Actions on Comments and Points from the written committee report.

Robert Svoboda (co-spokesperson), Milind Diwan (co-spokesperson), Robert Wilson (Physics working group leader), Maury Goodman (deputy spokesperson).

Actions on committee comments are in blue.

The committee has provided the collaboration with valuable advice and recommendations. Their report is likely to be of use to future reviews and to various stakeholders. We have produced this list of actions to record how we have incorporated their advice into our planning process. Comments requiring no action are also indicated. The list of Challenges and Risks noted will be captured in a tracking list to aid us in future reviews.

1 WC detector

We list here, in bullet point form, what we consider the key strengths and challenges of the proposed WC detector, and the key risks which we think should be considered when making a technology decision. A similar list for the LAr detector follows in the next section.

1.1 WC detector – key strengths

- There is a long history of successful water Cerenkov detectors for this type of physics, most notably from the IMB, Kamiokande, Super-Kamiokande, and SNO experiments. This is a well-developed technology and has been used in two previous long-baseline neutrino oscillations experiments (K2K and T2K). The basic principles of a WC detector are well understood and are unlikely to yield any surprises.
- The LBNE collaboration contains broad expertise on water Cerenkov technology, including members of all of the water Cerenkov experiments listed above.
- The WC detector offers the largest achievable detector mass. It thus provides the largest sample of events to work with, which would bring significant benefits to atmospheric neutrino oscillation studies, supernova detection, relic SN neutrinos.
- This large event sample offers the potential to greatly improve the statistics to the extent that improved analysis techniques would allow non-QE events to be included in the signal. In their absence the two detectors, as proposed, have a comparable number of signal events. The advantage is size would be particularly important at low energies, where the CP-sensitivity is potentially high but the statistics are poor.
- The use of an open water tank makes access easy for a broad range of calibration devices, and substantial experience exists on how to calibrate a large water Cerenkov detector. This means that estimates of detector performance are likely to be well founded.
- We have noted the analysis of these key strengths. No further action needed.

1.2 WC detector – key challenges

- The WC technique works best for simple final states, as it becomes difficult to properly reconstruct the overlapping Cerenkov rings from final states with many charged particles. The energy range of LBNE is not well tuned in this respect, as most of the cross-section at LBNE energies is for more complicated final states which currently contribute backgrounds rather than signals.
- We understand that the WC technique is best tuned for simple final states. This is the key reason that the detector mass needs to be large so that sufficient number of these events can be captured. On the other hand the simple final states also allow for greater confidence in the energy resolution of the event. Action: this is an analysis issue that will be tracked.
- The relatively poor rejection (compared to a LAr, see the figure) of (primarily) neutral-current background events produces a large background under the key second-maximum appearance peak.
- This is an important concern that will be addressed with improved analysis and possibly an alternate beam spectrum. However, most of the sensitivity of the experiment to θ_{13} and CP

comes from the first oscillation maximum. The impact on mass hierarchy is in one region of δ_{CP} values as shown in the answers to questions (Section 2, page 6). Action: continue to improve analysis and optimization of the beam.

- The current reconstruction algorithms are limited to unambiguous reconstruction of QE events only, resulting in low efficiency compared to the total neutrino interaction rate.
- We understand that the efficiency for the water detector is low due to the current algorithm that uses only the simplest final states, and in particular the QE events. Even so, the science goals of the project are satisfied. Efforts are underway at T2K and LBNE to include more complex multi-ring events in the analysis, which will increase the efficiency. We note also that current estimates are based on the Super-Kamiokande performance parameters, but the nominal baseline design for the LBNE WCD has much better time resolution (1.2 ns versus 3.0 ns) and 35% better pixel density per unit area, so it is reasonable to anticipate better performance. Action: Continue to improve analysis and cut optimization to improve efficiency.
- The use of Cerenkov light for particle detection means that the Cerenkov threshold makes the detector blind to low-energy charged particles, which would hamper the reconstruction of some channels.
- We understand that the particles below the Cherenkov threshold cannot be detected. This limitation causes two problems for accelerator neutrino beam physics: it dilutes the QE sample with non-QE final states and also negatively affects the energy resolution. The energy lost to below Cherenkov threshold particles is low, and therefore the effect on the energy resolution is not large. Many of the events in which pions are below threshold can be separated using subsequent muon decays. These detailed resolution effects are included in our studies. Action: No action needed.
- Optimizing physics sensitivity for other topics such as solar or geo neutrinos would require costly upgrades to the detector.
- We note that such upgrade paths also make the WC choice attractive in terms of broader scientific agenda. Action: No action needed.
- It would not be possible to run a WC detector as a near detector, requiring larger corrections to the measured near detector distributions in order to extrapolate them to the far detector.
- The current concept for a near detector is for a very fine-grained magnetized detector with water target layers that can measure events in great detail. Such as detector will be capable of measuring the flux and relevant cross sections with sufficient precision. It is also plausible, though we don't believe necessary, to use a small water Cherenkov detector with micro-channel plate photon detection. Action: continue to improve the requirements of the near detector and associated design.

1.3 WC detector – remaining significant risks in our assessment.

- Simulations to date assume a 5% systematic error in background normalization and no systematic error in background shape, both of which seem very optimistic. The poor state of our knowledge of the cross-sections for individual exclusive channels could easily result in a distortion of the energy spectrum of the mis-reconstruction background, thus altering the apparent ratio of the first to the second maximum appearance peaks and the shape of the peaks themselves, and furthermore does it differently for neutrinos and anti-neutrinos. This could lead to a false CP-violation signal (or mask a real one). Near detector measurements will help, but cannot eliminate this possibility, as the near detector will be unable to determine in every case what channel produced each background event, and therefore the extrapolation to the far detector is uncertain. The plausible size of this systematic has not yet been estimated.

- We understand that this is the most important analysis issue. The committee also raised this concern in the pre-presentation list of questions and comments. We have a conceptual plan based on experience from previous experiments such as MINOS, T2K, etc. Specifically MINOS achieved ~5% systematic uncertainty on electron neutrino appearance backgrounds. Our conceptual plan is provided in the answers to questions (Section 2, page 1). Action: continue to improve the requirements on systematic uncertainties and the role of the near detector.
- The construction of such a large WC detector requires a cavity of unprecedented size at large depth. This creates schedule, cost, and even project failure risks which should be carefully considered.
- The LBNE project has engaged the world's foremost experts in underground construction in cavity construction in its Large Cavity Board. This group recorded a unanimous positive opinion, which is documented in a large number of detailed technical evaluations, test bores, and design studies from the construction industry. The committee did not have the opportunity to review the extensive cavity documentation. Action: item is already being tracked in the project.
- The collaboration currently assumes a 40% increase in the light-collection efficiency from either concentrators or wavelength-shifting plates. However no actual final design exists and detailed simulations of the effect of such systems on the physics sensitivity have not been completed. If such light collectors turn out not to be feasible this would require a much larger number of phototubes to achieve the same physics return.
- This risk has been studied by the project manager, and the fall back to the larger number of phototubes to meet the science requirements has been included in the project contingency. Action: item is already being tracked as part of the project.
- Although the phototubes currently being considered are smaller diameter than those used in SuperKamiokande, and therefore are less susceptible to implosion, a full engineering evaluation of implosion risks and mitigation schemes has not been completed. This introduces additional uncertainty in the light collection efficiency.
- The risk regarding implosion abatement design is included in the cost of the project. This has been thoroughly reviewed by a recent technical design review, which included data from recent implosion studies by the project. Action: item is already being tracked as part of the project.

2 LAr detector

2.1 LAr detector – key strengths

- The near-photographic imaging of events would allow reconstruction and particle identification for each track and excellent track/shower separation and π^0 rejection. This would allow unprecedented reconstruction of neutrino interactions. . This is the basis for the lower predicted backgrounds not arising from the intrinsic ν_e contamination of the beam, as can be seen in the figure. The excellent reconstruction capability could lead to background rejections even higher than currently assumed.
- The use of ionization rather than Cerenkov light removes the Cerenkov threshold and makes the detector sensitive to all charged particles.
- Many of the operational parameters, like the electron drift lifetime, can be calibrated *in situ*.
- The rich new data would attract significant global interest and supply many challenging analysis topics to engage the community, giving opportunities to young physicists to make a mark.
- There is no experience in operating a LAr detector of this scale underground. Its entirely new capabilities could lead to totally unexpected discoveries, which has happened many times in underground physics.
- The possibility of building a small LAr detector for use as a near detector should lead to reduced systematic uncertainties in the comparison of the near and far detector measurements.
- We understand this analysis of the key strengths of the LAr approach. Action: No further action needed.

2.2 LAr detector – key challenges

- There is no experience in operating a LAr detector of this scale anywhere, particularly underground. This could lead to delays/overruns due to unexpected problems.
- The project team has developed a risk management strategy and are evaluating the schedule/costs and critical milestones. Action: item is already being tracked as part of the project.
- The detailed reconstruction of LAr data is still in a very early stage.
- Considerable effort is underway for reconstructing the LAr simulation data. Action: item is already being tracked as part of the project.
- Great care is needed to maintain overall cleanliness and purity to maintain the drift electron lifetime.
- The project will develop a cleanliness plan and a design manual for the detector facilities before construction. Action: item is already being tracked as part of the project.
- It should be noted that a large LAr detector consists in the repetition of a large number of basic cells. This committee believes that most of the needed elements have been or will be tested in large set ups: cryostat, liquid purity, wire structure, HV, low temperature electronics. The extrapolation from the 600 ton of Icarus to 40kT may therefore be less risky

than the factor 70 in mass seems to imply. However the new detector design will require extensive prototype testing for construction details, cryogenic systems, TPC and electronics optimization response measurements.

- The extensive prototyping program including a 1 kt prototype is being evaluated as part of the project. This has been thoroughly reviewed by the recent technical design review. Action: item is already being tracked as part of the project.
- The muon veto system assumed for shallow deployment must have extremely high rejection to maintain proton decay sensitivity.
- We are re-evaluating this requirement. A simulation effort is in progress to understand the entering kaon backgrounds and rejection of these cosmogenic kaons using kinematic cuts. Action: simulation effort is underway at universities. Results expected in a few months.
- The design of a low cost sensor of the primary scintillation light for triggering on non-beam physics at low energy is not yet complete.
- An R&D program for the photon system is in progress. There are various approaches including wavelength shifting bars. Action: R&D effort will be carefully tracked and strengthened.
- The impact of spallation isotopes from neutron interactions in LAr at 800ft is potentially a large problem for the SN physics, and is not yet well understood.
- Our initial evaluation of the spallation backgrounds at 800 ft is included in the answers to the committee questions (section 2, page 16). One of the expected spallation products is ^{40}Cl with a half life of 95 sec with a endpoint of 7.5 MeV. The rate at 800 ft level is estimated to be about 500 Hz (there is no direct experimental data). Although considerable portion of the supernova spectrum is above 10 MeV, full sensitivity to low energy physics in liquid argon would require locating the detector at greater depth. Action: We will refine our calculations and also attempt to obtain data from running experiments.

2.3 LAr detector – remaining significant risks in our assessment.

- Simulations to date assume a 5% systematic error in background normalization and no systematic error in background shape, both of which seem very optimistic. The poor state of our knowledge of the cross-sections for individual exclusive channels could easily result in a distortion of the energy spectrum of the mis-reconstruction background which alters the apparent ratio of the first to the second maximum appearance peaks and the shape of the peaks themselves, and furthermore does it differently for neutrinos and anti-neutrinos. This could lead to a false CP-violation signal (or mask a real one). Near detector measurements will help, but cannot eliminate this possibility, as the near detector will be unable to determine in every case what channel produced each background event, and therefore the extrapolation to the far detector is uncertain. The plausible size of this systematic has not yet been estimated. The impact of this uncertainty for LAr is less owing to the smaller overall background.
- We understand that this is the most important analysis issue. The committee also raised this concern in the pre-presentation list of questions and comments. We have a conceptual plan based on experience from previous experiments such as MINOS, T2K, etc. Specifically MINOS achieved ~5% systematic uncertainty on electron neutrino appearance backgrounds. Our

conceptual plan is provided in the answers to questions in Section 2, page 1. Action: continue to improve the requirements on systematic uncertainties and the role of the near detector.

- The assumed rejection efficiency of the muon veto needed for an 800-ft siting is aggressive and undemonstrated. This could result in a significant reduction in the fiducial volume which can be used for the critical $p \rightarrow K\nu$ proton decay channel unless the detector is located at the greater depth. Cosmogenic production may reduce sensitivity to new non-beam physics at the shallow level.
- We understand that the risk can be reduced by placing the detector deep; we are investigating the cost of the muon veto and the deep deployment versus the risks of the 800 ft laboratory. Action: the costs of deep deployment for liquid argon are being evaluated along with the background issues for a shallow deployment.
- The photon detector light collection system may need to be enhanced to allow efficient detection of the lowest-energy SN burst neutrinos and other low energy physics.
- We note that there is a significant R&D program in progress. Action: Strengthen the R&D program on the photon system.

3 Conclusions and Recommendations.

The material presented in the previous sections is intended to be mostly factual. In this section we offer, as requested, our best scientific judgement of the relative merits of the two technologies.

- The proponents of both technologies have produced an impressive body of technical development and wide-ranging and sophisticated simulation and analysis work to support their proposed detectors.
- *In light of the presented materials the committee unanimously agrees that both technologies represent significant scientific opportunities, that either detector could be built at an acceptable level of risk, and that current knowledge supports the view that either is likely to deliver its expected performance, and that either detector would make world-leading measurements relevant to all of the major science goals.*
- By design, the performance of the two detectors for the headline long-baseline oscillation physics is comparable. Future analysis developments could lead to substantial improvement of the ability of the LAr detector to reject backgrounds not arising from the intrinsic ν_e contamination of the beam, while analogous developments could lead to a substantial increase in the efficiency for the WC detector to reconstruct more complex events and hence increase its useful rate. Given the relative maturity of the two technologies the committee feels that there is more scope for advances in the LAr case. The committee recommends that the collaboration should carefully judge which of the two advances is more likely, as this could have a substantial effect on the relative capability of the two detectors.
- We understand that the issue of advances in analysis is of paramount importance. The collaboration physics working group has produced sensitivity estimates for cases in which the WCD efficiency is increased by modest amount and the background rejection of LAr detector is improved. The plots for LAr potential improvement are included in the answers to the committee questions in this document. The sensitivities improve only modestly because they are limited by the irreducible backgrounds in the case of LAr. Studies are underway for the Water Cherenkov detector, but they are not yet complete. Action: Collaboration will continue to improve analysis techniques to find potential gains in background reduction and signal efficiency for both technologies.
- The major unanswered question is the effect of background uncertainties on CP sensitivity. The lower background level should make LAr less sensitive to systematics in the backgrounds. In the view of the committee the greater ability of the LAr to reconstruct complicated final states may yield a further reduction in this risk.
- Our current analysis shows that LAr should have lower overall background levels than the WCD because of its ability to reconstruct complicated final states. Action: No other action needed.
- A significant issue in the long-baseline experiment is to cleanly measure the anti-neutrino sample from the large contamination of neutrino events (or, to a lesser extent, to do the converse). This requires a magnetized near detector, and it would be important to be able to make these measurements with the same target material in the near and far detectors.

Therefore the potential to build a magnetized LAr detector at the near site seems a significant advantage for the LAr option.

- The near detector is currently designed to be magnetized for either choice of far detector technology. Action: No further action needed.
- Given existing limits from Super Kamiokande, the best opportunity for a significant discovery in proton decay is in the p -> Kν channel, and in this channel the LAr detector has the clear advantage. The committee notes that the impact of continued SK data taking, and the desire for complementarity in p decay final states reinforces this conclusion.
- We note that the LAr detector has superior sensitivity to this particular proton decay mode. For the other leading mode ($e^+\pi^0$) we are investigating background reduction techniques for the water detector. Proton decay is one of the important science goals of the experiment; nevertheless, there are no definitive theoretical proton decay models that convincingly define a numerical target for discovery, and therefore the size of the LBNE detectors is based on the requirements for beam oscillation physics. Action: continue to improve the background rejection techniques for proton decay.
- The greater size of the WC detector gives it a clear advantage for some of the other physics, in particular, for the SN burst measurement, although the LAr could see a striking signature of the hierarchy and give important information on collective phenomena in the neutrino sphere. If Super Kamiokande continues to run, the complementary information provided by a LAr detector in the event of a galactic SN would be valuable.
- The complementary supernova capabilities of the two detector technologies are an important consideration for the detector technologies. The Supernova Working Group is of the opinion that the mass hierarchy effects in supernova spectra are extremely model dependent and quite uncertain considering our lack of knowledge of the internal dynamics of the supernova. For other science topics such as eliciting information on black hole formation, statistics are the dominant consideration. Action: continue to work with theorists to understand the supernova models and their uncertainties.
- The LBNE experiment will be the leading experiment at the Intensity Frontier. As such, very good “buy in” from the US high energy community is essential. Although it obviously did not conduct a survey of the field, the committee felt that the LAr, as a new technology on this scale, could create more opportunities to excite and thus recruit new young physicists in the project.
- The LBNE collaboration management is certainly concerned about the young physicists and their careers. The collaboration has created a special working group to promote the interests and careers of the younger members of collaboration. There are many opportunities in either detector technology such as development of multi-anode-photon counters for water Cherenkov and/or photon detection systems for Liquid Argon. Action: difficult to track, but the point is noted and important.
- The committee noted the value of enhanced infrastructure at the 4850 level at Homestake to a variety of other high-priority physics topics such as the search for Dark Matter and for neutrinoless double-beta decay. The committee felt that this added value to the overall US programme should not be discounted in the decision to put either detector at a deep site.
- The LBNE collaboration has produced a detailed “depth requirements document” for the broad array of physics topics for either detector type. The consensus in the collaboration is

that for the full scientific program the detectors must be located at the 4850 ft level. This requirement included a preliminary engineering analysis of the various available levels and found that the 4850 ft had the right mix of access and infrastructure. The LBNE depth determination was based on the science and engineering considerations for LBNE. Action: Importance of depth for LBNE physics is recognized, no further action needed.

- The committee unanimously agrees that, that on the question of scientific capabilities, that the prospect for the LAr detector to refine our understanding of neutrino oscillations, and to be sensitive to unexpected new physics, exceeds that from the WC detector.
- As a high-resolution detector in a long-baseline neutrino beam, a LAr detector will open a new window to neutrino physics, including sensitivity to unexpected new physics. For the main goal of electron neutrino appearance, studies have repeatedly found the sensitivity of the two detector approaches to be quite similar. For the other secondary goals of the experiment, the physics working group report found that some would benefit more from higher mass; others from higher resolution. Beyond the similar reach for understanding θ_{13}, the mass hierarchy and CP violation, it is unclear where refined understanding of neutrino oscillations in the future will emerge. Action: Nature will have the final say in new physics.