LBNE costs since they may be funded by others.

- Construction management will be self-performed by SURF.

The description of the facility layout, including graphics and cost models for the following detectors located at the 4850L are documented for each detector size: 5 kt [12], 17 kt [13], and 34 kt [14].

3.2.1.2 Siting at the Surface

The pre-conceptual design of the pit excavation and the surface structure is based on a NOvA-like facility roughly scaled to LAr detector size requirements. The UGI is based on work done by SURF engineers to scale the reference design utilities to a surface installation and detector requirements. The description of the facility layout, including graphics and cost models for the following detectors located at the surface have been documented for each detector size: 5 kt [15], 17 kt [16], and 34 kt [17].

3.2.2 CFFS at Soudan

Detector options evaluated at the Soudan site include detectors sited underground at the 27L and at the surface. In addition to the modifications made to the reference design as described above, all Soudan scopes incorporate the following:

- Tailoring of the reference design to the Soudan site and its existing infrastructure.

- Use of existing temporary warehouse space at no cost to the project.

- Construction administration performed by the University of Minnesota (U of MN) and construction management performed by an independent firm.

Details of the 27L and surface detector options at Soudan are described below.

3.2.2.1 Siting at the 27L

Two new shafts are required to provide primary personnel and equipment access and ventilation. The existing shaft would provide secondary egress. The sizes of the two shafts were established by LBNE based on the function that they would serve. They are the same for all detector sizes. Standardized 5 and 17 kt dimensions of all caverns, drifts, and shafts at the 27L were used by CAN Consulting Engineers to determine site specific shaft locations which determined the drift lengths required to connect caverns and shafts to each other and to existing underground enclosures. LBNE used this information to create the layout of 34 kt facilities. Soudan layouts were discussed with the LBNE ES&H manager to validate that emergency egress and ventilation system requirements were met. The 34 kt cavern and drift excavation design is based on the reference design and is at the pre-CD-1 level. The 5 kt and 17 kt excavation scopes are not as mature as the 34 kt design.

The UGI and surface infrastructure components are adapted and scaled from the reference design to apply to Soudan and specific detector size requirements and are less mature than the Homestake models.

The description of the facility layout, including graphics and cost models for the following detectors located at the 27L are documented for each of the detector sizes: 5 kt [18], 17 kt [19], and 34 kt [20].

3.2.2.2 Siting at the Surface

The pre-conceptual design of the pit excavation and the surface structure is based on a NOvA-like facility roughly scaled to LAr detector size requirements. UGI is the same as that for a Homestake surface option. The description of the facility layout, including graphics and cost models for the following detectors located at the surface are documented for each of the detector sizes: 5 kt [15], 17 kt [16], and 34 kt [17].

3.2.3 CFFS at Ash River

Detector options evaluated at the Ash River site are limited to siting the detectors at the surface. The pre-conceptual design of the pit excavation and the surface structure is based on a NOvA-like facility roughly scaled to LAr detector size requirements. UGI is the same as that for a Homestake surface option. The description of the facility layout, including graphics and cost models for the following detectors located at the surface are documented for each of the detector sizes: 5 kt [15], 17 kt [16], and 34 kt [17].

3.3 Beamline and its Conventional Facilities

In the context of the LBNE reconfiguration effort the following three options have been considered:

I. Beam to Homestake - NOvA continues running and NuMI components are not available for LBNE use. In this option NOvA can keep running until right before LBNE is ready to run.

II. Beam to Homestake - NOvA has finished data-taking and components from NuMI are available for LBNE use.

III. Use NuMI Beamline to aim to Soudan for continued 700 kW operation after the end of NOvA data-taking.

For option III, additional considerations are that i) NuMI cannot run at proton energies significantly below 120 GeV; ii) NuMI cannot be upgraded to run at beam power of much above 1 MW.

The assumptions for options I. and II. are that:

a. Although the LBNE to Homestake will be able to be upgraded to ≥2.3 MW of beam power, in the initial phase the shielding at the target hall roof is appropriate for 700 kW only; more concrete will be required (~1.5 ft) on the roof of the target hall.

b. New primary beam optics will be implemented, reducing the length of the primary beam and therefore sacrificing some, but still allowing for sufficient beam tuneability.

c. The Near Detector Hall will stay where it is now (independent of b), since locating it upstream provides insufficient rock cover above it. This implies that the muon range out distance will increase the when the primary beamline length is shortened.

d. NuMI-design horns with horn 1 upgraded for 700 kW will be used and run at 200 kA. This results in the same neutrino flux at the first oscillation maximum (2.4 GeV) as in the reference design, but a ~25% loss in flux at the second maximum (0.8 GeV).

3.3.1 Option I – Beam to Homestake, no NuMI components

In trying to reduce the Beamline Facility costs (Technical Components and Conventional Facilities) for the first phase of LBNE, additional value engineering proposals were considered [21], on top of the ones considered for the reference design. All the proposed changes have been reviewed by members of the Fermilab ES&H staff to ensure that they are compatible with radiological, environmental and personnel safety requirements.

Primary Beam: The main cost savings in the primary beam are related to the implementation of new primary beam optics reducing the length of the primary beam by 148' and therefore sacrificing some, but still allowing for sufficient, beam tuneability [22]. This allows for reduction of the apex of the beamline center and the corresponding soil embankment, for fewer drilled piers to rock and for moving the target hall, decay pipe and absorber hall further upstream, and therefore reducing conventional facilities costs [23], [24]. It also allows for reduction of the costs of technical components in this shorter beamline [21].

At the same time the embankment side slopes are increased to 30 degrees (the reference design has 21.8 degree slopes) and on the basis of updated MARS calculation, the soil shielding on top of the primary beamline is reduced from the 25 ft used in the reference design (same as for the Main Injector) to 23 ft. This provides the necessary shielding for 2.3 MW operation.

In addition, the optical transition radiation (OTR) 2D exit window profile monitor is eliminated from the beam instrumentation and the labor cost for beam loss calculations has been re-optimized.

Neutrino Beam: There are several sources of the cost savings in the Neutrino Beam area. These include using a NuMI style design for the target, horns, and target hall instrumentation in order to reduce the design time and the prototyping cycle. They also include using NuMI approach to support the baffle and the target and to make target repairs, implying a reduction in the scope of remote handling and its impact on conventional facilities [21]. By so doing, Phase 1 of a phased LBNE program produces a less optimized neutrino spectrum, more frequent target change-outs, and longer accesses for maintenance.

Due to improved MARS modeling, and by adding a water resisting liner around the target chase bath tub, the steel walls and floor of the target shield pile are reduced by 24 inches on each side. Eliminating the flexibility to install magnets from the target hall side reduces the footprint of the target hall complex further. The combination of all of the improvements in the neutrino beam allow a reconfiguration of the target hall complex to a three story facility with fewer drilled piers to rock, resulting in substantial savings for the conventional facilities [23], [24].

Additional cost savings come from reusing some onsite steel for the target shield pile shielding and postponing the installation and cooling of the target chase water-cooling panels until 2.3 MW operation. The panels were serving also as shielding, but carbon steel filler plates will be used instead [21].

Tritium interceptors were removed from the walls of the 200 m long decay pipe but retained at its floor [23], [24].

3.3.2 Option 2 – Beamline to Homestake, NOvA has finished data-taking

This option uses all the value engineering proposals applied in Scenario I. In addition some components are re-used from NuMI, which include:

- A few quadrupole magnets, a few quadrupole, kicker and lambertson magnet power supplies, a kicker magnet tank, and some beam instrumentation components for the Primary Beam
- Some target and Target Hall Instrumentation components, the horn power supply, part of the horn strip line, the steel door and lift table for the Target Hall Work Cell for the Neutrino Beam
- A few controls components for System Integration.

These components are worth about $10 M in TPC FY2010. Some of them, like the power supplies for the horns and the magnets, can be moved and repurposed quickly (in less than a month) and some of them will take several months. For all of them though, the moving and repurposing will take less than one year.

Many value engineering proposals were reviewed intensively by the LBNE beamline team with oversight by the Project Office, and a subset were accepted as forming the basis of a first phase LBNE beamline. A summary of all of the accepted value engineering proposals for reducing the cost of the LBNE neutrino beamline in phase 1 is presented in Table 2. The total identified cost reduction is $86M (FY2010) including estimate uncertainty contingency. (See section 5.1.6 for a discussion of the different contingency elements.)

3.3.3 Option 3 – NuMI Beamline

This option assumes that the Beamline has been already running at 700 kW and will continue with the same beam power. However, some investment will be required to permit operation at 700 kW in the low-energy configuration. (NOvA will run in the medium–energy configuration.) The main items are development of a target that works at 700 kW while inserted fully in the first horn, and returning Horn 2 to its previous "nest" to have the two horns 10 m apart. A document discussing ES&H concerns for long term running of the NuMI line can be found in [25]. Risks involved in long term running of the NuMI Beamline and possible mitigations are discussed in [26].

Table 2: Summary of LBNE beamline cost savings in FY2010 M$, including estimate uncertainty contingency, but not risk or top-down contingency.

Simplify Technical Systems Design	Cost Savings
Shorten primary beam 148'	0.8
Eliminate OTR profile monitor	0.2
Re-optimize beam loss calculation labor	0.5
Reduced target shield pile	4.4
Recycle old shielding steel	1.3
No target chase water-cooling panels in phase 1	3.7
NuMI design target and horns (200 kA)	13.0
Reduced target R&D in phase 1	3.0
NuMI design target hall instrumentation	2.3
Combined target-baffle module	0.7
No in-chase target handler	7.7
Reduce and combine vision systems	0.7
Total - technical systems	**38.2**

Re-use NuMI beamline components	Cost Savings
NuMI horn PS + stripline	3.6
Beamline Magnets	1.3
Magnet power supplies	0.5
Primary beam instrumentation	1.0
Target	0.8
Target hall instrumentation	1.9
Remote handling equipment	0.4
Total - reusing NuMI components	**9.5**

Simplify Conventional Facilities Design	Cost Savings
Target Hall Complex Reconfiguration	30.2
Shorten primary beam 148'	6.6
Reduced tritium interceptor	1.4
Total - Conventional Facilities	**38.2**

Grand Total	**85.9**

3.4 Near Detector and its Conventional Facilities

The near detector complex (NDC) envisioned for LBNE included post-absorber measurements of the tertiary muon spectra, neutrino measurements in an underground hall a few hundred meters after the absorber, and a global DAQ (GDAQ) system including a GPS to provide timestamps to the data and communication with the rest of the experiment [27]. From the standpoint of the near detector, the LBNE reconfiguration options considered can be classified into two categories, those that represent full or phased LBNE reference design, and those that employ the existing NuMI beam and near-site underground facilities. For the former, the same tertiary muon systems and same GDAQ (with the cost scaled by the number of neutrino detector channels) are employed for all options. For the latter, the same is true except that it is assumed that the existing GPS system in the NuMI hall will be re-used. The following describes the neutrino detectors anticipated for each option. In all cases, the starting point for the estimates was the LBNE NDC reference design.

3.4.1 Far Detector at Homestake - Near Detector and CF Options

There are several options associated with a phased LBNE program for a far detector at Homestake. Two options include building the NDC as contemplated, or not building it at all. These require little effort to determine the capability and the cost. The designs can be found in the LBNE CDR [27]. The remainder of the LBNE phasing options for the near detector involves the construction of one of the two shafts required for the LBNE near detector hall, and the deployment of a neutrino detector with modest capabilities into the shaft for remote operation.

The shaft [28] would be 22 feet in diameter as is required for the standard LBNE reference design, constructed to the elevation (575 ft) required for LBNE to allow the underground hall to be built in a later phase. A minimal surface building would be constructed. Site utilities would include electricity and water, but no sewer. In the shaft, no permanent crane, stairs or elevator would be constructed. The shaft would be lined with concrete and have a dehumidifier, sump pit and sump pump. No ventilation would be provided. During infrequent pit occupancy, ventilation would be provided by temporary installation of an elephant trunk.

There are three options for detectors [29] labeled Very Basic, Basic and Enhanced Basic, any of which would be placed in the shaft described above. The Very Basic option includes a neutrino detector that is a steel and scintillator sandwich similar to MINOS, but with no magnetic field. The detector has three sections – upstream, mid and downstream. The upstream and downstream sections are the same except the downstream is twice as long. The mid-section includes thinner steel (0.5cm instead of one inch) and makes crude measurements of the aggregate of electron neutrinos and anti-neutrinos vs. the aggregate of muon neutrinos and anti-neutrinos as a function of reconstructed (anti)neutrino energy. The Basic option employs the same up and downstream sections as the Very Basic option, but the mid-section is composed of alternating planes of high-pressure gas argon targets in a stainless steel manifold and scintillator. Through the whole detector is a magnet coil to generate a toroidal magnetic field (similar to MINOS). This detector measures CC interactions on the same target nucleus as the far site (argon) and can separate CC muon neutrino and anti-neutrino interactions. It also measures the NC interaction spectrum. The Enhanced Basic option includes a cylindrical liquid argon TPC enclosed in a solenoidal magnetic field and surrounded by detectors to separate muons from pions. It has enough instrumented mass to carry out a large fraction of the measurements contemplated for standard LBNE.

The major components of the Very Basic and Basic designs are based on some of the components of the LBNE reference designs, therefore, the costs are well understood. Since the challenges of remote operation have only been considered for one month, some additional contingency was applied to the costs for these options. For the Enhanced Basic design, there are significant design differences when compared with the standard LBNE designs. More contingency has been applied to this design to accommodate the larger project risk.

3.4.2 Far Detector at Soudan - Near Detector and CF Options

For on-axis options that employ a far detector at Soudan, the simplest phase one option is just to use the existing MINERvA and MINOS detectors. However, to achieve the best results from the far detector, a fully capable LBNE-type near detector would be required in a second phase, if not in phase 1. Two options that involve building detectors in the current MINOS near detector hall were initially considered [30]: a liquid argon detector and a fine-grained straw-tube tracking detector (FGD), each with the same fiducial mass as the LBNE reference design. Since the hall is narrower than that contemplated for LBNE, it is clear each design must be narrower and longer. For the FGD, the straw-tube length goes from 2.5 meters to 2 meters. For the liquid argon TPC, the transverse size is reduced to such a level as to threaten the viability of the detector. A redesign of the magnet would likely solve this problem. There is no difficulty designing to this option if necessary. However, given the limited time, only the FGD option has been considered for this exercise. Based on the relative costs of the LAr and FGD reference designs, it is believed that this approach would provide adequate budget for either type. In order to install and operate either design, significant infrastructure work is required, especially related to the ODH hazard associated with a large mass of liquid cryogen. This design has been developed quickly and must be considered to be relatively immature.

3.4.3 Far Detector at Ash River – Near Detector and CF Options

For off-axis options that employ a far detector at Ash River, as for the Soudan option, the simplest phase one option is just to use the existing NOvA, MINERvA and MINOS detectors, but eventually a fully capable LBNE-type near detector would be needed. It is not possible to fit either of the LBNE designs into the near-site off-axis hall that will be constructed to house the NOvA near detector. This leaves two options. The first is to build an on-axis FGD in the MINOS Near Detector Hall and a small non-magnetized off-axis liquid argon detector in the NOvA near hall [31]. The small liquid argon detector is surrounded by an array of steel/scintillator sandwiches that distinguish muons from pions. The second is to remove the NOvA detector and enlarge the off-axis cavern to accommodate an LBNE-type detector. Given the short time available for this study, only the first option has been developed so far. The same design maturity issues associated with the Soudan options are true here.

4 Phasing Options

Based on studies done by the Physics Working Group and preliminary cost estimates presented by the Engineering/Cost Working Group (discussed in detail in Section 5), the Steering Committee identified three viable configurations for a Phase 1 long-baseline neutrino experiment that have the potential to accomplish important science [32]. These have been chosen because they fit within the budget guidelines. Each has possible Phase 2 configurations that would extend the science reach of LBNE. A fourth option is identified by the LBNE Collaboration as potentially viable, and is also included. This section describes these four phasing options, for which costs are summarized in Chapter 5.

4.1 Phase 1 - 30 kt Detector at Ash River on the Surface

Phase 1 of this scenario utilizes the existing NuMI beamline at 700 kW, reconfigured for a low energy beam, as described in 3.3.3. A 30 kt LAr TPC detector on the surface would be constructed at the Ash River site adjacent to the existing NOvA detector at a baseline of 810 km and an off-axis angle of 14 mrad. The detector would be very similar to the 34 kt surface detector described in Section 3.1. The conventional facilities for the 30 kt detector would be very similar to those described for a 34 kt detector option at Ash River in Section 3.2.3.

In phase 1, a combination of the existing MINERvA detector, MINOS near detector, and the by-then existing NOvA near detector would serve as the near detector for this experiment. Given the large mass and therefore relatively high statistics in the far detector, a more sophisticated near detector is likely to be required as an early phase 2 project in order to limit the systematic errors. A pair of near detectors would be constructed in the existing NOvA and MINOS near detector halls at Fermilab as described in Section 3.4.3.

Possible phase 2 options for this configuration include:

- Construction of a full-performance LBNE-type near detector.
- Upgrading the NuMI beamline to accept beam power of 1.1 MW in conjunction with the construction of the first phase of Project X.
- Constructing an additional 15-20 kt detector underground at Soudan.
- Construction of a new neutrino beamline optimized for lower beam energy and capable of taking the full Project X beam power of >2 MW. This beam could be aimed directly at Ash River to provide a broad-band on-axis beam if appropriate.

4.2 Phase 1 - 15 kt Detector at Soudan 2340 foot depth

Phase 1 of this scenario utilizes the existing NuMI beamline at 700 kW, reconfigured for a low energy beam, as described in Section 3.3.3. A 15 kt LAr TPC detector would be constructed at the existing 27L, 2340 feet underground at the Soudan Laboratory, at a baseline of 735 km and on the NuMI beam axis. The detector would be very similar to the 17 kt detector described in Section 3.1. The conventional facilities for the 15 kt detector would be very similar to the 17 kt detector option described in Section 3.2.2.1.

In phase 1, a combination of the existing MINERvA detector and MINOS near detector would serve as the near detector for this experiment. After several years of operation, a more sophisticated near detector is likely to be required in a phase 2 project in order to limit the systematic errors.

Possible phase 2 options for this configuration include:

- Construction of a full-performance LBNE-type near detector.
- Upgrading the NuMI beamline to accept beam power of 1.1 MW in conjunction with the construction of the first phase of Project X.
- Construction of a 30 kt detector on the surface at Ash River.
- Constructing an additional 25-30 kt detector underground at Soudan.
- Construction of a new neutrino beamline optimized for lower beam energy and capable of taking the full Project X beam power of >2 MW.

4.3 Phase 1 - 10 kt Detector at Homestake on the Surface

Phase 1 of this scenario includes construction of a new beamline at Fermilab aimed at the Sanford Underground Research Facility in the Homestake Mine in Lead, South Dakota, and a 10 kt LAr TPC detector located on the surface, at a baseline of 1300 km and on the beam axis. The beamline is designed for 700 kW, but is upgradable to ≥2.3 MW, and uses components reused from the NuMI beamline, as described in Section 3.3.2. The 10 kt detector would be similar to the 17 kt detector described in Section 3.1. The detector is subdivided into two 5 kt modules, and the first of these would serve as the prototype for the second. Therefore, there is no 1 kt prototype in this scenario. The conventional facilities would be similar to that described in Section 3.2.1.2 for the 5 kt and 17 kt options. The only component of the NDC included in this phase 1 option is the muon monitor system located in the absorber hall. The experiment is expected to be limited by the statistics in the far detector for at least the first several years, but a full-function near detector is likely to be required in phase 2, to limit the systematic errors on the oscillation measurements before the end of the initial 10-year run.

Possible phase 2 options for this configuration include:

- Construction of a full-performance near detector.

- Upgrading the beamline to accept higher beam power in conjunction with the construction of the first phase of Project X.

- Construction of a 20-25 kt detector at the 4850 foot depth at Homestake, yielding a configuration with nearly the full capability of LBNE as originally planned.

4.4 Phase 1 - 10 kt Detector at Homestake at 4850L

Phase 1 of this scenario includes construction of a new beamline at Fermilab aimed at the Sanford Underground Research Facility in the Homestake Mine in Lead, South Dakota, and a 10 kt LAr TPC detector located underground at the 4850L, at a baseline of 1300 km and on the beam axis. The beamline designed for 700 kW, but upgradable to ≥2.3 MW, and uses components reused from the NuMI beamline, as described in Section 3.3.2. The 10 kt detector would be similar to the 17 kt detector described in Section 3.1. The detector is subdivided into two 5 kt modules, and the first of these would serve as the prototype for the second. Therefore, there is no 1 kt prototype in this scenario. The conventional facilities are similar to that described in Section 3.2.1.1 for the 5 kt and 17 kt options. The only component of the NDC included in this phase 1 option is the muon monitor system located in the absorber hall. The experiment is expected to be limited by the statistics in the far detector for at least the first several years, but a full-function near detector is likely to be required in phase 2, to limit the systematic errors on the oscillation measurements before the end of the initial 10-year run. This option would cost approximately $130M more than the surface option at Homestake discussed above, and would exceed the budget guidance from DOE unless additional, non-DOE funding sources could be found to cover the additional cost.

Possible phase 2 options for this configuration include:

- Construction of a full-performance near detector.

- Upgrading the beamline to accept higher beam power in conjunction with the construction of the first phase of Project X.

- Construction of an additional 25-30 kt detector at the 4850L at Homestake, yielding a configuration with the more than the full capability of LBNE as originally planned.

5 Cost Estimates

This chapter describes the cost estimates for both the technical system and CF options. In Section 5.1, the cost estimate methodology is presented for each level 2 subproject, then the methodology for estimating contingency and escalation is presented, and finally the estimation of a CD-1 type cost range is discussed. Section 5.2 presents a summary of the major options considered, including the viable options for Phase 1.

5.1 Cost Estimating Methodology

Each technical system and its CF have developed cost estimates using its own methodology. Sections 5.1.1 through 5.1.5 describe that methodology as well as the maturity of the cost information. Each of these sections includes information about subproject-specific considerations of contingency. Section 5.1.6 describes the overall contingency methodology, including estimate uncertainty, risk and top-down contingency. Section 5.1.7 describes the method used to estimate escalation. The estimation of a CD-1-type cost range is discussed in Section 5.1.8.

To the greatest extent possible, cost estimates have been based on the designs and utilizing the same methodologies used for the LBNE Project reference design described in Section 2.1. The reference design and cost estimates have been thoroughly reviewed both internally by the LBNE Project and in an independent Director's Review, and found to be sound. Therefore, they provide a solid basis for estimating costs of the various phasing options. However, in a number of cases, new information had to be developed for configurations that do not correspond to the reference design, e.g. conventional facilities for detectors located at Soudan or Ash River.

For the far detector and its conventional facilities, costs were developed for specific detector fiducial masses: 5 kt, 17 kt, and 34 kt. Costs for alternate fiducial masses (10 kt, 15 kt and 30 kt) were done through interpolation of scalable costs from the three fiducial masses, added to fixed costs.

Cost estimates presented here do not include the cost of operating the Far Site laboratory facilities during the design and construction period. The Sanford Underground Research Facility will be operated independently of LBNE for the Early Science Program and potentially for other subsequent experiments for at least the next five years. The Soudan Underground Laboratory and the Ash River sites will be operated independently of LBNE for the existing neutrino experiments and potentially other subsequent experiments. The Soudan Underground Laboratory will be operated independently of LBNE for the MINOS+ and possibly other experiments for a similar period, and the Ash River site will be operated for NOvA until at least the end of the decade. The cost to DOE of operating SURF is currently $10-15M per year, and that for the Soudan Lab is about $2M/year. Operations at Ash River have not yet begun. None of these operating costs are included in the LBNE cost estimates.

5.1.1 Estimates for the Liquid Argon Far Detector

The cost estimates for all options are derived by parametric scaling from the cost estimate presented at the March Director's CD-1 Readiness Review as the cost basis [33]. The estimate includes direct costs, indirect costs and contingency. Escalation is not included. The cost estimate and the detector parameters presented at the review [34] were merged into a single spreadsheet [35] that generates a cost estimate for a variety of user-defined configurations. Unit costs for constructed TPC components such as APAs are obtained from the estimate for the reference design and then the costs are scaled by the number of components required for each option.

The cost estimates for design and tooling are the same for all options. Project management costs are scaled by the estimated project duration from CD-3 to CD-4. Contingency is re-calculated at the lowest level of the cost estimate and scaled appropriately.

The quality of the TPC cost estimate for all options is the same as for the reference design. The costs of the options differ primarily in the number of components constructed and installed. The cost estimates for the 17 kt and 34 kt options include a 1 kt engineering prototype ($24M). For the 5 kt options, a surface storage tank is included ($7-11M).

5.1.1.1 Cryostat and Cryogenic System

The cost estimate for the reference design cryostat and cryogenics systems was performed by Arup Energy and evolved through three design cycles [36] [37] [38] over a two year period. Cost estimates for cryostats located on the 300L, 4850L and lastly the 800L at Homestake were developed by Arup. The quality of the cryostat cost estimate is also the same as for the reference design as it is based on the same cost estimating methodology used by the membrane cryostat vendor. The Arup cost estimates predate a value engineering proposal to place the cryogenic refrigerator nitrogen compressors on the surface and change the delivery of argon from the surface to underground from liquid to cold gas form. Adjustments to elements of the Arup cost estimate have been made to incorporate this proposal. This change also has significant impact on the conventional facilities by reducing underground space and electrical power requirements, and eliminating the need for pressure reducing stations periodically down the shaft.

The Arup cost estimate for the cryostat and cryogenic system were deconstructed in reference [35]. The Arup cost estimate for each major system included a break-down by equipment M&S cost, transportation cost to the underground cavern and labor costs for installation and testing. The cost estimate report included the relevant material take-off quantity for the system in some cases, e.g. cryostat surface area. For systems with no defined material take-off quantity, a reasonable scaling quantity was chosen, e.g. total liquid argon mass for one cryostat (24.64 kt) for the liquid filtration system.

The scaled cost of each system is split into a fixed and variable fraction. We make the assumption that equipment M&S costs scale almost linearly with the system size, i.e. the fixed cost fraction is small. This assumption is supported by comparing quotes for stainless steel pipe and cryogenic valves of varying sizes. We also make the assumption that labor costs are independent of the system size and are 100% fixed cost. This assumption is considered reasonable for systems that are within a factor of 2x of the Arup reference design.

Two factors were used to scale the cost of transporting materials to the work site. The Arup reference design assumed material would be transported through the Yates shaft and the transportation cost was estimated from the volume of material. For underground options, the transportation cost is scaled by the relevant material take-off quantity, e.g. cryostat surface area. The transportation cost for surface options is assumed to be 20% that of the underground options.

The Arup design included cryogenic piping to transport liquid argon from the surface to the 800L as well as nitrogen and argon vent lines. The estimate has been adjusted for the change from liquid to gas delivery of the argon. The piping includes 53m of horizontal and 500m of vertical run. The cost per meter of each pipe was identified from the piping line list. The unit cost for carbon steel pipe for the high pressure nitrogen lines is based on internet quotes. The resulting unit cost for each pipe size was used to estimate the installed cost for transfer piping for detectors at varying depths.

The Arup design report included a risk based contingency analysis and recommended assigning a 30% contingency to the cryogenic system. The contingency on the cryogenic system and cryostat was increased to 50% for estimating these options.

5.1.2 Estimates for Conventional Facilities at the Far Site

Developing cost models for the far site detector options began with the reference design at the Homestake 4850L cost estimate. The reference design was reconfigured into a "base case" spreadsheet model for each option which ensured that all project components were accounted for. Base case models were then scaled to apply to each detector size, location, and elevation option. All cost models were developed as part of an iterative process that incorporated more refined estimates as they were developed for the different components of the estimate models.

5.1.2.1 Surface CF Cost Models

Surface detector cost models for Ash River, Soudan and Homestake are all based on recent actual construction costs for rock excavation and surface structures from the NOvA project at Ash River with some site specific "site adapt" additions made to each site as appropriate. Using actual construction costs for the surface detector options allows a reduction in the construction cost contingency from 35% to 30%. For the Soudan and Ash River options only, construction management costs for all detector options were estimated to be 14% of the construction cost based on a S. Dixon analysis of NOvA change order costs.

The estimates for pit excavation and surface structure component for the surface detector options are at conceptual design level. The underground infrastructure (UGI) and surface utility cost model, and the construction management plus the University of Minnesota (UMN) construction administration cost models are at a pre-conceptual level of maturity. Details can be found in [15], [16], [17].

5.1.2.2 Homestake Underground 4850L CF Cost Models

The 5, 17, and 34 kt underground excavation cost models were created by SURF engineers by applying the re-scoping assumptions to the reference design and then scaling these costs to develop the 5 kt, 17 kt and 34 kt cost models. The SURF/LBNE construction management team firm of Kiewit reviewed the reconfigured excavation cost models. The 5 kt and 17 kt excavation cost models applied to Homestake are not as mature as the 34 kt design.

UGI costs were initially reviewed and modified by SURF in a scaling exercise. A subsequent iteration involved a more rigorous examination of UGI costs by SURF and LBNE which resulted in UGI systems required for fire/life safety, or for early science at Homestake, being omitted from the LBNE scope and they became a SURF responsibility. One notable item are materials required for the rehabilitation of the Ross and Yates shafts, which were initially included in the LBNE cost estimate since SURF had not identified any other source of funding for them. Recently, they have stated that they believe that they will be able to identified a source, and these costs have been removed from the LBNE cost estimate. If they were restored to the LBNE budget, this would increase the cost of the underground options at Homestake by approximately $30M. Iterations by the SURF electrical engineer resulted in detailed electrical cost estimates based on modified detector specifications and requirements. This process also resulted in SURF's decision that some medium voltage electrical work would be performed by SURF employees. The UGI estimate for the reference design was scaled in response to scope modifications made to the reference design and is near a CD-1 level of maturity. The UGI estimates for 5 and 17 kt at Homestake are less mature than the 34 kt UGI estimate.

Surface infrastructure for the underground detector option, including surface structures, was estimated by SURF engineers. The construction management cost model applied to Homestake was developed by SURF engineers and includes SURF staff performing as the construction manager. The surface infrastructure estimate for 34 kt was scaled in response to scope modifications made to the reference design and is near a CD-1 level of maturity. The surface infrastructure estimates for 5 and 17 kt at Homestake are less mature than the 34 kt surface infrastructure estimate. The SURF construction manager model is at a pre-conceptual level of maturity. Details can be found in [12], [13], [14].

5.1.2.3 Soudan Underground 27L CF Cost Models

Once underground facility locations and sizes were understood, the Homestake underground excavation cost models were applied to Soudan with some scaling of drift lengths. Independent of the cost models described above, the University of Minnesota (U of MN) contracted with the Minneapolis consulting firms of CNA Consulting Engineers and Itasca Consulting Group who were familiar to U of MN. CNA and Itasca developed independent cost estimates of the excavation for the caverns, drifts, and shafts, and for the headframe/hoist systems, which were reconciled with each other then compared to the LBNE cost models during a 2-day process in Minneapolis. The three cost models for the cavern and drift components of the scope were surprisingly comparable. CNA and Itasca also developed cost models for shafts and headframe/hoist systems were also comparable; however no valid cost model for the shafts and hoists could be developed from the Homestake design, so the third comparison was not available. The average of the CNA and Itasca shaft and headframe/hoist estimates was used for the cost model. The cavern and drift excavation cost models for the 34 kt model at Soudan is less mature than the reference design. The 5 kt and 17 kt cavern and drift excavation cost models applied to Soudan are not as mature as the 34 kt cost model. Shaft and headframe/hoist cost models at Soudan are pre-conceptual.

The UGI and surface components of the 27L detector options were developed by studying the existing infrastructure available at Soudan and site adapting and scaling the Homestake UGI and surface cost model to apply it to the Soudan site. Construction management costs for all detector options at Soudan were estimated to be 14% of the construction cost based on a S. Dixon analysis of NOvA change order costs. The Soudan UGI, surface component of the 27L models, and the construction management cost models are at a pre-conceptual level of maturity. Details can be found in [18], [19], [20].

5.1.3 Estimates for Beamline and its Conventional Facilities

The estimate for the LBNE Beamline and its conventional facilities is largely based on the LBNE reference design. However, a significant number of value engineering proposals have been developed to lower the cost of the first phase relative to the reference design, and following internal review, many have been incorporated into the current cost estimate [21], [22], [23]. Some of these are design changes which lower the cost with at most minimal change in functionality, for example shortening the primary beamline or simplifying the foundation of the target hall service building. Others are staging of certain items, for example not installing water cooling in the target hall that is not needed for 700 kW operation, and future investment would be required in a later phase of LBNE. For the NuMI options, rough estimates have been made as to the level of investment that would be required to allow reliable operation at 700 kW for at least 10 years beyond the currently planned end of the NOvA run.

5.1.3.1 Options 1 and 2– Beamline to Homestake with and without NuMI components

The cost estimating methodology and the quality of the estimate for these options is similar to that of the LBNE reference design, including the assignment of contingency. In several cases the cost was adjusted by scaling the number of components (e.g., shortening of the primary beam), or solutions were adopted similar to NuMI without introducing additional risks.

For Option 1 (without NuMI components), the cost savings from the reference design is a total of \$76.4M, evenly split between the Beamline and the Conventional Facilities. For Option 2 (with NuMI components), the savings is \$47.7M in Beamline and \$38.2M in Conventional Facilities, for a total of \$85.9M. (All costs are in FY2010\$ including estimate uncertainty but not risk and top-down contingency. Details are shown in Table 2 in Section 3.3.2.

5.1.3.2 Option 3 – NuMI Beamline

Two categories of costs were considered in this scenario: calculable costs for reconfiguration, and costs associated with recovering from or providing mitigations to prevent certain failures that may happen.

Calculable costs for reconfiguration: The calculable costs include: costs for project and task management; costs to develop a target that can operate at 700 kW in the low neutrino energy configuration and develop/replace target hall instrumentation; costs to revert Horn 2 to the position required for the low energy configuration; studies needed to develop backup solutions for the decay pipe cooling and the absorber cooling; costs for updating of the controls system and costs related to retrofitting NuMI's LCW and RAW water cooling systems.

The cost estimates are of similar quality as those for the reference design. The calculable costs for the reconfiguration sum up to: \$10 M TPC FY2010.

Costs associated with recovering from or providing mitigations to prevent certain failures that may happen: NuMI was originally designed for a 10 year lifetime at 400 kW of beam power. It has already run for seven years so far and the plan is that in 2014 in will start operating at 700 kW for at least 6 years. With extended running for the LBNE-alternate at 700 kW this approaches 30 years of operation of this Beamline, most of it at a beam power almost twice the original design.

Some systems that were not designed to be repairable may fail during this time. Although the probability of a failure is very hard to estimate, the following items could each be of the order of one year of downtime to mitigate if they fail and of the order of $10M (FY10$) each: decay pipe cooling, absorber cooling, decay pipe window failure (developing a hole), tritium mitigation systems [26]. The costs associated with these risks are rough estimates at this point and it would take engineering work of a few months to be able to have better quality estimates.

It is not clear at this moment which of these items would require mitigation prior to an extended run of the NuMI line and would therefore have to be included in the total project cost. For the sake of this exercise, an allowance of $10M has been included for the calculable costs plus $15M to cover a fraction of the cost of preventive mitigation of some of the identified major risk items. A 40% contingency has been added to these, yielding a TPC of $35M (FY2010).

5.1.4 Estimates for Near Detector

5.1.4.1 ND for Homestake FD

The lowest cost option, which is used in Phase 1 for the Homestake options, is to build only the muon monitor system that is placed immediately downstream of the absorber at the end of the decay pipe. In this case, the reference design cost estimate for this system is used, and the NDC project management cost is scaled accordingly.

For the Basic and Very Basic NDC designs [29], most detector elements are based on designs whose costs were estimated by the LBNE NDC project team for LBNE reference design; however, challenges associated with remote operation have only been considered for a few weeks. For the Enhanced Basic design, there are significant design differences when compared with the standard LBNE designs. More contingency has been applied to this design to accommodate the larger project risk. The cost of the shaft [28] was included with the reference design. The minimal surface building would be 25% of the reference design cost, scaled by area.

5.1.4.2 ND for Soudan FD

The assumption for phase 1 is that the existing MINERvA and MINOS near detectors would serve as the near detector. In phase 2, an LBNE-type detector would be constructed. As noted in Section 3.4.2 a cost estimate [30] has been made only for the FGD option, based on the FGD alternated design prepared for the Director’s review. More extensive modifications would have to be made to the LAr design to fit it into the MINOS hall, and due to the short time, and the fact that the FGD cost estimate is believed to cover this case, no cost estimate has been done for the LAr near detector option. While there is significant contingency applied to these costs, they were developed quickly and must be considered to be relatively immature.

5.1.4.3 ND for Ash River FD

The same estimate maturity issues associated with the Soudan options are true here [31].

5.1.5 Project Management

The LBNE Project Office reference design cost estimate has been scaled in proportion to the square root of the prorated cost of each scenario. This somewhat arbitrary scaling formula was used in recognition that the project office costs are likely to scale more slowly than linearly with the total project cost. That is, a project of half the cost is likely to require somewhat more than half the project management cost.

5.1.6 Contingency

For the LBNE reference design cost estimates, contingency was developed in 3 pieces and added to the base costs to create the TPC (without escalation): estimate uncertainty, risk, and project manager's top-down [39]. For the estimates developed for the reconfiguration options, these pieces similarly applied to base costs. This section will describe this process, and the details of the calculations can be found in the Phased LBNE Cost Summary Excel workbook [40], as compiled by the LBNE Project Manager.

In the reference design cost estimate, estimate uncertainty contingency was applied as a percentage at the WBS level, based on the judgment of the estimator using rules developed by the Project to assess estimate maturity. This covers the uncertainty in the cost of building something, assuming that it is built as planned. This contingency was carried over or adjusted, based on new uncertainties by the L2 Project Managers in the estimates for the reconfiguration system options as discussed in each of the sections above. The base cost, plus estimate uncertainty contingency, was transmitted to the LBNE Project Manager, for inclusion into the overall options and configurations estimates.

For the reference design, risk assessment was performed, mitigations developed, and residual risk quantified for specific risks and WBS elements [41], [42]. The cost of residual risk was added to these specific WBS elements as the next piece of contingency in the cost estimates. For the reconfiguration system options, this same percentage level of risk contingency was included on the corresponding WBS elements, proportioned by cost. The one exception to this is the LAr far detector estimates, where the risk was incorporated by the L2 Project Manager into the estimate uncertainty, and therefore not double counted in the risk contingency application.

During the final development of the reference design cost estimates, an evaluation was done by the LBNE Project Manager of the level of contingency on each major system, and where deemed necessary, additional contingency applied top-down as the third piece of the contingency development. The L2 Subproject-specific top-down PM contingency is applied consistent with the reference design estimate, proportioning by the revised cost of the L2 Subproject. In addition,$50M that was held outside of any L2 Subproject in the reference design cost estimate was added to the TPC. For the reconfiguration system options, the corresponding level of contingency is effectively spread to the individual level 2 elements, such that the overall contingency is roughly the same as for the reference design.

In the summary cost estimate tables in Section 5.2, the sum of all three types of contingency is totaled in the column labeled "Total Contingency."

5.1.7 Escalation

The LBNE reference design cost estimate was made in constant dollars, using FY2010 as the base year. Since the cost estimates for the various LBNE phasing options are based on those for the reference design, the same base year of FY2010 is used. The reference design costs were escalated based on a set of laboratory-specific labor and M&S escalation rates (one for BNL and Fermilab and another for LANL). These rates were obtained from the respective laboratory Budget Offices. An additional rate table was used for conventional facilities, which was obtained from an A/E consultant [43]. These tables are given in the draft Project Management Plan [44]. A resource weighted average escalation factor (ratio of costs in a given year to those in the base year) is calculated using the escalation rates in [44] applied to the resources given in the reference design resource loaded schedule [39]. These escalation factors by fiscal year are shown in Table 3.

Table 3. Integrated escalation ratios of cost in each fiscal year relative to those in the base year FY2010.

Year	(Cost in FY)/(Cost in FY10)
FY10	1.000
FY11	1.011
FY12	1.024
FY13	1.057
FY14	1.094
FY15	1.151
FY16	1.186
FY17	1.220
FY18	1.261
FY19	1.314
FY20	1.319
FY21	1.348
FY22	1.374

To estimate an overall escalation factor for phase 1 of LBNE, a representative profile was made with a “reasonable” ramp up and ramp down at the beginning and end, with peak annual funding of $100M, and which integrates to $750M as-spent dollars for the period FY2013 – FY2022. The escalation values in Table 3 were applied to determine the de-escalated values each year. The escalated (at-year cost) and unescalated (FY2010 cost) profiles used for this exercise are shown in Fig. 1. The ratio of escalated to unescalated cost is 1.23. Based on this and to be conservative, an overall escalation factor of 1.25 was used to convert the FY2010 base-year cost estimate into an at-year cost estimate. Further details of the calculation can be found in [40]. It is worth noting that the escalation rates we use here are somewhat higher than those posted by the DOE Office of Science, Office of Project Assessment [45]. Using the rates in [42] would result in an approximately 5% ($35M) reduction in our escalated TPC estimates.

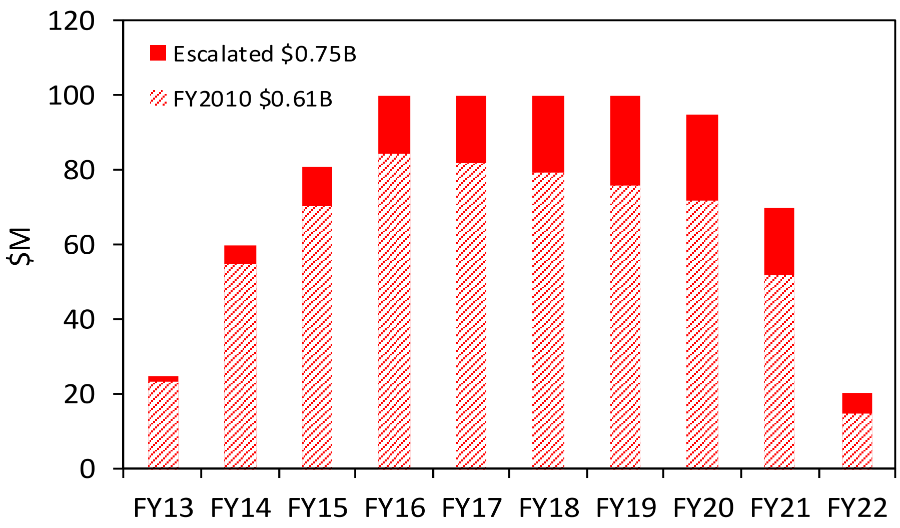

Fig. 1. Cost profile used for estimating overall escalation factor.

5.1.8 Cost Range Development

The cost estimates presented here are based on the LBNE reference design cost estimate, which is approaching CD-1 readiness. As part of preparation for CD-1, the LBNE Project developed a *cost range* for the reference design. This cost range was developed from an analysis of the reference design maturity and followed the procedures in the DOE Cost Estimating Guide DOE G 413.3-21 [46], using, as the DOE Guide recommends, the Association for the Advancement of Cost Engineering (AACE) cost range criteria table. The reference design cost estimate was thoroughly reviewed in a week-long Director's Review held 26-31 March [3] and was found to be sound: "the estimated cost ranges are realistic and consistent with the budgetary and technical objectives and are justified by the supporting documentation." The cost range presented ranged from 13% above to 25% below the point cost estimate, including all contingency factors [47]. Since the cost estimates presented here are based to the greatest extent possible on those developed for the reference design and are based on the same methodology, it is reasonable to estimate the cost range for each option using the same range relative to the point cost estimate, including all contingency factors. The range so obtained, rounded to the nearest $10M, is shown together with the point cost estimate in the summary tables in Section 5.2.

5.2 Summary of Cost Estimates

Cost estimates for various phase 1 options have been assembled from the individual level 2 cost estimates described above and they are summarized in [40]. The following set of tables, taken from [40], summarize the cost estimates for five different options, each for several different far detector sizes. These options are:

- Far detector only, located underground (4850L) at Homestake (Table 4).

- Far detector on the surface at Homestake, LBNE beam, no near detector, muon detectors only (Table 5).
- Far detector underground (4850L) at Homestake, LBNE beam, no near detector, muon detectors only (Table 6).
- Far detector underground (2340 ft) at Soudan, NuMI low-energy beam, no new near detectors (Table 7).
- Far detector on the surface at Ash River, NuMI low-energy beam, no new near detectors (Table 8).

In each table, cost estimates are shown for the Far Site (far detector and supporting conventional facilities), near site (beam, near detector systems and supporting conventional facilities), and the scaled project office cost. The base budget without contingency is shown together with the estimated total contingency yielding the estimated total project cost in FY2010 dollars (TPC3). The contingency is typically about 40%, as it was for the reference design. The contingency is a bit higher for the underground than for the surface detector configurations, reflecting the greater uncertainty of underground construction, and a little higher for the Soudan or Ash River cases than the Homestake case, reflecting the lower maturity of the designs for the NuMI options. The escalation factor of 1.25, discussed in Section 5.1.7, is applied to give an estimated TPC in at-year (AY) dollars.

A cost range relative to the escalated TPC, as discussed in Section 5.1.8 is presented for each option. The effective contingency at the top end of the cost range is also shown. At the upper end of the cost range, the contingency is typically 55% to 60%, which we believe is adequate or even conservative given the maturity of the designs and the state of the cost estimate basis. That is, we believe that the upper end of the cost range represents a conservative upper bound on the cost of each option. Note also that the cost range goes below the at-year TPC value, reflecting the fact that there remain opportunities for reducing the cost of each of the options before the project is baselined.

In each table, for each option, the cost estimate is shown for detector masses of 5, 17 and 34 kt, for which specific cost estimating was done. Figures 2 and 3 plot the cost estimates versus detector mass for the LBNE (Homestake) and NuMI options respectively. Straight line fits are shown for each, together with the parameters of the fit. In all cases, the cost slope is roughly the same at about $15M/kt. (The apparent slope differences are not significant, and mainly reflect the accuracy of these pre-conceptual estimates). The main difference is in the fixed cost offset, which is larger in the underground than the surface cases, and larger in the Homestake cases with beam than in the others. The cost difference between underground and surface implementation is about $130M at Homestake and about $175M at Soudan. The larger value at Soudan reflects the need to provide two new shafts and roads and other facilities to access them, partially offset by the shallower depth than at Homestake.

Cost estimates for additional detector mass configurations are also shown in each of the tables, to indicate detector masses which are consistent with the overall cost guideline that the TPC not exceed $700-800M. These are obtained by interpolating between the cost estimates for the three masses listed above and are highlighted in light blue each of Tables 4-8. Three of these – 10 kt on the surface at Homestake plus a new neutrino beam, 15 kt underground at Soudan, and 30 kt on the surface at Ash River – are the configurations that have been identified by the Steering Committee as viable options for a Phase 1 long-baseline experiment that have the potential to accomplish important science at realizable cost.

Table 4: Cost estimates for construction of a far detector underground at Homestake without a beam or near detector.

	FY2010 M$				AY M$		AY M$		*Top*
	Base				Esc.		Range		*End*
	Budget	Total Cont.		TPC3	@ *1.25*		*0.75*	*1.13*	*Cont.*
34 kt detector at Homestake (4850) only									
Total	461	195	42%	657	**821**		610	930	*61%*
Project Office	36	13	36%	49	61				
Far Site Cost	425	183	43%	608	760				
25 kt detector at Homestake (4850) only									
Total	*424*	*180*	*42%*	*604*	***755***		*560*	*860*	*62%*
Project Office	*34*	*12*	*36%*	*47*	*58*				
Far Site Cost	*390*	*168*	*43%*	*557*	*697*				
17 kt detector at Homestake (4850) only									
Total	348	148	43%	496	**620**		460	700	*61%*
Project Office	31	11	36%	42	53				
Far Site Cost	317	137	43%	454	567				
5 kt detector at Homestake (4850) only									
Total	216	93	43%	308	**385**		290	440	*63%*
Project Office	24	9	36%	33	41				
Far Site Cost	191	84	44%	276	344				

Table 5: Cost estimates for construction of a beamline and far detector on the surface at Homestake.

	FY2010 M$				AY M$		AY M$		*Top*
	Base				Esc.		Range		*End*
	Budget	Total Cont.		TPC3	@ *1.25*		*0.75*	*1.13*	*Cont.*
34 kt detector at Hometake (surface) + LBNE beam (phase 1) + no ND									
Total	644	247	38%	892	**1,115**		830	1270	*58%*
Project Office	42	15	36%	57	71				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	356	144	40%	499	624				
17 kt detector at Hometake (surface) + LBNE beam (phase 1) + no ND									
Total	528	203	38%	730	**913**		680	1040	*58%*
Project Office	38	13	36%	51	64				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	243	100	41%	343	429				
10 kt detector at Hometake (surface) + LBNE beam (phase 1) + no ND									
Total	*457*	*174*	*38%*	*631*	***789***		*590*	*900*	*58%*
Project Office	*35*	*13*	*36%*	*48*	*60*				
Near Site Cost	*247*	*89*	*36%*	*335*	*419*				
Far Site Cost	*175*	*73*	*42%*	*248*	*310*				
5 kt detector at Hometake (surface) + LBNE beam (phase 1) + no ND									
Total	406	154	38%	560	**700**		520	790	*55%*
Project Office	33	12	36%	45	56				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	127	53	42%	180	225				

Table 6: Cost estimates for construction of a beamline and far detector underground at Homestake.

	FY2010 M$				AY M$		AY M$		Top
	Base				Esc.		Range		End
	Budget	Total Cont.		TPC3	@ 1.25		*0.75*	*1.13*	*Cont.*
34 kt detector at Hometake (4850) + LBNE beam (phase 1) + no ND									
Total	717	287	40%	1,004	**1,255**		940	1420	*58%*
Project Office	45	16	36%	61	76				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	425	183	43%	608	760				
17 kt detector at Hometake (4850) + LBNE beam (phase 1) + no ND									
Total	604	241	40%	845	**1,056**		790	1200	*59%*
Project Office	41	15	36%	56	69				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	317	137	43%	454	567				
10 kt detector at Hometake (4850) + LBNE beam (phase 1) + no ND									
Total	*530*	*210*	*40%*	*740*	***926***		*690*	*1050*	*58%*
Project Office	*38*	*14*	*36%*	*52*	*65*				
Near Site Cost	*247*	*89*	*36%*	*335*	*419*				
Far Site Cost	*245*	*108*	*44%*	*353*	*441*				
5 kt detector at Hometake (4850) + LBNE beam (phase 1) + no ND									
Total	474	186	39%	660	**825**		620	940	*59%*
Project Office	36	13	36%	49	61				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	191	84	44%	276	344				

Table 7: Cost estimates for construction of a far detector underground at Soudan, including an allowance for necessary investments in the NuMI beamline to permit reliable long-term operation

	FY2010 M$				AY M$		AY M$ Range		*Top End*
	Base Budget	Total Cont.		TPC3	Esc. *@ 1.25*		*0.75*	*1.13*	*Cont.*
34 kt detector at Soudan (2340) + NuMI LE Beam (700 kW) + no ND									
Total	529	220	42%	749	**936**		700	1060	*60%*
Project Office	38	14	36%	52	65				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	465	196	42%	662	827				
17 kt detector at Soudan (2340) + NuMI LE Beam (700 kW) + no ND									
Total	403	169	42%	572	**715**		530	810	*61%*
Project Office	33	12	36%	45	57				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	345	147	43%	492	615				
15 kt detector at Soudan (2340) + NuMI LE Beam (700 kW) + no ND									
Total	*385*	*162*	*42%*	*540*	***675***		*500*	*770*	*60%*
Project Office	*32*	*12*	*36%*	*44*	*55*				
Near Detector			*-*						
NuMI upgrades/maintenance	*25*	*10*	*40%*	*35*	*44*				
Far Site Cost	*328*	*141*	*43%*	*461*	*577*				
5 kt detector at Soudan (2340) + NuMI LE Beam (700 kW) + no ND									
Total	269	113	42%	382	**477**		360	540	*61%*
Project Office	27	10	36%	37	46				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	217	93	43%	310	387				

Table 8: Cost estimates for construction of a far detector on the surface at Ash River, including an allowance for necessary investments in the NuMI beamline to permit reliable long-term operation. The cost of detectors on the surface at Soudan would be very similar.

	FY2010 M$				AY M$		AY M$ Range		*Top End Cont.*
	Base Budget	Total	Cont.	TPC3	Esc. *@ 1.25*		*0.75*	*1.13*	
34 kt detector at Ash River (surface) + NuMI LE beam (700 kW) + no ND									
Total	419	167	40%	586	**732**		550	830	*59%*
Project Office	34	12	36%	46	57				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	360	145	40%	505	631				
30 kt detector at Ash River (surface) + NuMI LE Beam (700 kW) + no ND									
Total	*391*	*156*	*40%*	*547*	***684***		*510*	*780*	*60%*
Project Office	*33*	*12*	*36%*	*44*	*55*				
Near Detector			-						
NuMI upgrades/maintenance	*25*	*10*	*40%*	*35*	*44*				
Far Site Cost	*333*	*135*	*40%*	*468*	*585*				
17 kt detector at Ash River (surface) + NuMI LE beam (700 kW) + no ND									
Total	300	121	41%	421	**527**		390	600	*60%*
Project Office	29	10	36%	39	48				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	246	101	41%	348	435				
5 kt detector at Ash River (surface) + NuMI LE beam (700 kW) + no ND									
Total	174	71	41%	245	**306**		230	350	*61%*
Project Office	21	8	36%	29	36				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	128	53	42%	181	226				

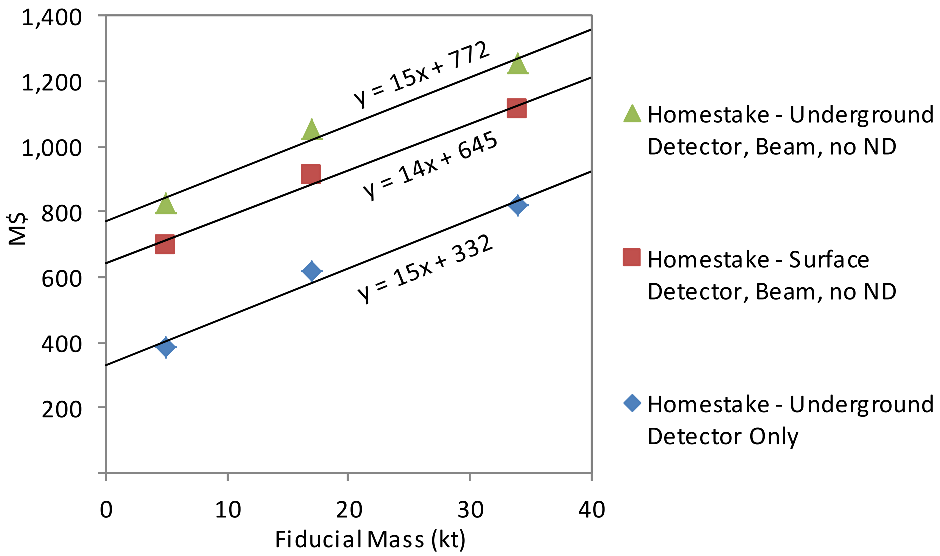

Fig. 2. Total Project Cost versus far detector fiducial mass for Homestake options.

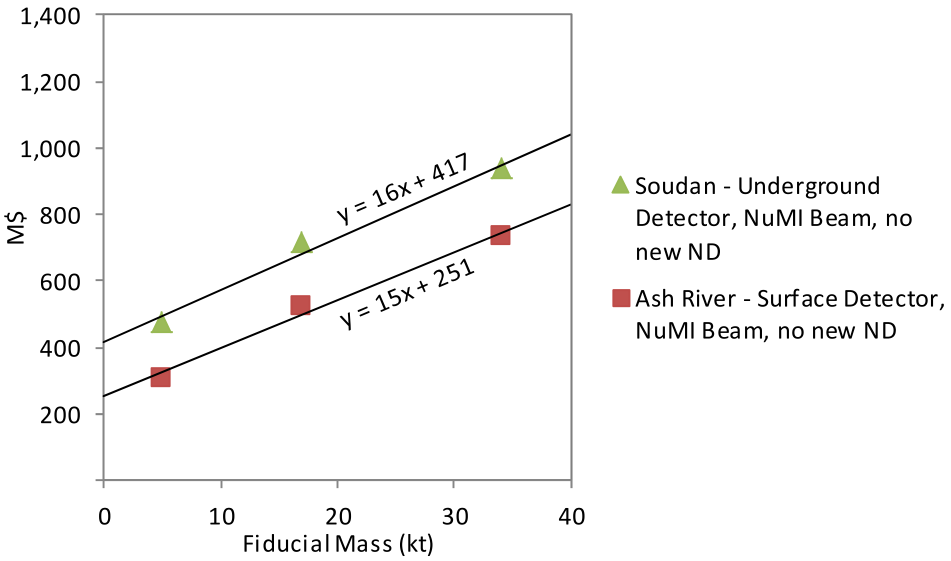

Fig. 3. Total Project Cost versus far detector fiducial mass for NuMI options.

6 Comparison with Reference Design and Cost Estimate

In the course of developing the phasing options and alternatives discussed in this report, many value engineering proposals were considered to lower the cost of project, and after careful review, some were implemented. These fall into three broad categories:

- Simplifications which result in little or no loss of functionality.
- Staging opportunities which would require later investment to restore full functionality.
- Transfer of scope and corresponding cost to others, based on the evolving understanding of facility management responsibilities.

Some of these value engineering proposals were in process at the time of the Director's Review in March 2012 and were intended to be incorporated into the project plan for the previously scheduled CD-1 DOE Review, some were proposals that were previously planned to be fully considered between CD-1 and CD-2, and others were new ideas developed during the reconfiguration process, some of which followed from comparison of modes of construction and operation at the different candidate facilities. The accepted value engineering proposals reduced the estimated cost of many of the phasing and alternative options, and they are discussed at the appropriate points in this report. Many of them also apply to the full LBNE project scope and would lower the cost estimate that was presented to the Directors Review.

This section summarizes those value engineering changes and the cost estimate as applied to the full LBNE scope, and compares it with that presented at the Director's Review. Cost figures cited in this section include escalation and all contingency factors. In making detailed comparisons with the Director's Review cost estimate, the additional $50M that was held outside of any L2 Subproject (see section 5.1.6) was spread proportionally across the individual near- and far-site WBS elements. For this section only, a higher escalation factor of 1.284, based on the net escalation in the Director's Review cost estimate [39], has been applied.

Liquid Argon Far Detector: At the time of the Director's Review, a plan to substantially simplify the cryogenic system for the LAr-FD [48] was under development; it was formally approved by the LBNE Project Management Board in May 2012. The major elements of this change are:

- Moving the compressors for the nitrogen refrigerator from underground to the surface.
- Route the cryogenic pipes down the Ross Shaft rather than the Oro Hondo Shaft.
- Deliver argon underground in the form of cold gas rather than liquid. This eliminates the need for pressure reducing stations every ~800 feet along the shaft.

The net savings from this change is about $35M.

Conventional Facilities at the Far Site: Changes in the CFFS scope and cost result from several factors:

- Changes in experimental requirements.
- Revised infrastructure requirements.
- SURF, rather than an outside contractor, performing the construction management function.
- Scope transfers from LBNE to SURF.

The major changes in experimental requirement follow from the changes in the cryogenic system discussed above. Moving the compressors to the surface reduces underground space, power and cooling requirements. Routing the piping down the Ross Shaft eliminates the need to renovate the Oro Hondo shaft; eliminates a new ventilation bore hole from the 3950L to the 4850L and corresponding development at the 3950L; and allows use of existing buildings at the head of the Ross Shaft for cryogenic equipment rather than developing a new "campus" at the head of the Oro Hondo. In addition, the high-bay area above the cryostat was made more narrow such that it is now the same width as the cryostat pit (elimination of the "muffin top"). The net savings from these and other smaller changes is about $95M.

A hard-nosed evaluation was made of the infrastructure supporting LBNE operations at the 4850L, to distinguish that which is absolutely necessary from that which is merely desirable. Examples include the scope of potable and industrial water supplies, redundant power and cyber infrastructure feeds, the frequency of lighting in the west access drift which will be used only as a secondary egress route, and various underground "finishes." Some of these changes were inspired by comparison between the proposed infrastructure at Homestake with the actual infrastructure at the Soudan Lab. The net savings from these infrastructure reductions is about $50M.

In the plan presented at the Director's Review, it was assumed that an outside A/E firm would be hired as a Construction Manager. This model followed from the original DUSEL plan, which had been developed in the context of a much larger and more complex facility than is planned for LBNE alone. In the course of evaluating the actual scope of LBNE, it was concluded that the SURF staff at Homestake have sufficient core expertise to allow them, with appropriate additional staff, to serve this function for LBNE construction, as they have been doing for successful development of the Davis Campus. This change of the construction management reduces overheads and eliminates the need to pay the profit of an external firm. The net cost reduction is estimated to be approximately $70M.

In the course of evaluating the underground infrastructure requirements, and in the context of considering the configuration of SURF if LBNE builds its phase 1 detector on the surface, it was realized that there was a non-negligible component of underground infrastructure which was assigned to the LBNE budget, but which is required to support the Early Science Program, independent of the requirements for or even of the existence of LBNE. Following guidance received from DOE at the beginning of the reconfiguration process, these components were removed from the LBNE plan and transferred to SURF. This reduced the LBNE budget by approximately $100M.

The cost estimate presented at the Director's Review included approximately $30M for materials necessary for the on-going renovation of the Ross and Yates shafts. The shaft renovation was considered to be a SURF responsibility. However, SURF had been unable to identify a source of funding for these materials, and since the shaft renovation would also be necessary for an underground installation of LBNE, LBNE agreed to provide budget for these materials. During the course of the reconfiguration work, SURF notified LBNE that they believed that they would be able to find other sources of funding for these materials [49], and therefore this amount was removed from the LBNE budget.

The total reduction in the CFFS cost estimate is approximately $320M. Table 9 summarizes the Far Site cost reductions, including the LAr-FD and the CFFS.

Table 9: Summary of scope and cost reductions at the Far Site, in $M, with escalation and all contingency factors applied.

LAr Far Detector	Cost Savings
Simplified Cryo System	35
Total - LAr Far Detector	**35**

Far Site Conventional Facilities	Cost Savings
Changed exp requirements	95
Revised infrastructure requirements	50
SURF as Construction Manager	70
Scope transferred to SURF	100
Yates/Ross shaft materials	30
Total - Far Site CF	**345**

Grand Total - Far Site	**380**

Neutrino Beam and Conventional Facilities at the Near Site: The value engineering changes to the LBNE neutrino beamline design have already been presented in sections 3.3.1 and 3.3.2 and summarized in Table 2. The total cost reduction presented there of $86M is in FY2010 dollars, and includes only estimate uncertainty contingency. Including risk, top-down contingency specific to the beamline, and the proportional share of the $50M of top-down contingency that was held outside of any L2 Subproject, the total cost reduction is approximately $130M.

Near Detector Complex: The focus of the reconfiguration work was on developing minimal designs that could be deployed in an excavation consisting just of the one of the shafts planned for the full near detector hall (section 3.4.1), or modifications to the reference designs to adapt them to space in the NuMI near detector hall (sections 3.4.2 and 3.4.3). No value engineering proposals were developed that would apply to the full-scope LBNE near detector.

Project Management: The estimated cost of the Project Office has been scaled to the reduced cost of the project, as described in section 5.1.5. For the full-scope LBNE with all of the value engineering changes discussed above having been applied, the estimated reduction in Project Management cost is approximately $15M.

The total of these value engineering changes is summarized in Table 10. It should be noted that these cost savings result from changes in the detailed scope of the project, i.e. simplifying or eliminating items that are not absolutely necessary, and not from any reduction in the unit or fixed costs that appear in the basis of estimate documents developed for the full LBNE cost estimate presented to the Director's review. Table 10 also indicates how much of the cost reduction represents true scope and cost reductions and how much represents transfer of costs and work scope from LBNE to SURF.

Table 10: Summary of value engineering cost reductions for the full LBNE, in $M, with escalation and all contingency factors applied.

	Cost Savings
Project Office (scaled cost)	15
Beamline	130
Far Site	380
Total Value Engineering Savings	**525**

	Cost Savings
True Scope/Cost Reductions	395
Cost Transfer to Others	130
Total Value Engineering Savings	**525**

The application of these value engineering changes to the full LBNE project, with a new neutrino beam aimed at Homestake which is capable of handling a 700 kW beam power and is upgradeable to ≥2.3 MW; a full-performance near detector complex, and a 34 kt fiducial mass liquid argon TPC far detector at the 4850L at Homestake, would reduce the cost of the full LBNE Project by the amount shown in Table 10. The cost estimate presented at the Director's Review was $1.98B in at-year dollars with all contingency applied, and the CD-1 level cost range was $1.47B - $2.24B [39], [47]. With the recent value engineering changes, if LBNE were to be pursued in a single phase, the current estimated cost would be around $1.45B, with a CD-1 type cost range of about $1.1B - $1.65B. Thus a first phase costing $700M - $800M would represent about half the total cost of the full project, and LBNE could be essentially completed in two phases of this magnitude.

7 Evaluation of Relative Risks

In preparation for CD-1 for the original, full-scope LBNE, and extensive and formal risk analysis was performed, including risk identification; analysis of risk probabilities and cost and schedule impacts; development of mitigation plans for the most significant risks, which were included in the resource loaded schedule presented at the March 2012 Director's Review; and quantification of residual risk, including residual probability and cost and schedule impact [41], [42]. The results of the risk analysis were used to inform decisions about major project alternative, most notably the beamline configuration and the far detector technology, and as a component of the contingency development (see Section 5.1.6). Since options considered for reconfiguring LBNE are based as much as possible on the reference design presented to the Director's Review, much of the previously developed risk analysis still applies. For this reason, as well as the lack of time in developing the reconfiguration options, a new formal risk analysis has not been performed. This section does not discuss the full array of risks already developed and documented [42], but rather is limited to a relatively high-level summary of the major differences in risks among the different options.

Conventional Facilities at the Far Site Risks

Surface vs. Underground: In general, the risks of conventional facilities construction and detector construction underground are greater than on the surface, both due to the greater uncertainty of construction conditions and less flexibility in finding solutions if unexpected problems are encountered. This is reflected, at least in part, in the higher contingency for the underground options (Tables 4, 6 and 7) than for the corresponding surface options (Tables 5 and 8).

Geotechnical Risks: The excavation risks due to uncertain ground conditions are similar at both the Homestake and Soudan underground sites. Both proposed sites are near existing excavations (existing drifts and the Ross campus at Homestake, the existing Soudan 2 and MINOS caverns at Soudan), but no geotechnical investigations have been performed for the propose specific locations. The Soudan site does come with additional risk due to the need to sink two new shafts, although the existence of the currently operating shaft gives confidence that this additional risk is not large. The geotechnical risks are also similar for the surface sites at Homestake (adjacent to the existing Oro Hondo shaft) and Ash River (adjacent to the existing NOvA building).

Liquid Argon Far Detector Risks

Far Detector Location: The detector design is essentially identical for both underground locations. For surface locations, the design is modified only modestly, and is essentially identical for all locations. Therefore there is no significant difference among the different options regarding detector construction. Commissioning risks are somewhat larger for underground locations due mainly to the reduced flexibility in reacting to unexpected circumstances.

Far Detector Size: The detector construction and commissioning risks are very similar for all detector sizes, but are somewhat larger for larger detectors, both directly from the number of components involved and because dealing with unexpected problems will take longer with a larger mass detector. The major commissioning risks are already addressed for all detector sized ≥10 kt fiducial mass by segmenting them into two modules. See section 6.8 of [50]. For detectors of fiducial mass ≥15 kt, a large "1 kt" prototype (actually 0.23/0.40/0.83 kt fiducial/active/total mass) is included in the project plan [50]. For the smaller mass detectors, the 35 t prototype currently under construction will allow prototyping of various detector elements, and the first of the two far detector modules will serve effectively as the prototype for the second.

Neutrino Beamline Risks

LBNE Beamline: The construction of a new beamline for the Homestake options entails additional risk that is not present in the NuMI-based options, for which the beamline exists. However, these risks have already been captured in the risk analysis done in preparation for CD-1 and are reflected in the contingency. The value engineering changes made since the Director's Review add modest risk, since the modified designs are not as well developed as for the Director's Review design. However, this additional risk is small since a) the modifications are more ones of detail than of fundamental design, and b) all were subjected to thorough internal scrutiny before being accepted. One category of value engineering changes, however, is worth noting. The plan to re-use certain NuMI components in building the LBNE beamline (see sections 3.3.1 and 3.3.2 and Table 2) entails the risk that these components may not be available when LBNE would need them, either due to some of them no longer being functional or due to programmatic considerations at the time. Reflecting these additional modest risks, the contingency on the reconfigured beamline, including conventional facilities, has been increased from 35% to 37%.

NuMI Beamline: Although this beamline already exists, there are non-negligible risks in its use for a reconfigured LBNE. This beamline was designed for 10 years of operation at 400 kW proton beam power, but by the end of a 10-year run for the reconfigured LBNE it would have run for about 8 years at the design beam power, plus at least 16 years at almost twice the design beam power. As summarized in Section 5.1.3.2 and discussed more fully in [25] and [26], there are a number of key components which could fail during such a long-extended run and which were not designed to be maintained. In addition, there are radiological risks related to the long-term buildup of tritium and possible changes in hydrological conditions that are key to the tritium management in the NuMI beam. Although current evaluation suggest that these would not be insurmountable problems were they to occur, and although an allowance has been included in the cost estimate for the NuMI options to allow preventive mitigation of some of the potential problems, the risk of not being able to complete a long LBNE run is present.

In addition, there are fundamental performance limits of the NuMI beamline which would limit its long-term capability. First, with a design beam power of 400 kW, it cannot utilize much more than about 1 MW of proton beam power, and certainly not the full power that Project X would be able to provide. Second, the smaller diameter decay pipe than in the LBNE design limits the ability to provide flux at lower neutrino energies. The longer decay pipe adds a longer high-energy tail which provides background but little signal to the ν_e appearance oscillation physics. Third, the requirement that there no beam loss in the long "carrier" pipe, which brings the beam through the aquifer, prevents operation at beam energy below 120 GeV, eliminating a mechanism to provide lower neutrino energies. These limitations could only be mitigated by construction of a new beamline of similar design and similar cost to the LBNE beamline.

Physics Risks

Cosmic Ray Background in a Surface Detector: The relatively long live time per beam pules of an LAr TPC, set by the maximum drift time (1.4 ms in the current design for surface implementation) make it vulnerable to cosmic ray backgrounds. Although the vast majority of cosmic ray events can be identified as such and eliminated, the expected low beam event rate in a long-baseline experiment make it possible that very rare cosmic ray events could mimic beam-induced events. This is currently a topic of intense study by the LBNE Science Collaboration.

Mitigations that are already included in the detector design are reduced drift length (2.3 m vs. 3.7 m underground), which reduces the live time and helps with pattern recognition due to the greater segmentation, and the inclusion of a photon detector system to aid in timing events to the beam spill. The Collaboration is currently studying all of the kinematic variables that could be used to distinguish background from signal to determine if the existing detector design is adequate. Early studies suggest that a number of possible cuts can be applied which will reduced the background to a level substantially smaller than the ν_e appearance signal without inducing large inefficiencies or biases in the signal [51]. However, more work needs to be done to adequately quantify this.

Additional potential mitigating measures include:

- Modestly increasing the overburden, from the currently assumed ~3 m of rock equivalent to, for example, 10-20 m.
- Utilizing the local topography to provide shielding against large zenith-angle cosmic rays from roughly the same direction as the beam, which may be the most dangerous source of background. Given the flat terrain at Ash River, this is not an option there.
- Further shortening of the drift length.
- Providing optical segmentation to better localize the light signal, e.g. by making APA and CPA planes opaque and non-reflecting.
- Building a tracking veto system with good timing.

Cost estimates will need to be developed for those mitigations that are shown to be necessary and effective.

This risk could be eliminated by placing the detector at a substantial depth underground. The additional cost of going underground at Homestake would put the total project cost above the maximum guidance given by DOE OHEP (see Section 2.3). If foreign collaborators or other non-DOE funding sources could be identified, then placing the detector underground at Homestake could be possible.

Near Detector Risks: The Homestake options do not include a near neutrino detector in the first phase, and the NuMI options assume that in phase 1 the existing MINERvA, MINOS or NOvA near detectors, which are not optimized to work with a LAr TPC far detector will be used. This risks that the experiment will become systematics limited at an early stage; this risk is certainly greater for the Homestake options. This risk is being intensively studied by the LBNE Science Collaboration [52] to quantify the expected systematic errors for the mass hierarchy and CP violation measurements, and determine for how long the statistical errors will dominate. Studies consider what can be done utilizing all available including the tertiary muon monitors, knowledge gained from the NuMI beam, normalization using the ν_μ spectrum measured at the far detector and the by-then well-measured values of θ_{23} and Δm^2_{32}. These studies include a range of near neutrino detectors, ranging from none (only muon monitors), to a far-off-axis detector on the surface, to a simple detector-in-a-shaft as described in Section 3.4.1, to the full LBNE near neutrino detector. This will give a range of costs of mitigating this risk, varying from none to the cost of a surface detector (very crude estimate on the order of \$20M), to that of a detector-in-a-shaft (~\$30M-\$35M for the Very Basic or Basic options, including the shaft cost) to the cost of a full near neutrino detector (\$130M).

Assuming that statistical error will dominate for the first several years of running, this risk can be addressed by building a near neutrino detector in an early phase 2. For the Homestake options, such a phase 2 project would cost about \$130M, and if started promptly after phase 1 and could be completed within a few years. If foreign collaborators or other non-DOE funding sources could be identified, then this phase 2 near detector could be completed simultaneously with the phase 1 beam and far detector.

8 Conclusions

Based on the well-developed Conceptual Design and corresponding cost estimates for the LBNE Project, a large number of potential configurations for phasing LBNE or alternates to it have been studied for technical feasibility and to estimate their costs, including full contingency and escalation estimates. The cost guideline is that the first phase should have an estimated Total Project Cost no more than $700-800M, and that the CD-1-type cost range should be consistent with the LBNE CD-0 cost range of $660-940M. In parallel with this effort, the Physics Working Group studied the science capabilities of a similar set of options, evaluating their capabilities for accelerator-based neutrino oscillation measurements as well as non-accelerator physics: proton decay searches, sensitivity to supernova neutrinos, and measurements with atmospheric neutrinos. Based on the combination of the physics and cost information, the Steering Committee identified three phase one options that would provide significant scientific results and are consistent with the budget guideline that the first phase cost should be limited to $700-800M, including contingency and escalation. These three are:

- 30 kton surface detector at Ash River (NuMI low energy beam, 810 km baseline)
- 15 kton underground (2340 ft) detector at Soudan (NuMI low energy beam, 735 km baseline)
- 10 kton surface detector at Homestake (new beamline, 1,300 km baseline)

Their estimated costs are summarized and compared in Table 11. All three are consistent with the cost guidelines and with the CD-0 cost range; however, the first two are moderately less expensive than the third.

Each of these first-phase options is more sensitive than the others in some particular physics domain, but none of them is configured with the long baseline and underground detector that is needed to be able to achieve all of the main science goals of LBNE. The Steering Committee strongly favored the option to build a new beamline to Homestake with an initial 10 kton LAr-TPC detector on the surface. The physics reach of this first phase is very strong; more over this option is seen by the Steering Committee as a start of a long-term world-leading program that would achieve the full goals of LBNE in time and allow probing the Standard Model most incisively beyond its current state. Ultimately this option would exploit the full power provided by Project X. With an additional investment of an estimated $135M, it would be possible to place the 10 kton detector underground at Homestake, which would provide all of the elements needed to begin to address the full range of research envisioned for LBNE.

Table 11: Comparison of cost estimates for the three options identified by the Steering Committee as viable options for a Phase 1 long-baseline neutrino experiment.

	FY2010 M$				AY M$		AY M$		*Top*
	Base				Esc.		Range		*End*
Option	Budget	Total	Cont.	TPC3	@ *1.25*		*0.75*	*1.13*	*Cont.*
30 kt detector at Ash River (surface) + NuMI LE Beam (700 kW) + no new ND									
Total	*391*	*156*	*40%*	*547*	***684***		*510*	*780*	*60%*
Project Office	*33*	*12*	*36%*	*44*	*55*				
Near Detector			-						
NuMI upgrades/maintenance	*25*	*10*	*40%*	*35*	*44*				
Far Site Cost	*333*	*135*	*40%*	*468*	*585*				
15 kt detector at Soudan (2340 ft depth) + NuMI LE Beam (700 kW) + no new ND									
Total	*385*	*162*	*42%*	*540*	***675***		*500*	*770*	*60%*
Project Office	*32*	*12*	*36%*	*44*	*55*				
Near Detector			-						
NuMI upgrades/maintenance	*25*	*10*	*40%*	*35*	*44*				
Far Site Cost	*328*	*141*	*43%*	*461*	*577*				
10 kt detector at Hometake (surface) + LBNE beam + muon monitors									
Total	*457*	*174*	*38%*	*631*	***789***		*590*	*900*	*58%*
Project Office	*35*	*13*	*36%*	*48*	*60*				
Near Site Cost	*247*	*89*	*36%*	*335*	*419*				
Far Site Cost	*175*	*73*	*42%*	*248*	*310*				

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Note: References to LBNE documents (lbne-doc-nnnn) refer to the most recent version as of the time of the writing of this report. More recent versions may exist with updated information that is not included in this report. Some documents are password protected; to request access, please contact the Working Group Deputy Chair.

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