Conceptual Design Report
The Neutrino Experiment

Volume: Cryogenic Systems

February 9, 2015

Editor's Note: This document has been prepared in an ad hoc manner to provide a summary of the scope of the LBNE project as of January 2015. It pulls content from version 8 of LBNE's CDR vol 4 and includes some changes made since 2012, with notes added; the changes may not be reflected consistently throughout the document, as a thorough editing pass has not been made. It is planned to update this document in 2015 consistent with the plan resulting from the iIEB's efforts. Changes to note in particular about the current plan relative to the 2012 design include:

- House two detectors, of fiducial mass 10 kton and 30 kton, respectively, in separate, parallel caverns. Outfit the smaller cavern as soon as possible and outfit the larger in a later phase of work. (The 30-kton detector was not part of the 2012 design; its configuration, to be determined by the international collaboration, is not discussed in this interim report.)

- Place the compressors for the nitrogen refrigeration system on the surface, and place the remainder of the refrigeration system in the 10-kton cavern. Deliver argon and nitrogen in gas form to the smaller cavern, where liquification will take place. Liquid will be transferred to and from the detector in the 30-kton cavern.

- Make detector shallower and longer. Build APAs of width 2.3 m and height 6 m (2012 dimensions were 2.5 m $\times$ 7 m). Increase the length of the 10-ton detector from 25 m to 30 m.

- Replace the far detector prototyping plan known as LAr1 by a plan to build and test a prototype with full-size TPC components at CERN.

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Chapter 1

Introduction

1.1 Introduction to the LBN Project

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The The Neutrino Experiment (LBN) Project team has prepared this Conceptual Design Report (CDR) which describes a world-class facility to enable 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.

Although the Standard Model of particle physics presents a remarkably accurate description of the elementary particles and their interactions, it is known that the current model is incomplete and that a more fundamental underlying theory must exist. Results from the last decade, revealing that the three known types of neutrinos have nonzero mass, mix with one another and oscillate between generations, point to physics beyond the Standard Model. Measuring the mass and other properties of neutrinos is fundamental to understanding the deeper, underlying theory and will profoundly shape our understanding of the evolution of the universe.

1.1.1 About this Conceptual Design Report

The LBN Conceptual Design Report is intended to describe, at a conceptual level, the scope and design of the experimental and conventional facilities that the LBN Project plans to build to address a well-defined set of neutrino-physics measurement objectives. At this Conceptual Design stage the LBN Project presents a *Reference Design* for all of the planned components and facilities, and alternative designs that are still under consideration for particular elements. The scope includes

- an intense neutrino beam aimed at a far site
- detectors located at the near site just downstream of the neutrino source
- a massive neutrino detector located at the far site
- construction of conventional facilities at both the near and far sites

The selected near and far sites are Fermi National Accelerator Laboratory (Fermilab), in Batavia, IL and Sanford Underground Laboratory at Homestake (Sanford Laboratory), respectively. The latter is the site of the formerly proposed Deep Underground Science and Engineering Laboratory (DUSEL) in Lead, South Dakota.

This CDR is organized into six stand-alone volumes, one to describe the overall LBN Project and one for each of its component subprojects:

- Volume 1: The LBN Project
- Volume 2: The Beamline at the Near Site
- Volume 3: Detectors at the Near Site
- Volume 4: The Liquid Argon Detector at the Far Site
- Volume 5: Cryogenic Systems
- Volume 6: Conventional Facilities at the Near Site
- Volume 7: Conventional Facilities at the Far Site

Volume 1 is intended to provide readers of varying backgrounds an introduction to LBN and to the following volumes of this CDR. It contains high-level information and refers the reader to topic-specific volumes and supporting documents, also listed in Section 1.1.5. Each of the other volumes contains a common, brief introduction to the overall LBN Project, an introduction to the individual subproject and a detailed description of its conceptual design.

1.1.2 LBN and the U.S. Neutrino-Physics Program

Global?n its 2008 report, the Particle Physics Project Prioritization Panel (P5) recommended a world-class neutrino-physics program as a core component of the U.S. particle physics program [**?**]. Included in the report is the long-term vision of a large detector at the Sanford Laboratory and a high-intensity neutrino source at Fermilab.

On January 8, 2010, the Department of Energy (DOE) approved the Mission Need for a new long-baseline neutrino experiment that would enable this world-class program and firmly establish the U.S. as the leader in neutrino science. The LBN Project is designed to meet this Mission Need.

With the facilities provided by the LBN Project, the LBN Science Collaboration proposes to mount a broad attack on the science of neutrinos with sensitivity to all known parameters in a single experiment. The focus of the program will be the explicit demonstration of leptonic CP violation, if it exists, by precisely measuring the asymmetric oscillations of muon-type neutrinos and antineutrinos into electron-type neutrinos and antineutrinos.

The experiment will result in the most precise measurements of the three-flavor neutrino-oscillation parameters over a very long baseline and a wide range of neutrino energies, in particular, the CP- violating phase in the three-flavor framework. The unique features of the experiment – the long baseline, the broad-band beam, and the high resolution of the detector – will enable the search for new physics that manifests itself as deviations from the expected three-flavor neutrino-oscillation model.

The configuration of the LBN facility, in which a large neutrino detector is located deep underground, could also provide opportunities for research in other areas of physics, such as nucleon decay and neutrino astrophysics, including studies of neutrino bursts from supernovae occuring in our galaxy. The scientific goals and capabilities of LBN are outlined in Volume 1 of this CDR and described fully in the LBN Case Study Report (Liquid Argon TPC Far Detector) [?] and the 2010 Interim Report of the The Neutrino Experiment Collaboration Physics Working Groups [?].

1.1.3 LBN Project Organization

The LBN Project Office at Fermilab is headed by the Project Manager and assisted by the Project Engineer, Project Systems Engineer and Project Scientist. Project Office support staff include a Project Controls Manager and supporting staff, a Financial Manager, an Environment, Safety and Health (ES&H) Manager, a Computing Coordinator, Quality Assurance and Risk Managers, a documentation team and administrative support. The Beamline, Liquid Argon Far Detector and Conventional Facilities subprojects are managed by the Project Office at Fermilab, while the Near Detector Complex subproject is managed by a Project Office at Los Alamos National Laboratory (LANL).

More information on Project Organization can be found in Volume 1 of this CDR. A full description of LBN Project management is contained in the LBN Project Management Plan [?].

1.1.4 Principal Parameters of the LBN Project

The principal parameters of the major Project elements are given in Table 1.1.

Table 1.1: LBN Principal Parameters

Project Element Parameter	Value
Near- to Far-Site Baseline	1,300 km
Primary Proton Beam Power	708 kW, upgradable to 2.3 MW
Protons on Target per Year	6.5×10^{20}
Primary Beam Energy	60 – 120 GeV (tunable)
Neutrino Beam Type	Horn-focused with decay volume
Neutrino Beam Energy Range	0.5 – 5 GeV
Neutrino Beam Decay Pipe Diameter $\times$ Length	4 m $\times$ 200 m
Near Site Neutrino Detector Type	Liquid Argon Time Projection Chamber (LArTPC) Tracker
Near Site Neutrino Detector Active Mass	18 ton
Far Detector Type	LArTPC
Far Detector Active (Fiducial) Mass	54 (40) kton
Far Detector Depth	1480 m

1.1.5 Supporting Documents

A host of information related to the CDR is available in a set of supporting documents. Detailed information on risk analysis and mitigation, value engineering, ES&H, costing, project management and other topics not directly in the design scope can be found in these documents, listed in Table 1.2. Each document is numbered and stored in LBNE's document database, accessible via a username/password combination provided by the Project. Project documents stored in this database are made available to internal and external review committees through Web sites developed to support individual reviews.

Table 1.2: LBNE CD-1 Documents

Title	**LBNE Doc Number(s)**
Acquisition Plan	5329

Alternatives Analysis	4382
Case Study Report; Liquid Argon TPC Detector	3600
Configuration Management Plan	5452
DOE Acquisition Strategy for LBNE	5442
Integrated Environment, Safety and Health Management Plan	4514
LAr-FD Preliminary ODH Analysis	2478
Global Science Objectives, Science Requirements and Traceback Reports	4772
Preliminary Hazard Analysis Report	4513
Preliminary Project Execution Plan	5443
Preliminary Security Vulnerability Assessment Report	4826
Project Management Plan	2453
Project Organization Chart	5449
Quality Assurance Plan	2449
Report on the Depth Requirements for a Massive Detector at Homestake	0034
Requirements, Beamline	4835
Requirements (Parameter Tables), Far Detector	3747 (3383)
Requirements, Far Site Conventional Facilities	4408
Requirements, Near Detectors	5579
Requirements, Near Site Conventional Facilities	5437
Risk Management Plan	5749
Value Engineering Report	3082
Work Breakdown Structure (WBS)	4219

1.2 Introduction to the Liquid Argon Far Detector

ch:detector

1.2.1 Overview

The reference design Far Detector for LBNE is a liquid argon time projection chamber (LArTPC). The basic components of this detector type are a cryostat to contain the liquid argon (LAr), a TPC detection mechanism immersed in the LAr, readout electronics and a cryogenic system to keep the LAr temperature at 89 K and maintain the required purity.

As of 2014 the LBNE LArTPC, referred to as the LAr-FD, has been altered to consist of two massive detectors in separate, parallel caverns, oriented end-to-end along the beam direction (roughly east-to-west), and located at the 4850 level (4850L) of the Sanford Laboratory. The fiducial mass of first one to be built will be 10 ktons, the second, 30 ktons. Figure 1.1 shows the proposed layout of the Far Site, and Figure 1.2 shows the detector configuration. The cavern and related conventional facilities are described in Volume 6 of this CDR.

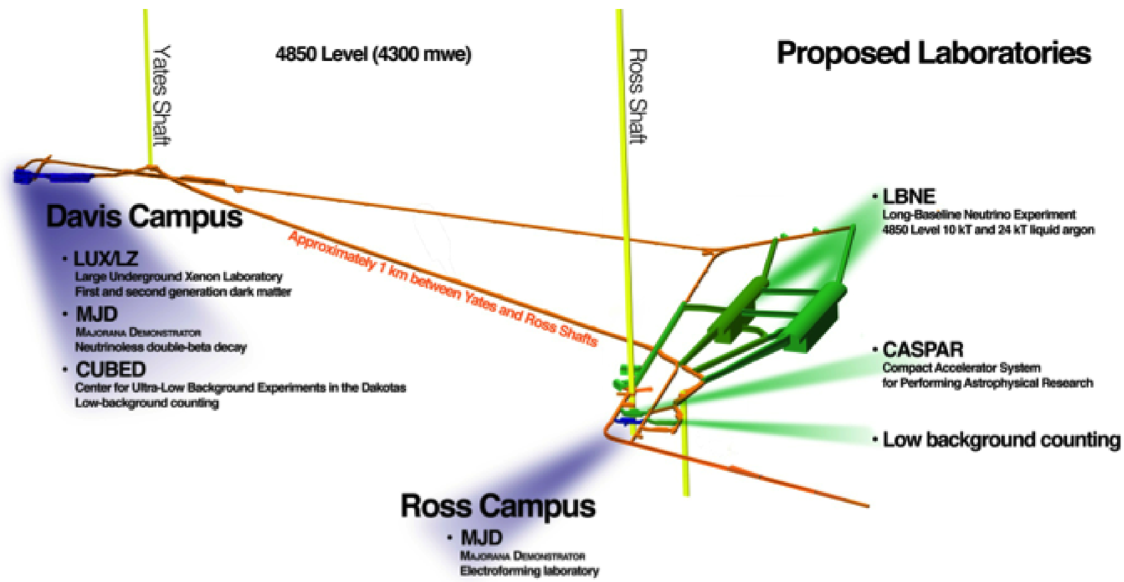

Figure 1.1: Location of LAr-FD caverns at the 4850L

The fiducial mass of the first is shown in Figure 1.3; a similar diagram for the second detector is not yet available.

In a LArTPC, a uniform electric field is created within the TPC volume between cathode planes and anode wire planes. Charged particles passing through the TPC release ionization electrons that drift to the anode wire planes. The bias voltage is set on the anode plane wires so that ionization electrons drift between the first several (induction) planes and are collected on the last (collection) plane. Readout electronics amplify and continuously digitize the induced waveforms on the sensing wires at several MHz, and transmit these data to the data acquisition (DAQ) system for processing. The wire planes are oriented at different angles allowing a 3D

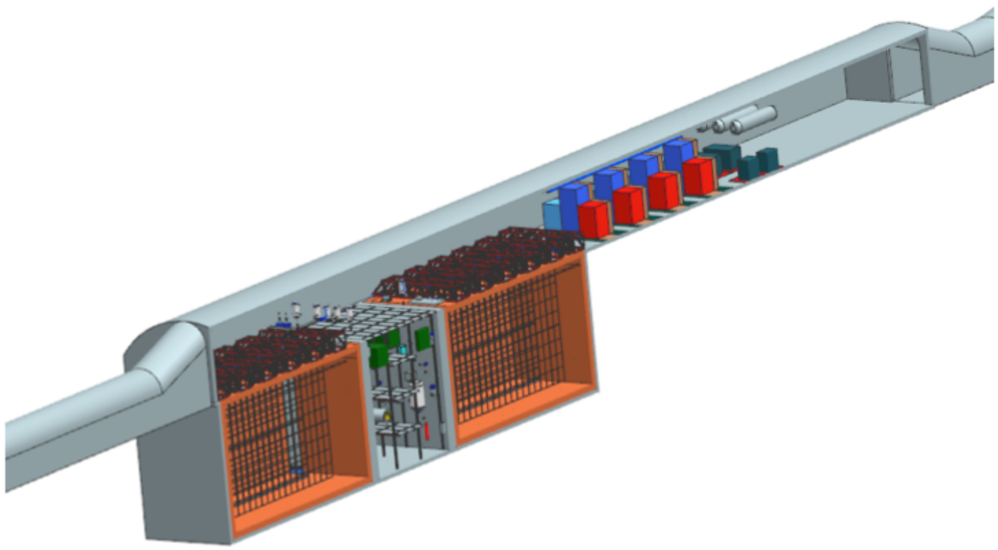

Figure 1.2: Detector configuration within the cavern. The TPC is located within a membrane cryostat, shown in orange. Cryogenic equipment is located at the far end of the upper cavern and the filtration equipment is in the septum area between the two cryostats.

fig:LAr-FD-con

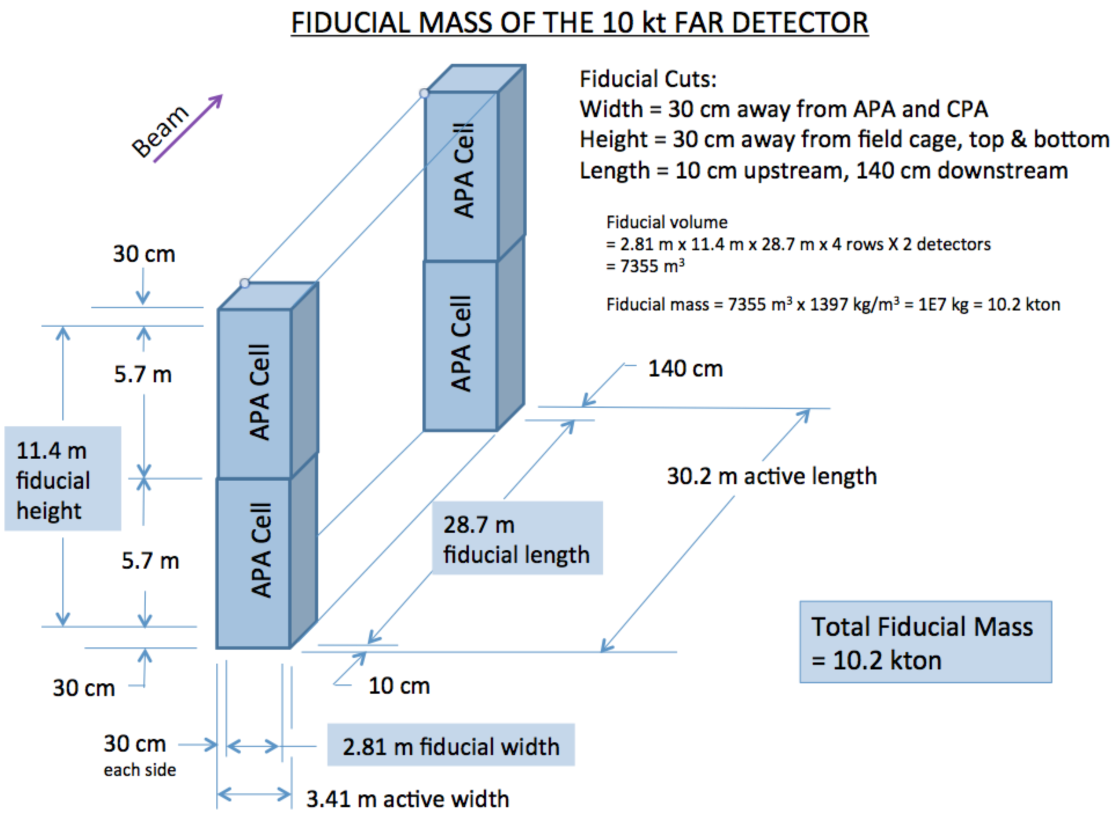

Figure 1.3: Fiducial mass of 10-kton detector

fig:10kt-fiduc

reconstruction of the particle trajectories. In addition to these basic components, a photon-detection system provides a trigger for proton decay and galactic supernova neutrino interactions.

The design of the LAr-FD has been developed and refined over the past five years. The starting point was the ICARUS T600 system [?], and the process was informed and guided by the experience with small LArTPCs in the U.S., particularly ArgoNeuT [?], the development of designs for MicroBooNE [?]. The LAr-FD concept is designed for assembly from small, independent elements which can be repeated almost indefinitely in any dimension to form the entire assembly within a large cryostat. Each of the elements provides an independent mechanical structure to support the elements it contains. To a large extent, scaling from detector volumes containing anywhere from a few to several hundred such elements is straightforward with small and predictable risk. Scaling in other areas of LArTPC detector technology, namely cryostat construction, LAr purification and electronics readout has been incorporated into the design.

1.2.2 Cavern Layout

> Editor's Note: The current plan is to create space for a 40-kton detector in two separate, parallel caverns, one for 10 kton and one for 30 kton, instead of excavating a single cavern. The smaller cavern would be outfitted as soon as possible and the larger would be outfitted in a later phase of work.

The first (smaller) LAr-FD cavern will be excavated into a "mailbox" cross section, as illustrated in Figure 1.1. The long axis of the cavern will point towards Fermilab, parallel to and in line with the neutrino beamline. The pit, the below-grade rectangular cavity inside of which the cryostats fit, will have dimensions as detailed in Figure 1.4 and illustrated in Figure 1.6.

The parameters for the larger cavern are given in Figure 1.5.

The 10-kton detector pit will be segmented into three volumes: a space for each cryostat plus a 15-m-wide clear space in the middle, called the septum, separated from the cryostat areas by 1.5-m-thick walls. Equipment and vessels used for filtering LAr to achieve high purity levels will be placed in the septum area.

The cavern (highbay) roof, located above the pit, will be 17.7 m wide by 164.1 m long, and its rounded "mailbox top" upper surface will arch to ~10 m in the center and ~5 m on the sides (springline). The curved upper surface will extend beyond

Cavern & Pit - Underground options only	
Configuration - End to End =1, Side by Side =2	1
Arrangement	End to End
Highbay length	164.1m
HIghbay length allowance	75.0
Highbay width	17.7m
Highbay springline height	4.5m
Highbay height at center of cavern	9m
Crown area	55m^2
Primary access	Ross Shaft
Secondary access	Yates Shaft
Concrete pit thickness	0.5m
Excavated pit width	17.7m
Pit depth	15.6m
Excavated pit depth	16.1m
Pit Length per cryostat (inside)	35.0m
Septum length per cryostat	7.5m
Septum wall thickness	1.50m
Excavated pit length	89.1m

Figure 1.4: Parameters for 10-kton detector cavern and pit, 2014 fig:cavern-pit

Cavern & Pit - Underground options only		
Configuration - End to End =1, Side by Side =2		1
Arrangement	End to End	
Highbay length		164.1m
HIghbay length allowance		75.0
Highbay width		17.7m
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Pit Length per cryostat (inside)		35.0m
Septum length per cryostat		7.5m
Septum wall thickness		1.50m
Excavated pit length		89.1m

Figure 1.5: Parameters for 30-kton detector cavern and pit, 2014 fig:cavern-pit

each end of the dual-cryostat detector along the long axis to provide additional space for ancillary equipment as well as for installation and maintenance operations.

Space will be provided for the nitrogen refrigerators, nitrogen compressors and necessary cryogen-storage vessels. Walkways will run the entire length of the cavern through the roof truss of the detector to provide personnel access along the cryostat roof. A separately ventilated emergency-egress passageway will be elevated over the roof truss section and extend to the east and west ends of the cavern highbay.

> Editor's Note: The illustration and dimensions in Figure 1.6 are for a detector with APAs of dimensions 2.5 m × 7 m and a total of 10 adjoined end-to-end along the beamline. The current configuration will use 2.3 m × 6 m APAs, in rows of 13 end-to-end, making the detector slightly shallower and longer than shown in the figure.

1.2.3 Cryostat Construction

The 10-kton cryostat construction uses commercial stainless-steel membrane technology engineered and produced by industry. These vessels are widely deployed in liquefied natural gas (LNG) tanker ships and tanks, and are typically manufactured in sizes much larger than that of the LAr-FD. This is an inherently clean technology with passive insulation.

The LAr-FD cryostat reference design was selected on the recommendation of the experienced engineering consultants from ARUP USA, Inc. [**?**] after consideration of an alternative design that uses segmented, internally self-supporting, evacuable, modular cryostats. Evacuation, in particular, appears not to be necessary; in September 2011, the Fermilab Liquid Argon Purity Demonstrator (LAPD) achieved purity levels of less than 100 ppt oxygen-equivalent, using the method that is planned for use in the LAr-FD. This confirms that the method works, obviating the risk to LBNE that an evacuable vessel will be required. Operation of a 35-ton prototype using membrane-cryostat technology has provided a further demonstration.

The LAr-FD membrane cryostats are sealed containers supported by the surrounding rock. This "in-ground" configuration offers access only from the top and protects against possible cryogen leaks out of the tank. The side walls consist of a series of membranes, foam insulation and reinforced concrete poured against the shotcrete covered rock. The inner (primary) membrane liner, made of stainless steel, is corrugated to provide strain relief from temperature-related expansion and contraction.

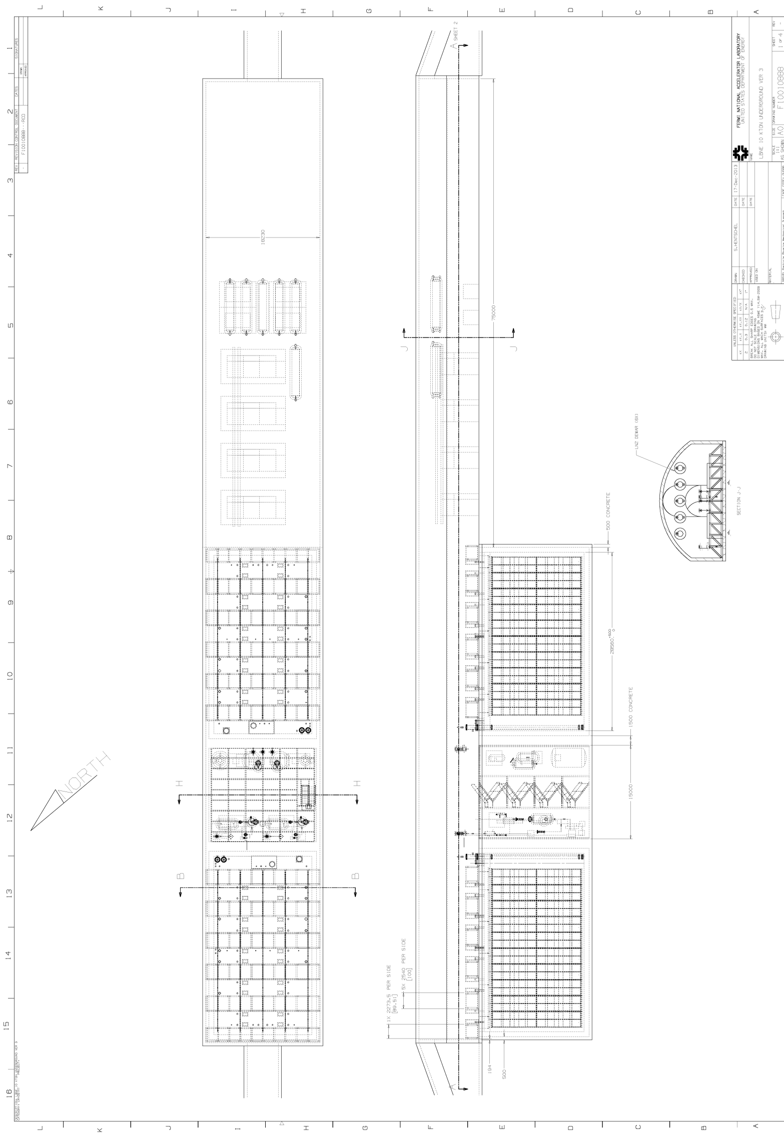

Figure 1.6: Dimensions for 10-kton detector cavern and cryostat, 2014. The left-hand figure is a top view of the cavern hall; on the right is an elevation view through the cryostat and highbay. fig:v5ch2-cave

1.2.4 Cryogenic Systems

Cryogenic systems are needed to manage the LAr, i.e., to keep it cold, pure and circulating smoothly during operations in order to maintain a sufficiently long drift lifetime for the ionization electrons. The major cryogenic systems used to perform these functions are the cryogen supply for cool-down and fill, gas filtration, argon condensing, liquid filtration and circulation and argon purity analysis.

The overall cryogenic system's layout and location is intended to optimize safety and efficiency. It is designed to minimize:

- the risk of personnel injury to any Oxygen Deficiency Hazard (ODH)
- heat ingress to the cryogenic system (by minimizing piping length and pump power)
- the volume of the argon system external to the cryostat and hence the potential for argon escape or contamination

It is also designed to provide safe access to refrigeration equipment that requires periodic maintenance.

Cryogenic systems are located on the surface and within the cavern. Figure 2.11 illustrates the cryogenic systems layout, which is described in Section 2.6.

The required flow rate of liquid argon to be sent for purification is expected to decrease over time. The initial maximum flow rate will be 51 m^3/hr (224 gpm). The liquid-argon volume in one cryostat will turn over every five days at this rate. Longer term, the rate will decrease to 25 m^3/hr with a turn-over rate of 11 days. As a point of comparison, ICARUS T600 has a maximum turn-over rate of eight to ten days.

1.2.5 LAr Purification

The purification of LAr is accomplished with standard industrial equipment, using molecular sieves and chemically reducing materials, which are scalable within the contemplated range to accommodate the estimated irreducible material-outgassing from warm materials in the vapor space above the liquid argon, called the ullage.

1.2.6 Time Projection Chamber

The Time Projection Chamber (TPC) is the active detection element of the LAr-FD. The construction concept is shown schematically in Figures 1.7 and 1.8. A TPC is located inside each cryostat vessel and is completely submerged in LAr at 89 K. Five planes line up across the width: three Cathode Plane Assemblies (CPA) interleaved with two Anode Plane Assemblies (APA). These planes are oriented vertically and parallel to the beamline such that the electric fields applied between them are perpendicular to the beamline. The TPC's active volume within the cryostat is 12 m high, 14 m wide and 30 m along the beam direction.

A "drift cell" is associated with one APA and the two CPAs on either side of it; it is defined as the volume between the enclosed APA's two surrounding CPAs, and bordered by the CPAs' edges. The maximum electron-drift distance between a CPA and an adjacent APA (half of the drift cell) is 3.4 m. Both the CPAs and APAs measure 2.3 m along beamline dimension and 6 m in height; they are each a few cm wide.

Each row of CPAs and APAs is stacked two-high to instrument the 12-m active depth. Each row contains 13 such stacks placed edge-to-edge along the beam direction, forming the 30-m active length of the cryostat's TPC and resulting in a total of 52 APAs and 78 CPAs per cryostat. A "field cage" surrounds the top and ends of the cryostat to ensure uniformity of the electric field. The field cage is assembled from panels of FR-4 sheets with parallel copper strips connected to resistive divider networks.

Each APA has three wire planes that are connected to readout electronics; two induction planes (labeled U and V in Figure 1.7) and one collection plane (X). A fourth wire plane, grid plane (G), is held at a bias voltage but is not instrumented with readout electronics. The grid plane improves the signal-to-noise ratio on the U plane and provides electrostatic discharge protection for the readout electronics.

1.2.7 Electronics, Readout and Data Acquisition

Requirements for low noise and for extreme purity of the LAr motivate locating the front-end electronics in the LAr (hence "cold electronics") close to the anode wires, which reduces the signal capacitance (thereby minimizing noise). The use of CMOS electronics in this application is particularly attractive since the series noise of this process has a noise minimum at 89 K. The large number of readout channels required to instrument the LAr-FD TPCs motivates the use of CMOS ASICs. Signal zero-suppression and multiplexing will be implemented in the ASIC, minimizing the number of cables and feedthroughs in the ullage gas, and therefore reducing contamination from cable outgassing. Figure 1.9 shows the conceptual architecture of a front-end electronics design that meets the requirements for LAr-FD. The entire electronics chain is immersed in the LAr.

All signal feedthroughs will be placed at the top of the cryostat, where they are

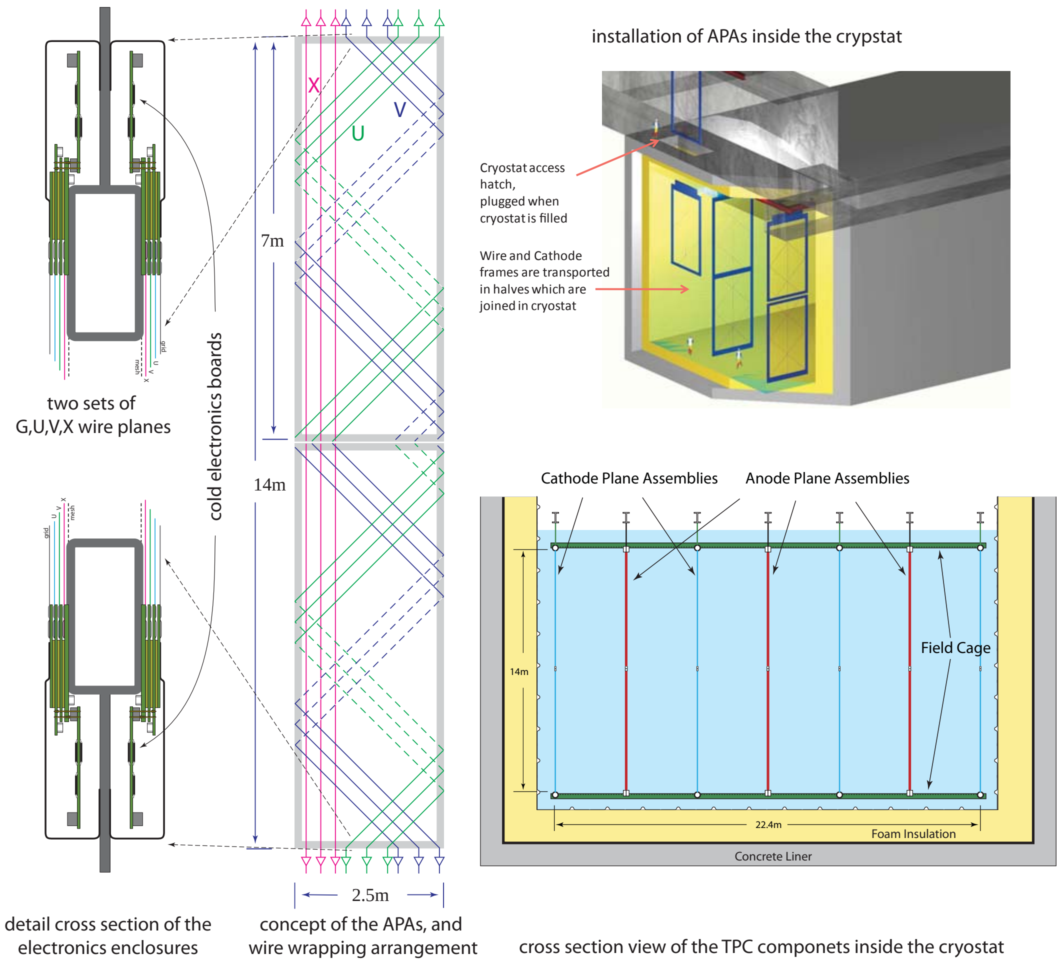

Figure 1.7: TPC modular construction concept; the APA and CPA arrangement has been changed to two APAs and three CPAs as of 2014, see Figure 1.8.

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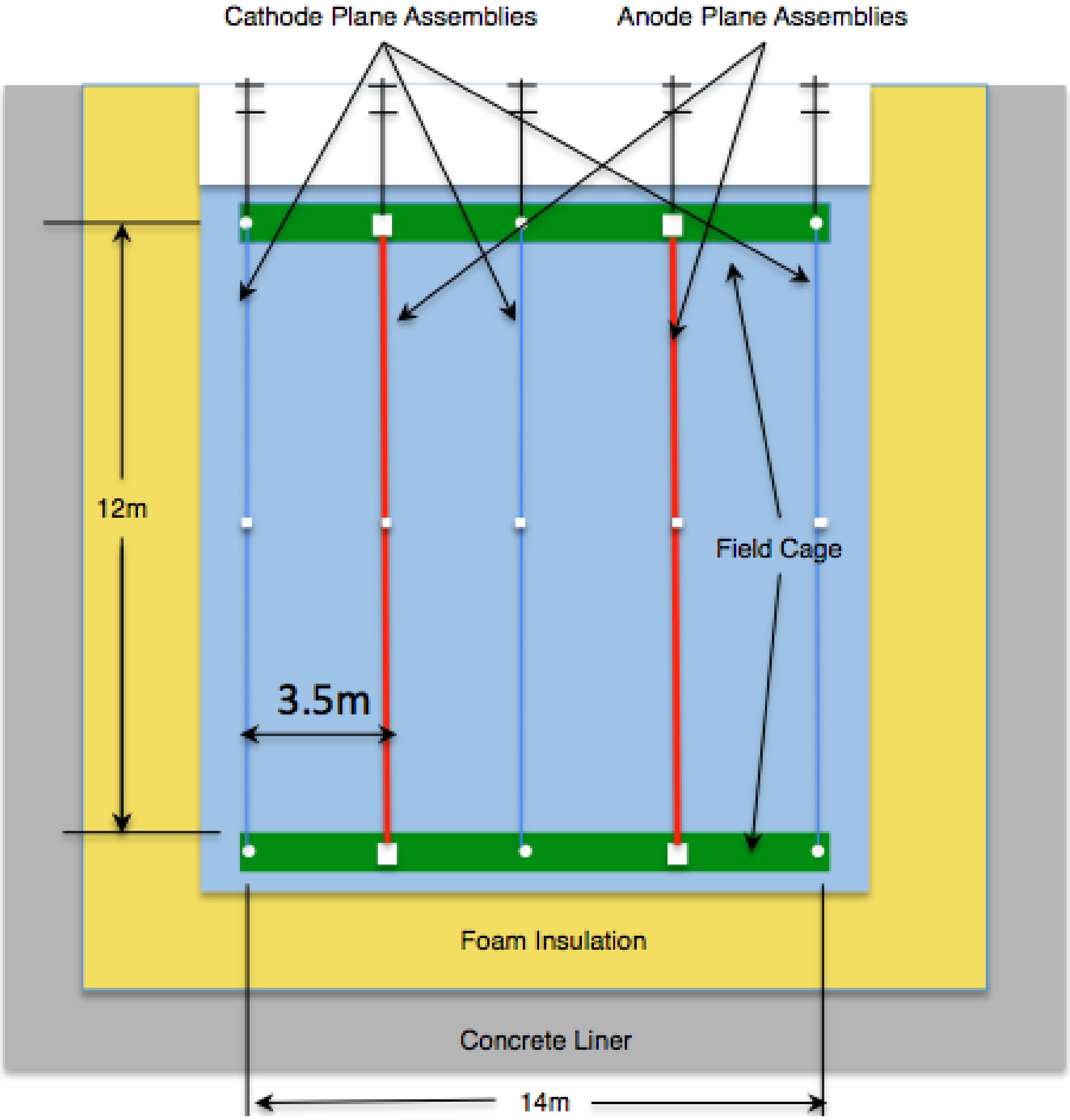

Figure 1.8: APA and CPA arrangement, 2014

fig:cpa-apa-ar

easily installed, are always accessible, are at low hydrostatic pressure and pose no risk of LAr leakage. The cold electronic system will include digitization, buffering, and a high level of digital output multiplexing (ranging from 1/128 to 1/1024). Output data links will include redundancy to eliminate the effect of any single-point failure.

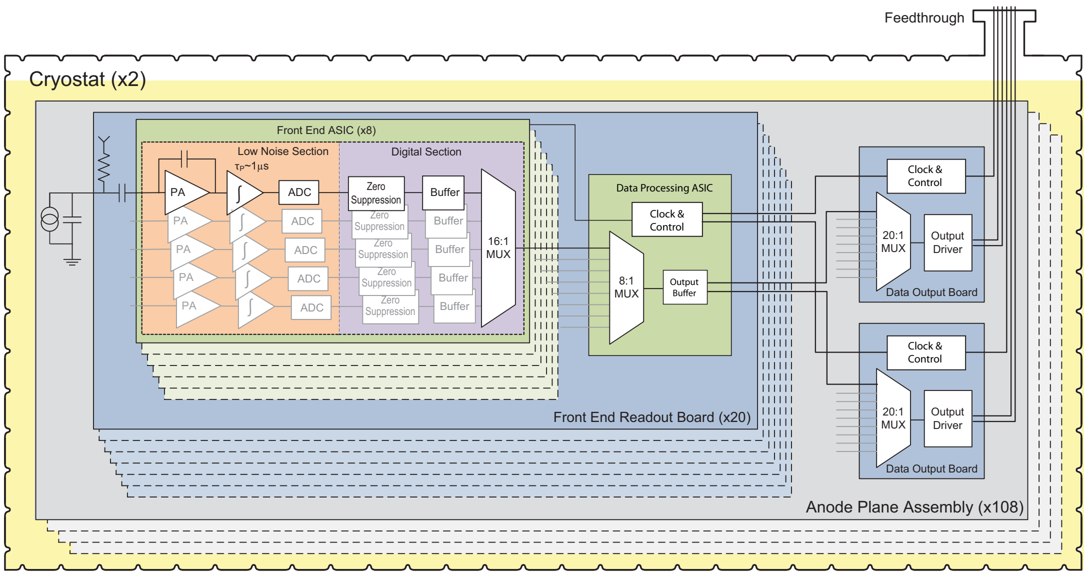

Figure 1.9: Conceptual front-end electronics architecture

fig:tpc-elec-s

1.2.8 Photon-Detection System

Identification of the different possible charged-particle types depends on accurate measurements of ionization along tracks. This requires accurate determination of the time of interaction, or event time, t_0, which leads to the absolute location of the event along the drift axis, and allows the determination of Q_0, the true ionization charge.

For non-accelerator physics events, t_0 is not known a priori. However, LAr is an excellent scintillator, generating of order 10^4 128-nm photons per MeV of deposited energy. Detection of scintillation photons provides a prompt signal that allows unambiguous location of particle positions along the drift axis.

The reference design for the photon detection system is based on acrylic bars, which are either coated in TPB or doped in bulk. The 128 nm photons interact with the TPB on the surface and 430 nm light is re-emitted. The signals will be routed out of the cryostat to standard readout electronics.

Twenty light-guide and SiPM assemblies, or “paddles”, will be installed within each APA frame prior to wire winding. The SiPM signals will be used as a software “trigger” in the DAQ to define the event time, t_0, for non-accelerator events. This system provides a t_0 signal throughout the entire detector in contrast to a system similar to that used in MicroBooNE and ICARUS, where light is detected outside the detector volume.

1.2.9 Detector Installation and Operation

Detector components will be shipped in sealed containers to the Far Site by truck and lowered to the cavern. Shipping containers will be moved to a clean area over the septum area between the cryostats. There the components will be unpacked from the sealed container and lowered through an access hatch into the cryostat.

The construction of the two cryostats and the installation and commissioning activities will be staged such that both TPCs can be tested cold while one cryostat still remains available as a potential LAr storage vessel. The LAr in one cryostat can be transferred to the other, and back again, if necessary, until all the tests complete successfully. Once both TPCs are known to work properly at LAr temperature, the second fill will take place.

To protect the membrane on the floor of the cryostat during TPC installation, a temporary floor will be installed. After each pair of APAs is installed, they will be connected to the DAQ system and the wire integrity tested. All wires on previously installed APA pairs will also be tested. The wire integrity test will be performed during cryostat cool-down as well. A relatively slow cool-down rate will ensure that the temperature-induced stresses in the APA frames and wires are kept well below the level experienced during testing.

An installation and integration detector mock-up will be constructed at Fermilab to confirm that interfaces between detector systems are well defined and to refine the installation procedures.

1.3 Principal Parameters

The principal parameters of the LAr-FD are given in Table 1.3.

Table 1.3: LAr-FD Principal Parameters for 10-kton Detector

table:param-su

Parameter	Value
Active (Fiducial) Mass	13.8 (10.2) kton
Number of Detector Modules (Cryostats)	2
Drift Cell Configuration within Module	2 wide $\times$ 2 high $\times$ 13 long
Drift Cell Dimensions	2 $\times$ 3.4 m wide (drift) $\times$ 6 m high $\times$ 2.3 m long
Detector Module Dimensions	14 m wide $\times$ 12 m high $\times$ 30 m long
Anode Wire Spacing	$\sim$4.8 mm
Wire Planes (Orientation from vertical)	Grid (0°), Induction 1 (36°), Induction 2 (-36°), Collection (0°)
Drift Electric Field	500 V/cm
Maximum Drift Time	2.1 ms

1.3.1 Design Considerations

TPCs operated to date have been constructed with an anode wire spacing in the range of 3 mm (ICARUS) to 4.8 mm (Fermilab cosmic-ray stand). The amount of ionization charge collected on the wires increases with larger wire spacing, resulting in a better signal-to-noise ratio without serious consequences (the radiation length of LAr is $\sim$ 30 times larger than the typical wire spacing). The electron-π^0 separation efficiency of a TPC with 5-mm wire spacing is only a few percent lower than one with 3-mm wire spacing. It is also clear that a TPC with larger wire spacing requires fewer wires and readout channels, resulting in lower cost.

Only two wire planes are required to reconstruct events in three dimensions, however three wire planes will be implemented to provide N+1 redundancy. The third will improve the pattern-recognition efficiency for a subset of multi-track events in which trajectories can overlap in two views. The collection-plane wires are most commonly used for calorimetric reconstruction and are oriented vertically (0°) to minimize both the wire length and the electronics noise.

Editor's Note: The following paragraph refers to a wire orientation of 45 degrees. The chosen wire orientation has been changed to 35.7 degrees from vertical. The study and documentation justifying this choice is in LBNE-docdb-9374.

A study of wire orientation has shown that for a TPC with three instrumented wire planes, the optimum orientation of the induction plane wires should be between $\pm 40°$ and $\pm 60°$ when the collection plane wires are at $0°$. The ideal orientation for the more isotropic low-energy events, e.g., supernova-neutrino interactions, is $\pm 60°$. The selected induction-plane wire orientation of $\pm 45°$ has better position resolution in the vertical direction than $\pm 30°$ and has shorter wires compared to a wire orientation of $\pm 60°$. The induction plane wires are wrapped around the APA frames so that the readout electronics can be located on the top or bottom of the TPC. As a result, it is natural to arrange the APAs vertically in a two-high configration.

Access to the top of the cryostat is required to install and connect cabling. Therefore, risk of personnel injury and detector damage, both of which increase with height, form the primary considerations for the the detector height, 12 m. The The height of the APA has been chosen, accordingly, to be 6 m, resulting in 6-m-long collection-plane wires and 7.3-m-long induction plane wires.

The 2.3 m width of the APA was chosen to facilitate construction and to allow standard, over-the-road transport.

The choice of cryostat width is based on the desired cryostat shape and cavern span. From a cryogenics standpoint, the ideal cryostat for a modular TPC would be a cube since membrane-cryostat capital and operating costs scale linearly with the surface area. This shape is not ideal for cavern excavation, however. In the absence of a geotechnical investigation for the cavern location, the cavern span has been limited to $\sim$30 m on the advice of rock engineers. A detector width of 14 m results after making allowance for cryostat insulation, and personnel access both above and within the cryostat.

A drift field of 500 V/cm was chosen based on experience from similar detectors such as ICARUS, ArgoNeuT and the Fermilab cosmic-ray test stand. At this electric field, $\sim$ 30% of the ionization electrons produced by the passage of a minimum ionizing particle (MIP) recombine and create scintillation light that provides a fast trigger. The remaining ionization electrons drift to the APA and produce wire-plane signals. The TPC could function at higher or lower drift fields but the relative yields of scintillation light and ionization electrons would change. The use of a higher drift field would require more care in the design of the high-voltage systems. The electron drift velocity is 1.6 mm/μs at 500 V/cm.

The 14 m width of the the detector can be divided into four drift cells with a maximum drift length of 3.41 m each. This drift cell length was chosen based on experience from other detectors, the required minimum signal-to-noise ratio and high-voltage considerations. The required minimum signal-to-noise ratio of 9:1 ensures that the tracking efficiency will be 100% throughout the entire drift cell. The TPC must be capable of detecting the smallest signal (1 MeV) produced in interactions that LBNE will study. This situation occurs when a MIP travels parallel to a wire plane and perpendicular to the orientation of the wires in the plane. A MIP loses 2.1 MeV of energy in each cm of travel, producing $\sim$ 40,000 ionization electrons along every 5 mm section of the track. About 28,000 electrons escape recombination and, ignoring the effects of LAr purity and diffusion, would all drift to one collection plane wire. The capacitance due to the maximum-length 7.3 m wire is 164 pF resulting in an equivalent noise charge (ENC) of 500 electrons in the CMOS amplifiers. The signal-to-noise ratio would therefore be 53:1 if all of the ionization electrons arrived at the wire. For a maximum drift distance of 3.41 m and a drift field of 500 V/cm, the required voltage on the cathode plane is 173 kV. This is within the range of commercially available high-voltage cables and within the range of current designs for cryogenic feedthroughs. Additional R&D would be needed for longer maximum drift lengths.

Ionization electrons will be lost due to impurities in the LAr. The fraction that survive passage to the anode planes is $e^{t/\tau}$, where$t$ is the drift time and τ is the drift-electron lifetime. The maximum drift time is the maximum drift length divided by 1.6 mm/μs which equals 2.3 ms for LBNE. The ICARUS detector has achieved a drift electron lifetime of $6 - 7$ ms. The Materials Test Stand (described in Section **??**) regularly achieves a drift-electron lifetime of $8 - 10$ ms. The Fermilab Liquid Argon Purity Demonstrator achieved a liftime of > 3 ms during initial tests. Based on this experience, and by careful selection of materials in the ullage, a drift-electron lifetime at least as good as ICARUS is expected. The signal-to-noise ratio would be 36:1 for a drift electron lifetime of 6 ms. A minimum lifetime of 1.4 ms is required to meet the 9:1 signal-to-noise ratio requirement.

The cloud of drifting ionization electrons will spread out in space due to the effects of diffusion. The maximum transverse RMS width of the electron cloud is 2.4 mm for the chosen drift distance and drift field. This is well matched to the 5 mm wire spacing.

1.4 Detector Development Program

As mentioned above, the design of the LAr-FD has benefited greatly from other experiments and related development activities. Development activities in the U.S. are described in the *Integrated Plan for LArTPC Neutrino Detectors in the US* [**?**]. This program includes non-LBNE activities such as the Fermilab Materials Test Stand, Fermilab electronics test stand, LAPD, photon detection, ArgoNeuT and MicroBooNE as well as LBNE activities such as the 35-ton prototype and LAr1.

The development plan is described in detail in Chapter **??**.

> Editor's Note: The far detector prototyping plan known as LAr1 has been replaced by a plan to build and test a prototype with full-size TPC components at CERN.

1.5 Participants

The design for the LBNE Far Detector is being carried out by an LBNE subproject team, headed at Fermilab but with participants also from Brookhaven National Laboratory, Argonne National Laboratory and Indiana University, in conjunction with an engineering design firm, Arup USA, Inc. This firm has assisted with cryostat and cryogenic-plant design. The detector is planned for construction at the Sanford Laboratory site, which is managed by the South Dakota Science and Technology Authority (SDSTA).

The LBNE Far Detector, called the LAr-FD, is managed by the Work Breakdown Structure (WBS) Level 2 Manager for the Far Detector subproject. The supporting team includes a WBS Level 3 Manager for each of its component systems: Cryogenics & Cryostat, Time Projection Chamber (TPC), Trigger & Data Acquisition (DAQ), Installation & Commissioning and Photon Detector. Figure 1.10 shows an organization chart down to Level 3 (L3).

The Conventional Facilities Level 3 Far Site Manager is the LBNE Project liaison with the LAr-FD subproject to ensure the detector requirements are met; this person is responsible for all LBNE scope at the Far Site. [Management of the Sanford Lab and the organizational relationship between it and the LBNE Project and Fermilab are in the process of being determined; this section will be updated when that is known.]

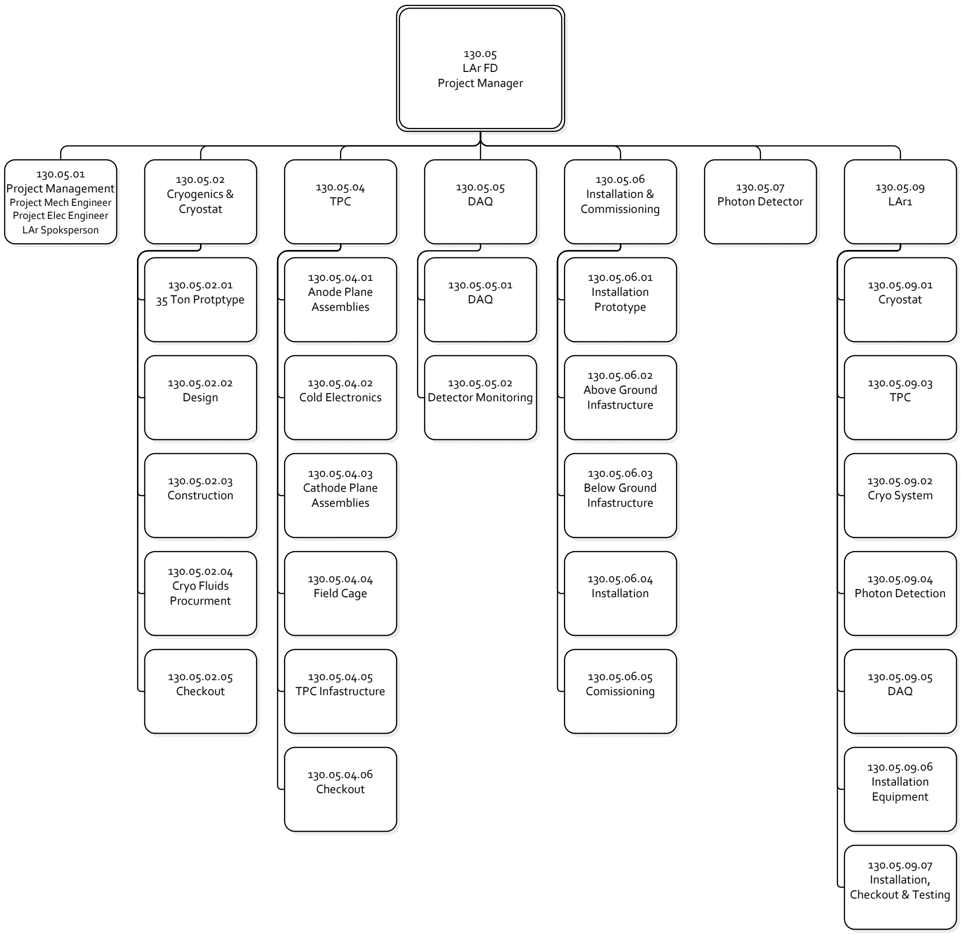

Figure 1.10: Organization chart for the Far Detector subproject (as of 2012)

Chapter 2

Cryogenics System and Cryostat

The scope of the Cryostat and Cryogenics subsystem includes the design, procurement, fabrication, testing, delivery and installation oversight of (a) a cryostat to contain the liquid argon (LAr) and the TPC, and (b) a comprehensive cryogenics system that together meet the required performance for acquiring, maintaining and purifying the LAr in the detector. This chapter describes a reference design for these interdependent detector elements.

> Editor's Note: The cryogenic system as described in the March 2012 Conceptual Design Report has been advanced by value engineering. LBNE document 7523 describes the conceptual design of a cryogenic system that would serve a 34-kton (fiducial mass) liquid argon time projection chamber sited deep underground at the 4850 foot level of the Sanford Underground Research Facility, Lead, South Dakota. The cryogenic system will now need to serve a 40-kton detector size instead of 34. The content of document 7523 is reproduced in this interim document, Sections 2.6 through 2.11, replacing the content from 2012. The numbering of the sections corresponds to the numbering from the March 2012 CDR. The other sections of this chapter are from March 2012 except where noted otherwise.

The scope of the reference-design cryogenic system and cryostat encompasses the following components:

- (updated 2014) The cryostats for the LAr-FD

- LAr tanker truck receiving facilities
- (updated 2014) Transfer system to deliver argon and nitrogen to the underground detector cryostats
- Boil-off gas reliquefaction equipment
- LAr-purification facility
- Cryostat-purge facilities

2.1 Introduction

The conceptual reference-design for the LAr-FD specifies two rectangular vessels each measuring 15.1 m width, 14.0 m in height and 33.5 m in length, and containing a total active mass of 13.8 kton of LAr. This membrane design is commonly used for liquified natural gas (LNG) storage and transport tanks (Figure 2.1). A membrane tank uses a stainless-steel liner to contain the liquid cryogen. The pressure loading of the liquid cryogen is transmitted through rigid foam insulation to the surrounding rock, which provides external support for the liner. The membrane liner is corrugated to provide strain relief resulting from temperature-related expansion and contraction (Figure 2.2).

The advantages offered by the membrane design relative to a self-supporting cryostat are:

- Efficient use of the underground cavern volume due to its direct attachment to the rock on floor and sides, which reduces the civil construction costs for the project
- Higher ratio of usable (fiducial) mass to total mass

Conceptual design studies and studies done by ARUP, USA [?] indicate that the implementation strategy for the cryogenics system is independent of the cryostat design. During the conceptual design studies two membrane cryostat vendors have been identified. Those vendors are GTT (Gaztransport & Technigaz) and IHI (Ishikawajima-Harima Heavy Industries). Each is technically capable of delivering a membrane cryostat that meets the design requirements for the LAr-FD. To provide clarity, only one vendor is represented in this CDR (GST system from GTT); this is for informational purposes only and should not be construed as preferring GTT over IHI. Nothing inherent in the IHI design changes the design approach.

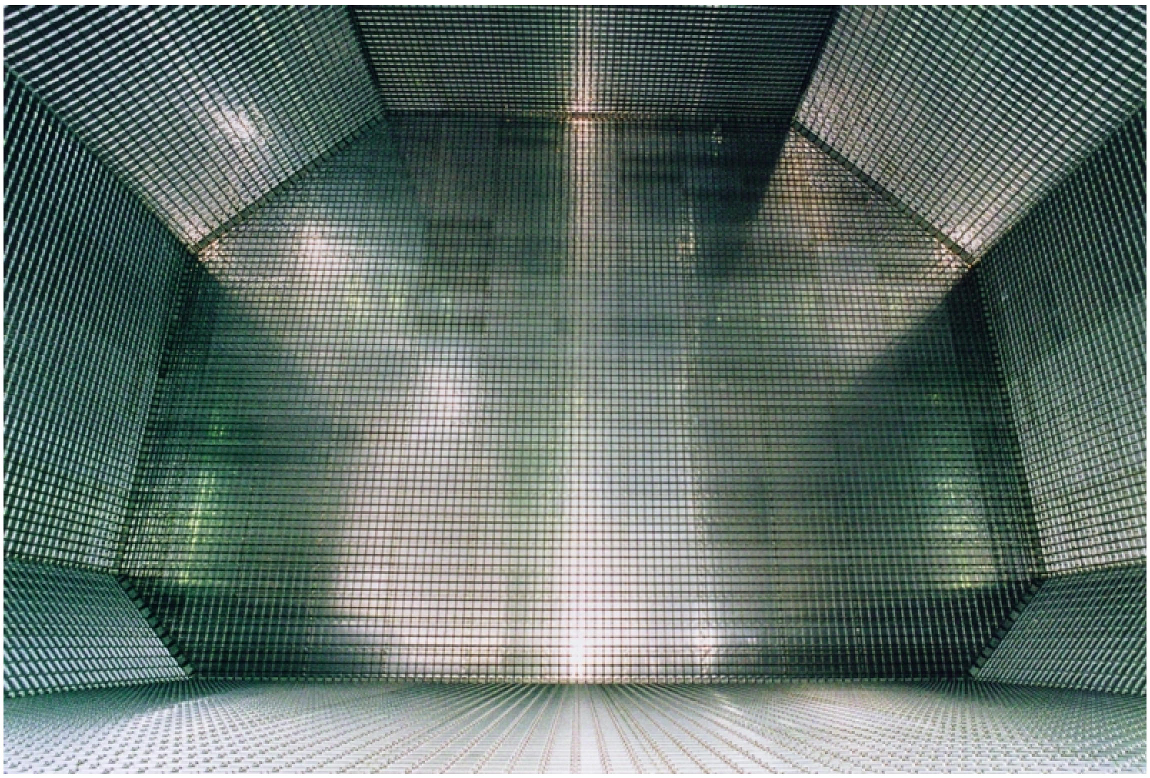

Figure 2.1: Interior of a LNG ship tanker. The tank shown is 24 m high by 35 m wide with interior grid-like corrugations on a 0.34-m pitch. By comparison, a single LAr-FD cryostat is 14 m high by 15.1 m wide.

fig:memb-tank-

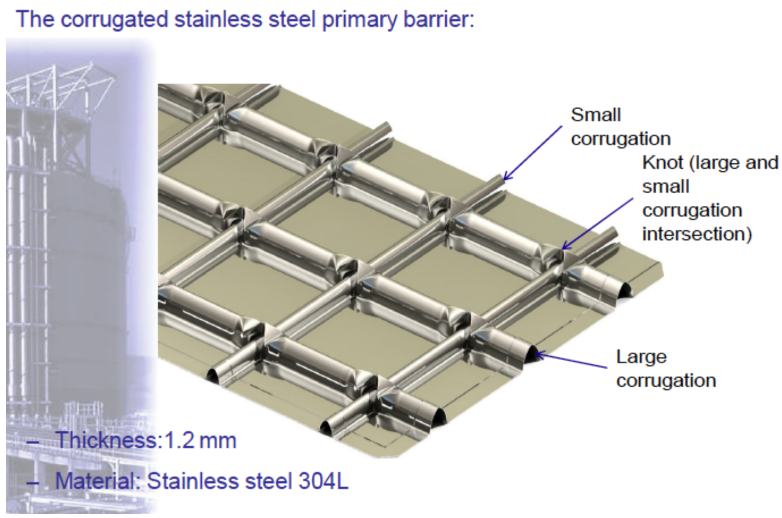

Figure 2.2: Primary membrane section (courtesy GTT)

2.2 Design Parameters

The requirements and parameters for the cryostat and cryogenic system design are within the LAr-FD requirements documentation [?] [?] and the parameter tables [?], respectively. The overarching system requirements are to provide a high-purity, stable liquid argon environment for the TPC and to provide mechanical support for the TPC. For components that pass through the ullage (the vapor space above the LAr), no sources of reliquefaction may be present. Tables 2.1 and 2.2 offer a brief overview of parameters for a single cryostat of LAr-FD.

2.3 Cryostat Configuration

2.3.1 Sides and Bottom of Tank

The membrane tank is a sealed container that relies on external support from the surrounding rock to resist the hydrostatic load of the contents. In order from innermost to outermost layers, the side walls of the membrane tank consist of the stainless-steel primary membrane; insulation; a secondary, thin aluminum membrane that contains the LAr in case of any leaks in the primary membrane; more insulation; a barrier to prevent water-vapor ingress to the cryostat; concrete; shotcrete and rock. This "in-ground" tank arrangement (i.e., offering access only from the top) protects against

Table 2.1: Design parameters for one LAr-FD Cryostat table:param-su

Parameter	**Value**
Total Volume:	7075 m^3
LAr Total Mass:	9.2 kton
Inner Height of the Tank:	14.0 m
Inner Width of the Tank:	15.1 m
Inner Length of the Tank:	33.5 m
Insulation:	Reinforced Polyurethane; 80 cm thick
Primary Membrane(GTT):	1.2-mm thick type 304L stainless steel with corrugations on 340 mm $\times$ 503 mm rectangular pitch
Secondary Containment(GTT):	$\approx$ 0.07-mm thick aluminum between fiberglass cloth; overall thickness is 0.8 mm located between insulation layers
Outer Concrete Layer:	0.5 m thick, inner surface treated with a vapor barrier
LAr Temperature:	89 $\pm$ 1 K
Depth of the Liquid (Liquid Head):	13.0 m
Design Operating Pressure (Above Liquid):	0.113 MPa
Design Operating Pressure (Bottom of Liquid):	0.2217 MPa
Rated Pressure Capacity of Tank:	0.52 MPa (calculated according to BS EN 14620) (British-Adopted European Standard / 29-Dec-2006 / 60 pages ISBN: 0580497763)

Table 2.2: Summary of parameters for the 4850L membrane cryostat

Property	**Reference-Design Cryostat**
Personnel access to cavern	Ross Shaft
Equipment transport to cavern	Ross Shaft and Yates Shaft (long items)
Construction access to pit	From above highbay
Type of crane in cavern	mobile construction
Base slab	Reinfoced concrete
Side walls	Reinforced concrete
Heating system	Redundant / Replaceable Electric system
Roof	Pre-fabricated steel truss modules with lower steel plate
Vapor barrier	Polymeric on concrete surfaces / steel plate on roof
Insulation / Secondary barrier / Membrane	GST system by GTT
TPC	Individual 2.3 $\times$ 6m frames lowered through 2m x 4m roof hatch. Assembled within cryostat and suspended by hangers passing through the roof.
LAr containment system	Full containment: Membrane / Secondary Barrier / Concrete Liner

possible cryogen leaks out of the tank — there is no place for the cryogen to go because it is surrounded on all sides by rock. The membrane cryostat is considered a “full containment" system in the LNG industry lexicon. The basic components of the membrane tank are illustrated in Figure 2.3.

2.3.2 Concrete Liner and Vapor Barrier

The formed concrete liner will be poured against the sides and bottom of the excavated rock pit. Conduits and heating elements will be embedded in the concrete liner to maintain rock temperatures above freezing to preclude any problems associated with freezing water and heaving as the rock temperature drops below the freezing point of water. The embedded conduits are encased approximately midway in the concrete side walls, end walls and bottom floor slab as depicted in Figure 2.4. The concrete liner and conduits are provided under the conventional facilities scope. The heating elements are provided by LAr-FD scope.

A vapor barrier is required on all internal surfaces of the concrete liner (base slab, side walls, end walls) and the roof to prevent the ingress of any water vapor into the insulation space. If water vapor were permitted to migrate into the insulation

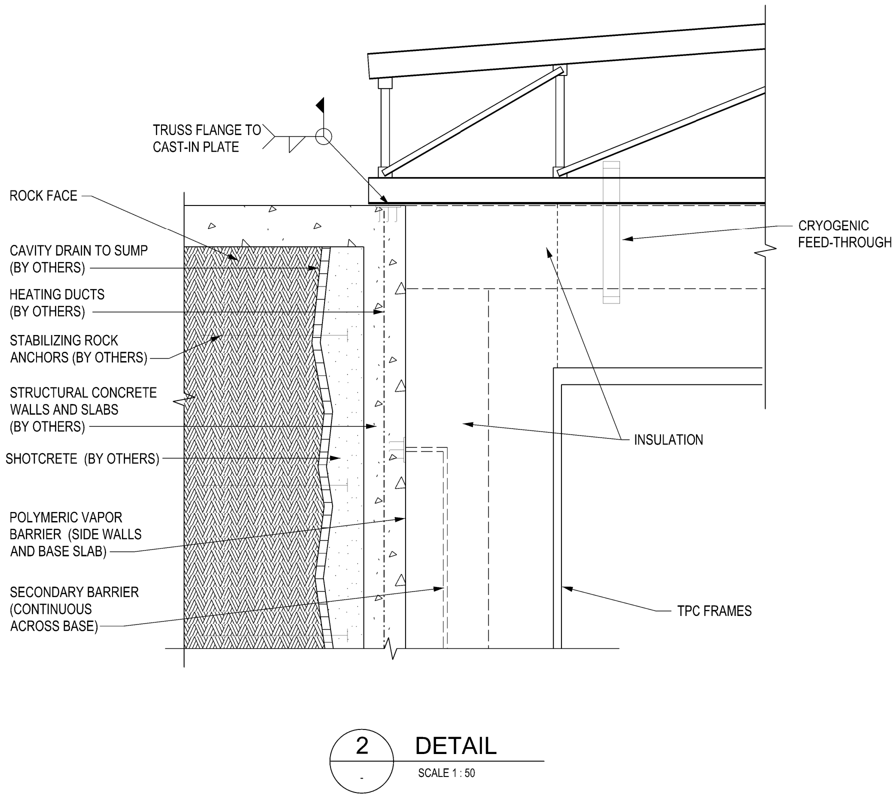

Figure 2.3: Composite system as installed for the LAr-FD reference design fig:composite-

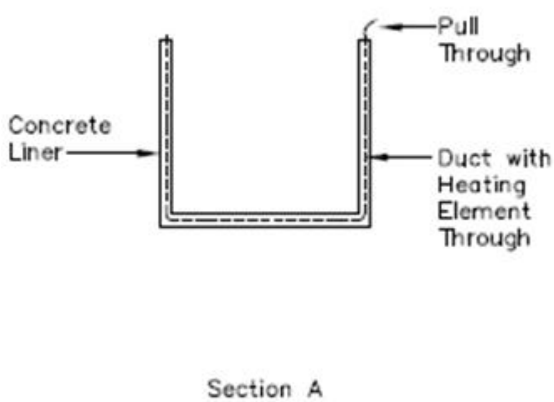

Figure 2.4: End view of concrete liner showing embedded conduits for heating elements (Courtesy Arup) fig:endview-li

space it could freeze and degrade the thermal performance of the insulation. The barrier must also reliably absorb the stresses and strains from all normal loading conditions. The selected vapor barrier material is a polymeric liner for the side and bottom surfaces. This has been used extensively in onshore LNG tank applications. The vapor barrier for the top will be solid steel plate welded together and to the underside of the roof truss.

2.3.3 Insulation System and Secondary Membrane

The membrane cryostat requires insulation applied to all internal surfaces of the concrete liner (base slab, side walls, end walls) and roof in order to control the heat ingress and hence the required refrigeration load. Choosing a reasonable, maximum insulation thickness of 0.8 m, and given an average conductivity coefficient for the insulation material of C $\approx$ 0.0283 W/m-K, the heat input from the surrounding rock is expected to be 13.7 kW per cryostat.

The insulation material, a solid fiberglass foam, is manufactured in 1-m $\times$ 3-m composite panels. The panels will be laid out in a grid with 3-cm gaps between them (that will be filled with loose fiberglass) and fixed onto anchor bolts embedded into the concrete at $\sim$3-meter intervals. The composite panels contain an outer insulation layer, the secondary membrane and an inner insulation layer. After positioning adjacent composite panels and filling the 3-cm gap, the secondary membrane is spliced together by epoxying an additional layer of secondary membrane over the joint. All seams are covered so that the secondary membrane is a continuous liner. A corner detail is shown in Figure 2.5.

The secondary membrane is comprised of a thin aluminum sheet and fiberglass cloth. The fiberglass-aluminum-fiberglass composite is very durable and flexible with an overall thickness of $\sim$1 mm. The secondary membrane is placed within the insulation space. It surrounds the internal tank on the bottom and sides, and it separates the insulation space into two distinct, leak-tight, inner and outer volumes. The outer insulation separates this membrane from the concrete. This sheet is connected to embedded metal plates in the vertical concrete wall at the upper edge of the tank. In the unlikely event of an internal leak from the cryostat's primary membrane into the inner insulation space, it will prevent the liquid cryogen from migrating all the way through to the concrete liner where it would degrade the insulation thermal performance and could possibly cause thermal stress cracks in the surrounding concrete. The liquid cryogen in the case of leakage through the inner (primary) membrane will be contained in the secondary membrane volume.

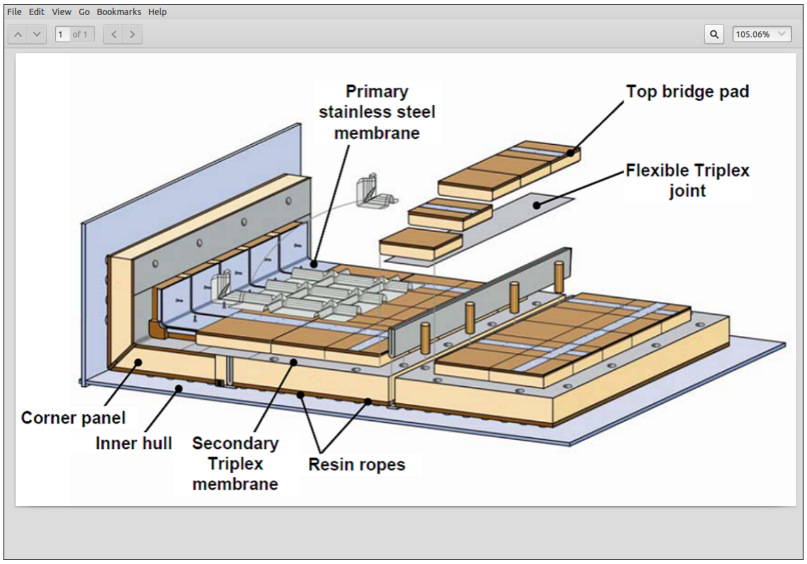

Figure 2.5: Membrane corner detail

2.3.4 Tank Layers as Packaged Units

Membrane tank vendors have a "cryostat in a kit" design that incorporates insulation and secondary barriers into packaged units. See Figure 2.6. Figure 2.3 illustrates how these layers would be used in the LAr-FD reference design.

2.3.5 Top of Tank

The stainless-steel primary membrane and the intermediate layers of insulation and water-vapor barrier continue across the top of the detector, providing a vapor-tight seal. Note that no secondary membrane is used or required for the cryostat top. The cryostat roof is a steel truss structure that bridges the detector. Stiffened steel plates hermetically welded to the underside of the truss form a flat vapor barrier surface onto which the roof insulation attaches directly; this is described more fully below. Fully fabricated roof trusses are placed across the roof with a 2.5-m spacing. Field-fabricated truss members and steel plates are welded between the prefabricated trusses to connect the two prefabricated sections. The roof is built up of alternating prefabricated and field-fabricated "in-fill" roof sections. This configuration was selected during the screening process because it provides an efficient, gas-tight solution that can be readily constructed within the cavern space.

The truss structure rests on the top of the concrete wall as shown in Figure 2.3

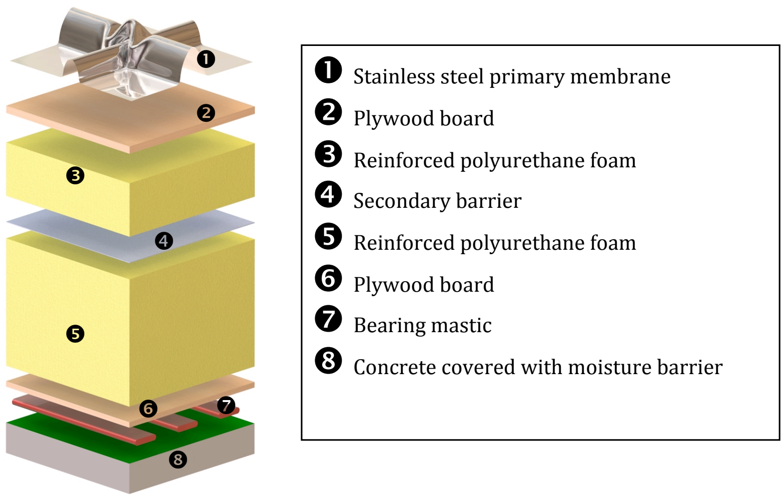

Figure 2.6: GST composite system from GTT

where a positive structural connection between the concrete and the truss is made to resist the internal upward force caused by the slightly pressurized LAr in the cryostat. The hydrostatic load of the LAr in the cryostat is carried by the floor and the side walls. Everything else within the cryostat (TPC planes, electronics, sensors, cryogenic- and gas-plumbing connections) is supported by the steel plates under the truss structure. All piping and electrical penetrations into the interior of the cryostat are made through this top plate to minimize the potential for leaks.

Studs are welded to the underside of the steel plates to bolt the insulation panels to the steel plates. Insulation plugs are inserted into the bolt-access holes. The primary membrane panels (also manufactured in smaller sheets) are first tack-welded then fully welded to complete the inner cryostat volume. Feed-through ports as shown in Figure 2.7 are located at regular intervals within the corrugation pattern of the primary membrane to accommodate TPC hangers, electrical and fiber-optic cables, and piping. The roof truss will be anchored to the top of the poured-concrete liner walls to resist the uplift caused by internal tank overpressure (Figure 2.8). The roof truss will be pre-fabricated off-site in ∼2 m wide, fully-welded modules and transported to the cavern as required by the installation schedule.

The prefabricated steel roof-truss modules are relatively lightweight (∼ 8,000 kg each) and require only moderate crane capacity. If the steel trusses need to be separated into smaller pre-fabricated units for transport to the underground site, assembly within the cavern space prior to installation is relatively straightforward. The truss construction is illustrated in Figure 2.8.

Figure 2.7: Nozzle in roof membrane cryostat (Figure courtesy GTT)

fig:v5ch2-roof

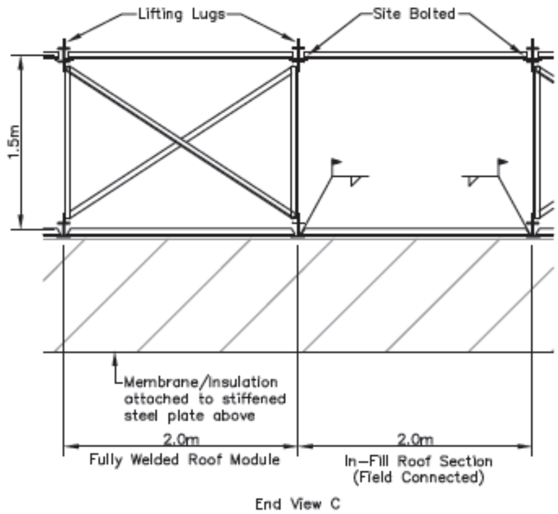

Figure 2.8: Roof truss structure (Courtesy Arup)

fig:roof-truss

Some equipment, such as monitoring instrumentation and pumps, will be installed within wells extending through the roof structure. All connections into the cryostat will be made via nozzles or penetrations above the maximum liquid level and mostly located on the roof of the cryostat. See figure 2.7 for a typical roof-port penetration.

2.4 LAr Circulation and Temperature-Profile Modeling

The liquid circulation in the LAr-FD cryostats has been modeled using computational fluid dynamics modeler software (ANSYS CFX).

A field cage, described in Section **??**, was modeled with half-inch slots cut every five inches, yielding a 10% porosity. Standard insulation thermal conductivity of 0.0283 W/m-K was used to model the heat flux into the LAr. and used an exterior temperature of 278 K and an internal temperature of 87.15 K. The temperature stability requirement on LAr-FD is ± 1 K. The model in Figures 2.9 and 2.10 clearly identifies convective currents flowing through the entire liquid bath with the highest velocities < 0.034 m/s, and a temperature gradient much less than 0.1 K across the entire fluid body. This indicates conformity with LAr-FD requirements and parameters.

2.5 Leak Prevention

The primary membrane will be subjected to several leak tests and weld remediation, as necessary. All (100%) of the welds will be tested by an Ammonia Colorimetric Leak Test (ASTM E1066-95) in which welds are painted with a reactive yellow paint before injecting gas with 25% ammonia into the bottom insulation space of the tank. Wherever the paint turns purple or blue, a leak is present. Both membrane cryostat manufucturers use this technique for certifying that a cryostat is leak-tight. Any and all leaks will be repaired. The test lasts a minimum of 20 hours and is sensitive enough to detect defects down to 0.003 mm in size and to a 10^{-7} std-cm^3/s leak rate (equivalent leak at standard pressure and temperature, 1 atm and 273 K). Both membrane cryostat manufucturers use this technique for certifying that a cryostat is leak-tight.

To prevent infiltration of water-vapor or oxygen through microscopic membrane leaks (below detection level) the insulation spaces will be continuously purged to provide one volume exchange per day.

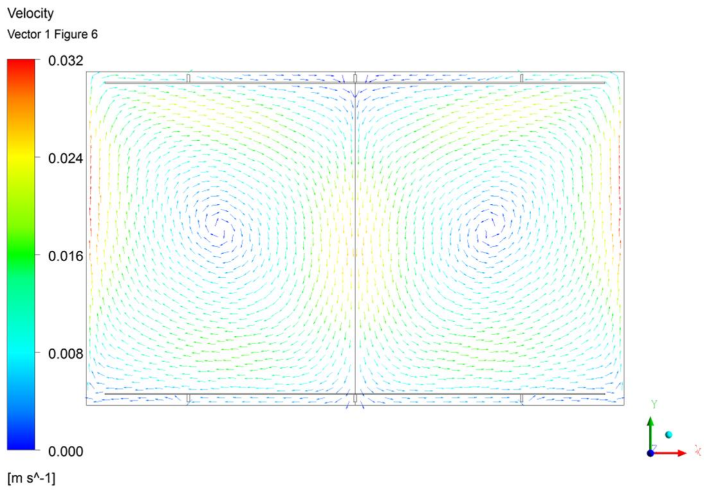

Figure 2.9: LAr velocity profile fig:LAr-veloci

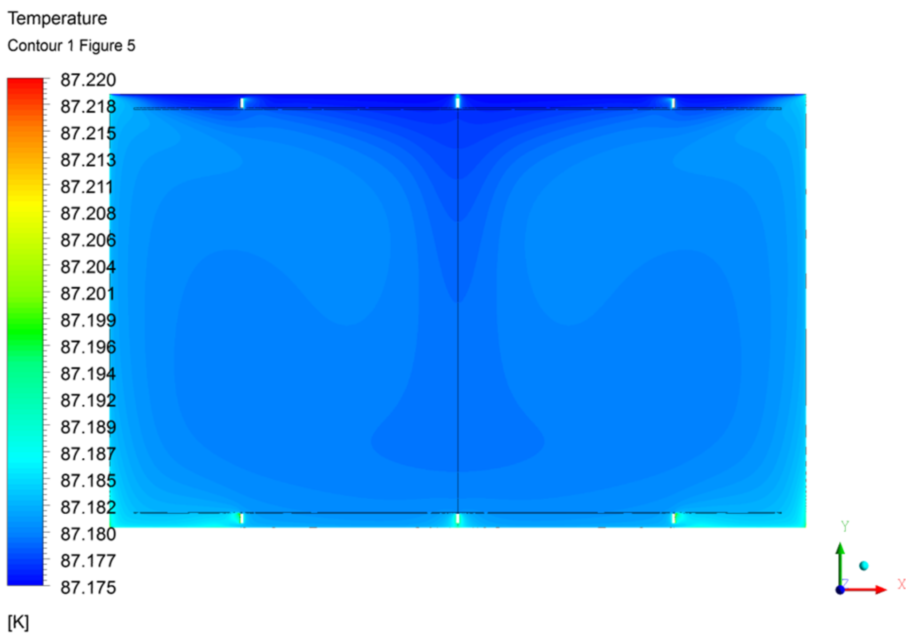

Figure 2.10: LAr temperature profile fig:LAr-temper

The insulation space between the primary and secondary barriers will be maintained at 0.103 MPa, slightly above atmospheric pressure. This space will be monitored for changes that might indicate a leak from the primary membrane. The outer insulation space will also be purged with argon at a slightly different pressure. The pressure gradient across the membrane walls will be maintained in the outward direction. Pressure-control devices and relief valves will be installed on both insulation spaces to ensure that the pressures in those spaces do not exceed the operating pressure inside the tank.

The purge gas will be recirculated by a blower to a small purge gas dryer and reused as purge gas. The purge system is not safety-critical, and an outage of the blower would have only a minimal, short-term impact on operations [**?**].

2.6 Cryogenic Systems Layout

Cryogenic systems are located on the surface and within the cavern. Figure 2.11 illustrates the cryogenic systems layout. On the surface near the Ross shaft there will be a cryogen receiving station. A 50-m^3 (69 tons liquid argon capacity) vertical liquid argon dewar will have two LAr truck connections to allow for receipt of liquid argon deliveries for the initial filling period. The liquid argon dewar serves as a buffer volume to accept liquid argon at a pace of about 5 liquid argon trailers (18 tons per trailer) per day during the fill period. An analyzer rack with instruments to check water, nitrogen, and oxygen content of the trailers will also be located in the vicinity. A large 280 kW vaporizer at the surface is used to vaporize the liquid argon from the storage dewar prior to the argon gas being transferred by uninsulated piping down the Ross shaft.

A 50-m^3 vertical liquid nitrogen dewar and fill connection is located near the liquid argon dewar. The nitrogen dewar is used to accept nitrogen deliveries for the initial charging and startup of the nitrogen refrigerator. It is also used for pressure control of the liquid argon storage dewar. A large vaporizer for the nitrogen circuit is located nearby to vaporize nitrogen to nitrogen gas that is used as the feed for the compressors of the nitrogen refrigerator. Four compressors are located in a compressor building located at the surface near the Ross shaft and cryogen receiving area. The compressors require a closed loop water cooling circuit. The closed loop water cooling circuit has recirculation pumps in the compressor building and an evaporative cooling tower located outside near the vaporizers. Only the compressors of the refrigerator are located on the surface. The compressors discharge high pressure (1.1 MPa) nitrogen gas into pipes that run down the Ross shaft. The compressors were chosen to be located on the surface because the electrical power

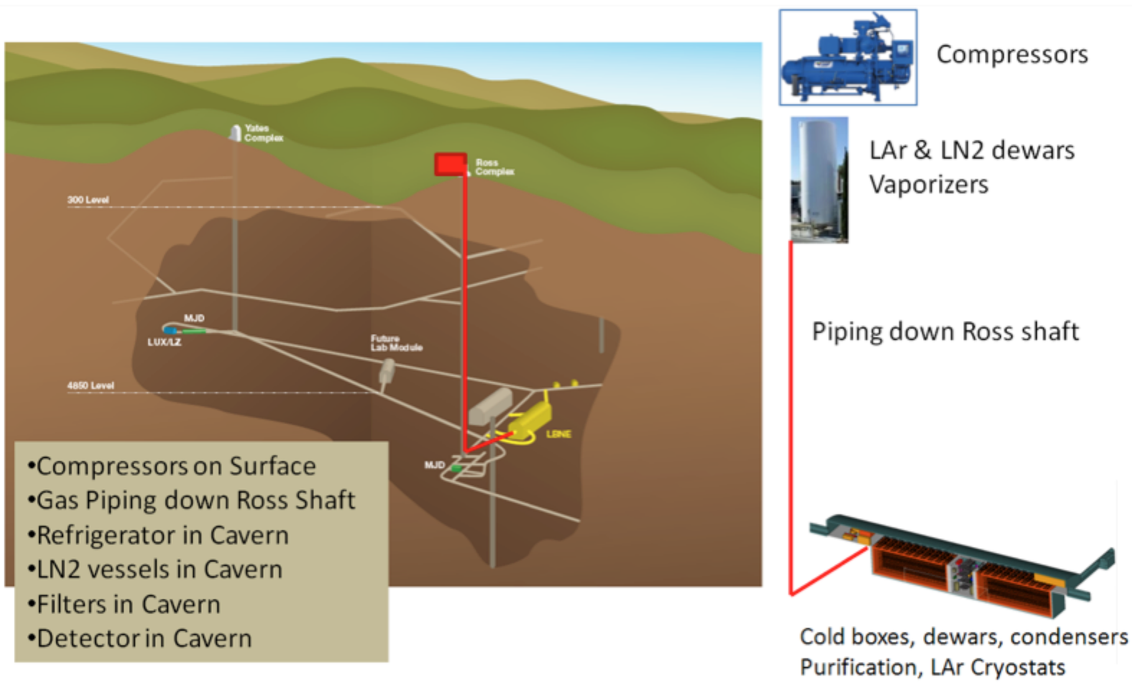

Figure 2.11: Graphical illustrations showing major pieces of equipment and their location at the surface, piping down the Ross shaft, and in the detector cavern fig:eqp-at-sur

requirement and cooling requirement is much cheaper to provide at the surface rather than at deep depth in the mine. Each compressor is an 850 horsepower machine running at 4160 volts. Four running compressors will require a total of 2.6 MW of electrical power at the surface.

The Ross shaft contains the vertical piping runs to connect the surface equipment with the equipment in the cavern. The vertical piping runs are described in Section 2.7. Piping run consist of a gas argon transfer line and the compressor suction and discharge lines. At the bottom of the Ross shaft at the 4850 level, the piping exits the shaft and runs along a drift to the detector cavern.

The detector cavern at 4850 level contains the rest of the nitrogen refrigerator, liquid nitrogen vessels, argon condensers, in-tank liquid argon recirculation pumps, and filtration equipment. The cavern equipment is described in Section 2.8. The nitrogen refrigerator equipment is located at the end opposite the Ross shaft. Fresh ventilation air is supplied down the Ross Shaft, enters the detector cavern and flows over the cryostats and then over the refrigerator equipment before being exhausted out that e nd of the detector cavern. The liquid nitrogen vessels in the detector cavern are located in the crown of the cavern. A space for the purification filters is opened up between the cryostats. It is known as the septum area. The 1.5 m thick concrete end wall for each cryostat is separated by 15 meters of clear space to create the septum area.

Each cryostat will have its own argon recondensers, argon-purifying equipment and overpressure protection system. Each set of systems is placed on the septum side of the wall closest to the cryostat it serves. Two 25-m^3/hr circulation pumps will be placed within each membrane cryostat to circulate liquid from the bottom of the tank through the purifier.

2.7 Pipework between Surface and Cavern

The piping between the surface and cavern is located in a utility chase down the Ross shaft. See Figure 2.12. The piping is single wall carbon steel pipe coated with a corrosion barrier. Table 2.3 lists the piping and its duty and size. The frictional pressure drop for the supply pipes match the pressure gained due to the static head from elevation change. Piping will be all welded construction. The nitrogen and argon being transferred in the Ross shaft piping will be at ambient temperature, in the gas phase. Having gas phase only in the 1.5-km vertical piping is an advantage over liquid transfer because the hydrostatic head for gas only piping is on order 0.05 MPa whereas for the liquid transfer it is 20 MPa. If liquid phase fluid was transferred it would require on order seven pressure reducing stations evenly spaced along the vertical drop. Using liquid cryogenic delivery was considered, and in fact was the choice in the March 2012 CDR. However, the cost of providing the excavated spaces and pressure reducing stations was costly as compared to using gas only transfer. For a liquid transfer option with pressure reducing stations, the piping would need to be routed down the Oro Hondo ventilation shaft which would need rehabilitation should that option be chosen. With gas only transfer to the cavern, we can run straight piping down the Ross shaft. The drawback of gas only transfer is that one must provide the liquid nitrogen refrigeration in the cavern to fill the cryostats by liquid argon condensation. Filling each cryostat with liquid argon in a reasonable period of time drives the refrigerator size and condenser sizing.

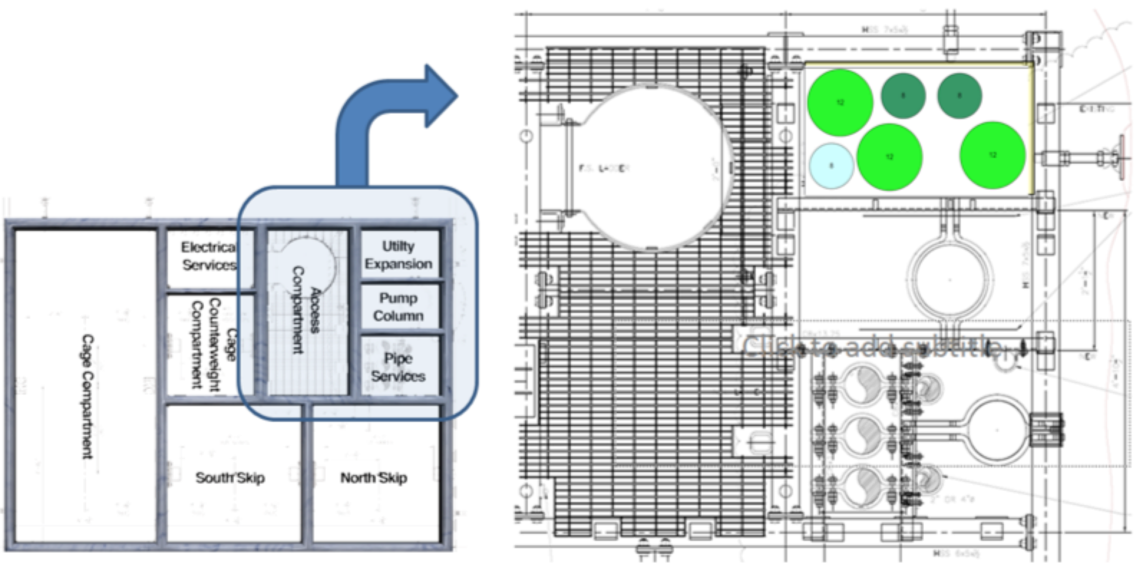

Figure 2.12: The framing of the Ross shaft is shown on the left. The utility area in the upper right corner contains the piping associated with the cryogenic system fig:framing-at

A preliminary oxygen deficiency hazard (ODH) assessment for the piping in the Ross shaft has been done. The mine fresh air ventilation is sizeable, 100,000 cfm supplied down the Ross and Yates shafts. If any of the pipes for the cryogenic system ruptured in the shaft they would only be able to reduce the oxygen content by a fraction to 20.5%, thus not being an oxygen deficiency concern.

Table 2.3: Piping between surface and cavern; location, duty and required size

table:pipeline

Description	**Duty**	**Size**	**Fluid Pressure**
Argon transfer	During filling and emptying	8" sch. 40	0.24 MPa
N2 Compressor discharge	continuous	Two 8" sch. 40 pipes	1.14 MPa
N2 Compressor suction	continuous	Three 12" sch. 40 pipes	0.19 MPa at bottom, 0.11 MPa at top

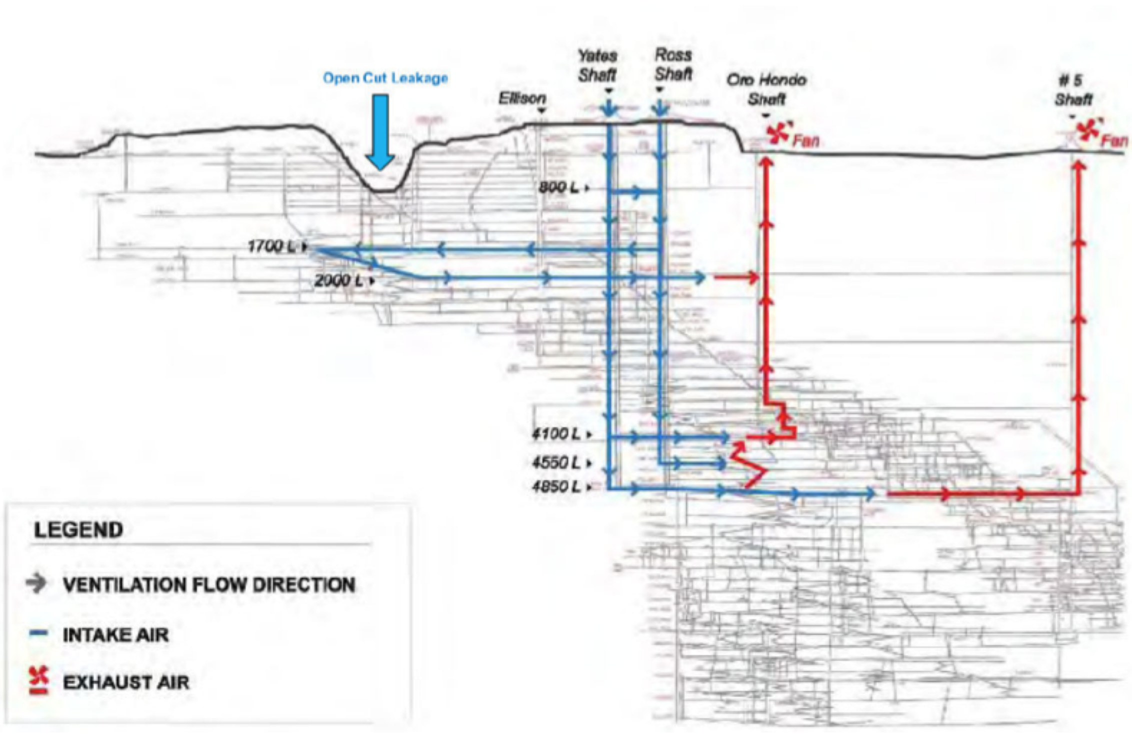

Figure 2.13: Homestake mine ventilation paths

fig:ventilatio

2.8 Equipment in the Cavern

There are four independent 85 kW nitrogen refrigerators in the cavern. The nitrogen refrigerator heat exchangers and expander sets are located at the east end of the detector hall. The heat exchangers (1.2 m diameter × 9.1 m long) will be in a horizontal orientation in order to fit them within the cavern. The liquid nitrogen produced by the refrigerators is stored in eight horizontal 12.5-m^3 (1.2 m diameter × 11 m long) liquid nitrogen vessels that are mounted in the crown space of the cavern over the refrigerator heat exchangers. These liquid nitrogen vessels in turn feed the argon condensers that are connected to the cryostat. The returning nitrogen gas from the condensers is routed through the refrigerator heat exchangers and warmed to ambient temperature. The nitrogen gas is then boosted by four 120 kW compressors located in the cavern to 0.19 MPa and returned up the nitrogen suction piping in the Ross shaft.

Three argon condensers (0.61 m diameter × 1.9 m long) for each cryostat are located at the septum end of the cryostat. The full power of the argon condensers is used during the initial filling phase of the cryostats to fill the cryostat by condensation of the gas argon transferred down the Ross shaft. The fill process is expected to take 9.5 months for the first cryostat and 11.6 months for the second. Additional information about the filling process is described in Section 2.9.

> Editor's Note: Filling times in preceding sentences refer to filling two 17-kton modules.

Purification filters are located in a septum space between the cryostats as shown in Figure 2.14. The filters (2.2 m diameter × 4.5 m high) contain dual media, a molecular sieve for removal of water and a copper coated catalyst media for oxygen removal. There is one gas filter that is used during the argon filling phase and one liquid filter for each cryostat for a total of three. Associated with the filters, there will be regeneration equipment such as heaters, gas blowers, and a hydrogen generator also located in the septum area.

2.9 Cryogenic System Processes

The functionality of the cryogenic system is shown in Figure 2.15. This diagram shows the interconnectivity between major functions of the cryogenic system. The major piping connections can be seen in Figure 2.16. The major functions serving

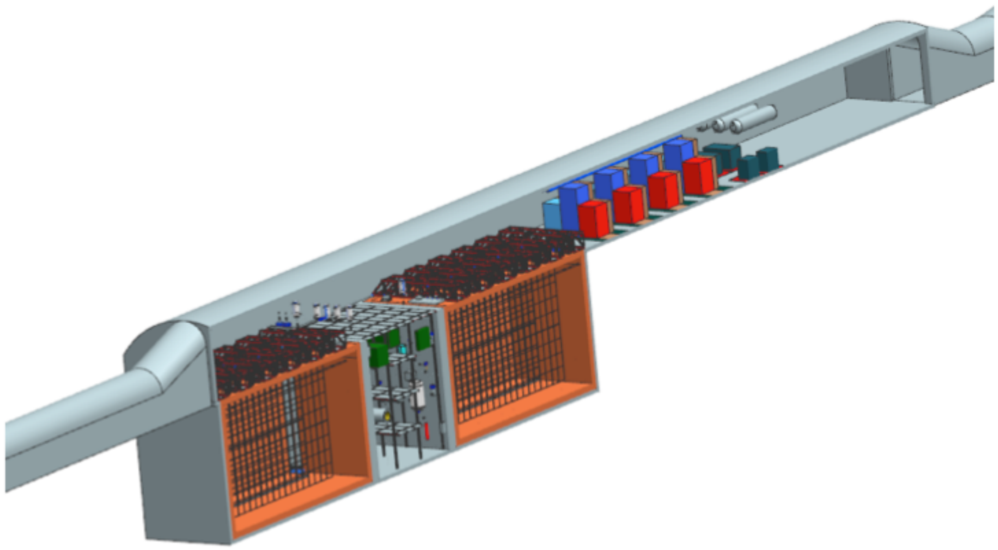

Figure 2.14: Isometric view of the detector cavern showing purification equipment in a septum space between the detector cryostats and refrigerator equipment at one end fig:det-cavern

the cryostat are cryogen supply for cool down and fill, gas filtration, condensing, liquid filtration and circulation, argon-purity analysis, and argon condensing. The methods presented in this section are motivated by experience from other LAr TPC cryogenic systems such as ICARUS and LAPD.

2.9.1 Cryostat Inital Purge and Cool-down

After cryostat construction and following installation of all scientific equipment, the cryostat will be cleaned, purged and cooled. Construction procedures leading up to this point will ensure that the completed cryostat does not cont ain debris and is free of all loose material that may contaminate the LAr.

Initial Purge

Argon piping will be isolated, evacuated to less than 0.1 mbar absolute pressure and backfilled with high-purity argon gas. This cycle will be repeated several times to reduce contamination levels to the ppm level in the piping. The reference-design choice for removing air from the membrane cryostat will be to flow/piston-purge argon, introducing the heavy argon gas at the bottom of the tank and removing the exhaust at the top. The bottom field cage (part of the TPC), serves an additional role as a flow diffuser during the initial purge. A matrix of small holes in the field cage will provide a uniform flow, approximately 10-mm diameter at a 50-mm pitch.

The flow velocity of the advancing argon-gas volume will be set to 1.2 meters/hour. This is twice the diffusion rate of the air downward into the advancing argon so that the advancing pure argon-gas wave front will displace the air rather than just dilute it. A 2D ANSYS model of the purge process shows that after 20 hours of purge time and 1.5 volume changes, the air concentration will be reduced to less than 1%. At 40 hours of elapsed time and three volume changes, the purge process is complete with residual air reduced to a few ppm. This simulation includes a representation of the perforated field cage at the top and bottom of the detector and heat sources due to the readout electronics. The cathode planes are modeled as non-porous plates although they will actually be constructed of stainless-steel mesh.

The computational fluid dynamics (CFD) model of the purge process has been verified with purge tests in an instrumented 1-m-diameter by 2-m-tall cylinder. Recognizing that obtaining the required purity levels by the flow-purging method needs to be clearly demonstrated, a Liquid Argon Purity Demonstrator (LAPD) project was undertaken at Fermilab. The LAPD is a right-cylindrical vessel, 3 m in diameter and 3 m tall. LAPD took gas-sampling measurements at varying heights and times during the purge process. Experimental measurements taken by the Liquid Argon Purity Demonstrator (LAPD) have verified the previous modeling of this purge process. During the first operation of LAPD, the vessel needed nine volume changes to reach single-digit contamination levels (ppm by volume) for oxygen, water and nitrogen. Following the purge, the LAPD vessel was cooled down and filled with LAr. On September 30, 2011, LAPD leaders presented initial results of this purge process in which purity levels of less than 100 ppt oxygen-equivalent were achieved. A second period of operation in FY13 has confirmed this approach yet again. The purge method works and it minimizes the risk to LBNE that an evacuable vessel will be required. This test will be repeated with a 35-ton membrane cryostat prototype.

Water Removal via Gas Flow

Water and oxygen will continue to be removed from the system for several days following the initial purge. Flowing gas will be used at the same rate, however at this stage the gas will be filtered and recirculated. Each cryostat contains five tons of FR4 circuit-board material and a smaller inventory of plastic-jacketed power and signal cables. These somewhat porous materials may contain as much as 0.5% water by weight. Water-vapor outgassing from these materials will be entrained in the gas

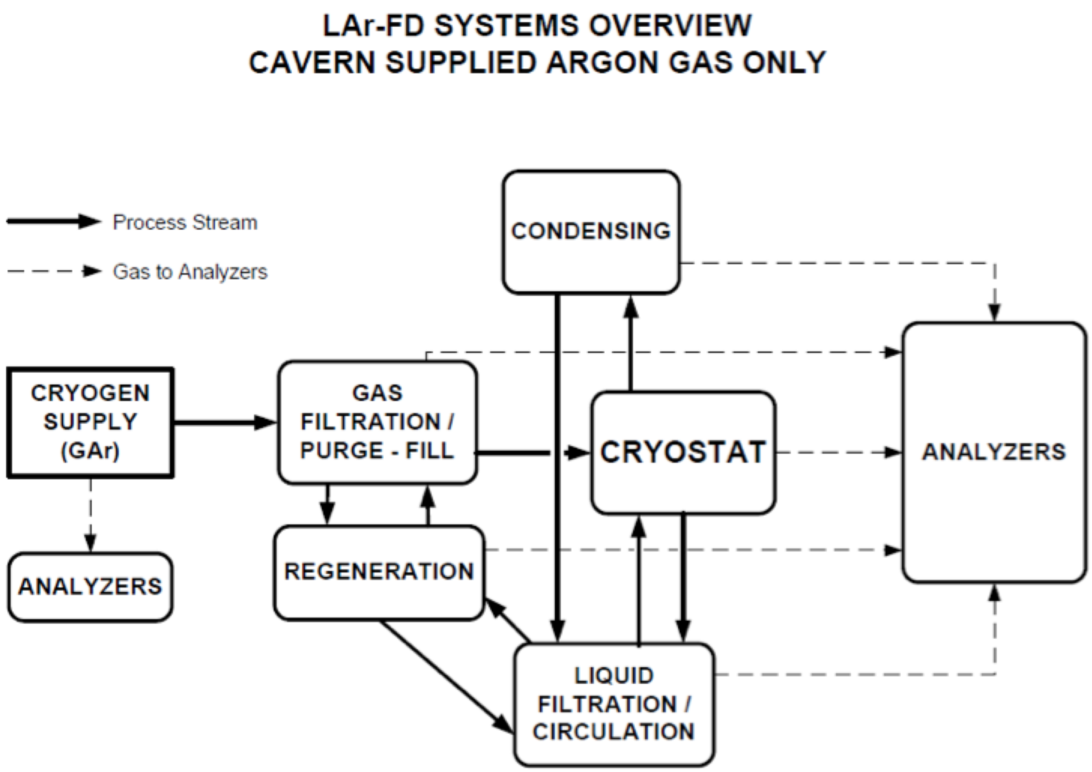

Figure 2.15: Cryogenic system functions

fig:v5ch2-LAr-

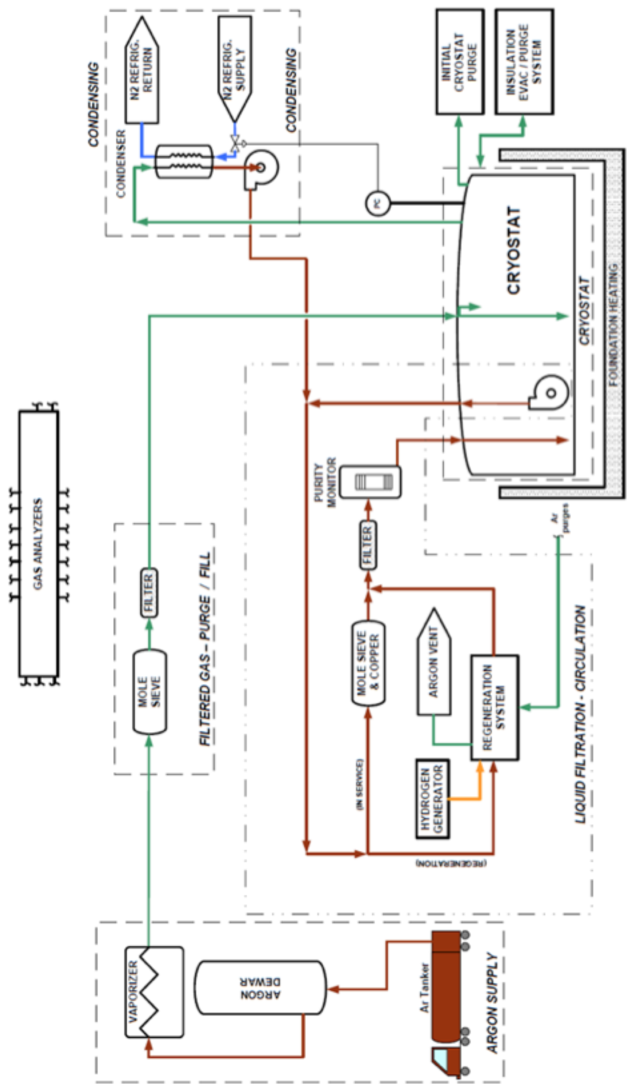

Figure 2.16: Cryogenic system block flow diagram fig:v5ch2-LAr-

flow exiting the top of the cryostat and will be removed from the gas stream by filters. Adsorbed water will also be removed from the metallic inner surfaces of the cryostat and piping system. Water deep within porous materials will remain; this is not a problem since the water diffusion rate in FR4 at room temperature is already quite low (0.3 $\mu m^2/s$) and the FR4 assemblies are relatively thick (1 cm).

Alternative Water-Removal Method: Evacuation

The traditional method for removing water and oxygen from LArTPCs is to evacuate the tank to $\sim 10^{-4}$ mbar and then backfill it with pure argon gas. Although the primary membrane of the reference-design cryostat is not a vacuum vessel, it is possible to evacuate it. A membrane-cryostat vendor reports that evacuation of the insulation spaces (external to the primary membrane) is normally done during the construction and leak-checking phases. A vacuum pressure of less than 200 mbar absolute in the insulation spaces has so far been achieved. As long as the pressure-differential direction across the walls is kept outward, it is possible to reduce the internal membrane-tank volume to these pressures as well.

Initial Cool-Down

Purified LAr will be distributed near the bottom of the cryostat to cool down the cryostat in a controlled spray. (A design is being tested in the 35 ton prototype which is to become operational in fall 2013). The boil-off gas will flow through the volume of the cryostat, then routed to the recondenser and liquid-filtration system. Simulation has shown that the liquid cool-down method can be controlled to stay within the available recondenser capacity. The required cooling rate is determined by the maximum stress that detector components can tolerate. For example, the 150-μm APA wires will cool much more rapidly than the APA frames. A mass flow control system with temperature-monitoring system will be used to control the temperature difference across the cryostat. The exact temperature difference required is yet to be determined; it will be based on input from the cryostat designer and the requirements of the TPC components and structure.

Initial Purge and Cool-Down Design Features

Internal piping is positioned within the cryostat to support the purge and cool-down procedure. Heavy argon vapor, which is a result of cooling down the membrane bottom with liquid, will promote purging after it rises from the base of the cryostat and is vented from the roof level. The LAr-supply pipework will have nozzles spaced along its length to distribute equal liquid-delivery flow rates across the bottom of the cryostat. The flow nozzles will be directed downward or to the side so that the injection velocity will not cause local vertical gas plumes or turbulent mixing but rather will spread across the bottom of the tank and produce a stable, upwardly advancing argon wave front. The vertical velocity of 1.2 m/hr for the gas purge includes a contingency for some level of turbulent mixing.

Main gas returns, used for pressure control, will be distributed along the cryostat roof. All nozzles and dead-end (stagnant) volumes located at the top of the cryostat will have gas-exhaust lines for the initial purge and for continuous sweep-purge of those volumes during normal operations. The sweep-purge during the initial stage of purging will be vented outside of the cavern. After all but trace amounts of air have been expelled, the gas returns will be routed to the recondensers before being returned to the cryostat. When cool-down to 120 K is complete (and during steady state operations), the gas returns will be sent to the recondenser to be liquefied by heat exchange with a liquid nitrogen stream. The recondensed liquid will be filtered and sent back to the cryostat to complete the cool-down operation. All purge gas will be contained and either vented outside of the cavern at a remote location, or recondensed and reused.

2.9.2 Liquid Argon Receipt

Each five-kton fiducial mass LAr detector module will hold an inventory of 9.2 kton of liquid argon. Initial purge operations are expected to consume and exhaust about 0.25 kton per module. Considering that some product will also be lost in transit, approximately 20 kton of LAr will need to be procured to fill the initial 10-kton detector. Planning the logistics and supply of LAr to the facility requires consideration of the following issues:

- total capacity of commercial air-separation plants within freight distance of the facility (the peak delivery potential)
- extent of boil-off that will occur in transit
- number of vehicle movements required and their impact on the local community
- costs and benefits associated with stockpiling LAr at the facility ahead of commencing the purge, cool-down and fill procedure
- provision of a temporary air-separation plant at the facility to generate liquid argon

- availability and cost associated with the delivery of high-purity LAr as opposed to lower-quality, commercial-grade argon combined with on-site, coarse purification

Total argon production in the United States is currently approximately 3.6 kton per day. Argon is normally co-produced along with large volumes of oxygen, so any project that requires large oxygen quantities may also spur additional argon production, enhancing the supply capacity. A 2013-2018 market-forecast report by the Freedonia group [?] indicates that the demand for argon will increase at a rate of 3.4% per year whereas the demand for oxygen will increase 4.8%.

The standard grade specification for argon is a minimum purity of 99.995%, allowing a maximum concentration of 5.0 ppm for O_2 and 10.5 ppm for H_2O. This is designated as Grade 4.5 in the gas-supply industry. Requiring higher-purity product would significantly reduce the volume of product available to the experiment, increasing cost and pushing out the schedule. Therefore, standard product will be procured from multiple vendors.

The most efficient mode of argon delivery is over-the-road tank truck with a maximum capacity of 18.7 metric ton (MT). The expected number of such deliveries needed is 510 over nine and one-half months to fill one cryostat (the second cryostat will take >11 months to fill due to reduced cooling power after one detector is full and pure). Rail delivery is not cost-effective as there are no rail spurs leading to the site. This mode would require transfer of product from rail tanker to a tank truck, introducing cost that exceeds the benefit.

Surface facilities are required for the offloading of LN and LAr road tankers. It will be necessary to procure approximately four trailer loads of liquid nitrogen (about 40 tons) for the initial filling of the LN refrigeration dewar and charging of a single refrigeration plant. Vehicle access and hard-surfaced driving areas are required adjacent to the LN_2 dewar and LAr-supply piping. An interim LAr storage dewar will hold the contents of a road tanker in order to minimize off-loading time. Road tankers will connect to a manifold and will use their on-board pumps to transfer the LAr to the storage dewar. Each tanker will be tested to ensure that the LAr meets the purity specification. The LAr will be stored in the surface dewar and vaporized before transporting by pipe feed to the underground cavern for liquefaction.

2.9.3 Cryostat Filling

Liquid argon will be delivered to the cryostat through the cryostat-filling pipework. Argon will be piped to the cavern in gas form from the surface and condensed/liquefied via the LN_2 exchange in the condenser units. The filling process will take place over many weeks due to the delivery schedule of liquid argon described in the previous section and the need to condense gaseous argon. Liquid-argon purification can begin once the liquid depth reaches about 2 m in the cryostat. At this depth, the recirculation pumps can safely turn on and direct up to 51 m^3/hr (224 gpm) of liquid argon through the purification system.

2.9.4 Argon Reliquefaction and Pressure Control

High-purity liquid argon stored in the cryostat will continuously evaporate due to the unavoidable heat ingress. The argon vapor (boil-off gas) will be recovered, chilled, recondensed and returned to the cryostat. A closed system is required in order to prevent the loss of the high-purity argon.

During normal operation the expected heat ingress of approximately 46.2 kW to the argon system will result in an evaporation rate of 1031 kg/hr and expanding in volume by a factor of 200 when it changes from the liquid to vapor phase. This increase in volume within a closed system will, in the absence of a pressure-control system, raise the internal pressure.

In LAr-FD, argon vapor will be removed from the top of the cryostat through the chimneys that contain the cryogenic feedthroughs. As the vapor rises, it cools the cables and feedthrough, thereby minimizing the outgassing. The exiting gaseous argon will be directed to a heat exchanger (a recondenser, illustrated in Figure 2.17) in which it is chilled against a stream of liquid nitrogen and condensed back to a liquid. As the argon vapor cools, its volume reduces and in the absence of pressure control further gas would be drawn into the heat exchanger, developing a thermal siphon. Therefore, a pressure-control valve on the boil-off gas lines will control the flow to the recondenser to maintain the pressure within the cryostat at 0.113 MPa $\pm$ 0.003 MPa. The liquid nitrogen stream (that provides the coolant for the recondenser) will be supplied from a closed-loop LN_2 refrigeration plant. The commercial refrigeration plant uses compression/expansion and heat rejection to continuously liquefy and reuse the returning nitrogen vapor. The estimated heat loads within the cryostat are listed in Table 2.4.

Each module of the detector has a dedicated nitrogen-refrigeration plant and a third and fourth plant will be on standby during normal operations. All four will be used for the initial cooldown of the cryostats because of the large volume of gas which must be cooled from 300K to liquid argon temperature (87K). Further, each module will have two 85-kW condensers to provide the cooling power needed during initial cooldown and filling operations where warm GAr is cooled and reliquefied to fill the cryostat. After filling, only one condenser is needed with the other providing

Table 2.4: Estimated heat loads within the cryostat table:cryo-hea

Item	**Heat Load (kW)**
Insulation heat loss	17.3
Electronics power	6.3
Recirculation-pump power	5.2
Total	**28.8**

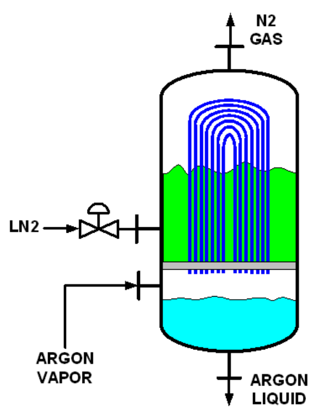

Figure 2.17: Liquid argon recondenser fig:v5ch2-reco

redundancy. This will ensure high availability of the recondensing system, minimize the need to vent high-purity argon and allow down-time for maintenance of the recondensers and the refrigeration plants.

2.9.5 Argon Purification

Since the tank is designed without penetrations below the liquid level, pumps must be used to transfer LAr from the cryostat. Vertical submersible pumps (see Figure 2.18) will be inserted into pump wells extending down from the cryostat roof. The pump suction must be located a minimum distance (normally ∼1.5 to 2 m) below the lowest liquid level at which they are to pump in order to prevent cavitation and vapour-entrapment. The pumps and pump wells will extend to the bottom of the cryostat. They could also be staggered at different elevations to allow flexibility in drawing liquid from different elevations. Vertical, submersible, cryogenic pumps are supplied by manufacturers such as Ebara and Carter Cryogenic Products.

The required flow rate of liquid argon to be sent for purification is expected to decrease over time. The initial maximum flow rate will be 51 m^3/hr (224 gpm). The liquid-argon volume in one cryostat will turn over every five days at this rate. Longer term, the rate will decrease to 25 m^3/hr with a turn-over rate of 11 days. As a point of comparison, ICARUS T600 has a maximum turn-over rate of eight to ten days. See the table in Figure 2.19 for a comparison of purification rates among other experiments and LBNE. To achieve the turn-down required between the short- and long-term flow rates, two removable 25 m^3/hr (112 gpm) pumps will be located at the end of the cryostat. Placing the pumps at this end of the cryostat will keep space clear for TPC installation. The purification skids are located at the 15 m wide septum which separates the two cryostats. The multiple-pump arrangement will provide a very high level of redundancy, which will extend the maintenance-free operating period of the cryostat.

The purification system consists of two filter vessels containing molecular-sieve and copper media filters. The filter is 2.4 m in diameter by 3.8 m tall. The filters are sized to provide effective media usage at low pressure drop (2 kPa or 0.3 psi) over the expected range of flow rates. One filter is for gas filtration during filling; the other is for liquid filtration. After filling is complete, the gas filter will be repurposed for liquid filtration.

The purifiers will be located close to the cryostat to minimize both the volume of LAr in the circulation pipework and the pump power required to achieve the desired flow rate. The cryostat liquid argon inventory is circulated through a purification filter to achieve and maintain the required purity. The purification filter, containing

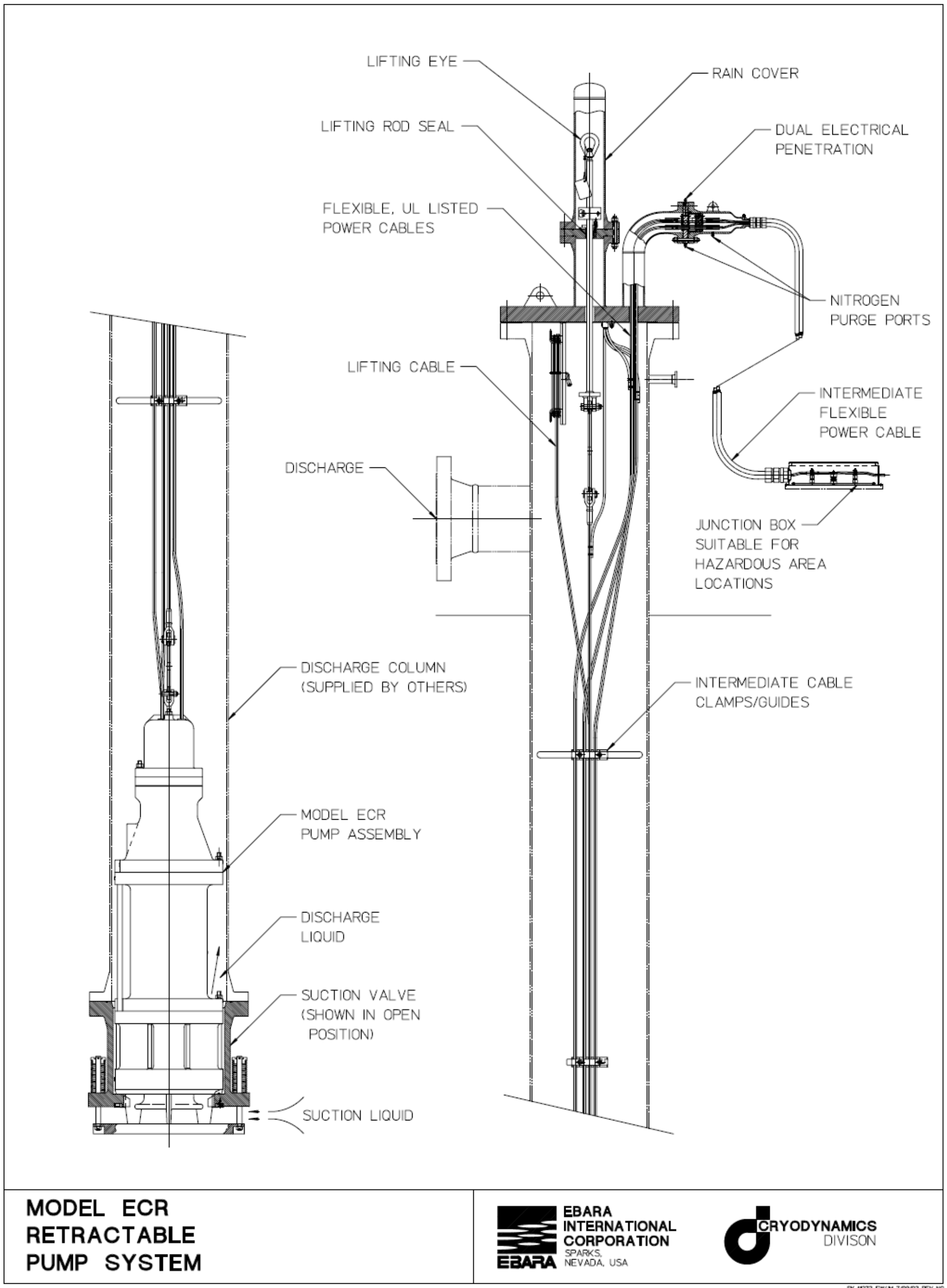

Figure 2.18: Vertical submersible pump

molecular sieve media to remove water and copper media to remove oxygen, will become saturated. The nearly saturated purification filter is regenerated to vent the contaminants. The liquid argon flow is switched to another purification filter for uninterrupted filtration.

A purity monitor after the purification filter will monitor the filter effectiveness. (Purity monitors measuring electron lifetime will also be in the LAr bath and resident in the cryostat. It is a requirement that purity levels reach < 200 ppt oxygen equivalent to match the required electron lifetime of the detector).

The regeneration of a filter is done in several steps. A saturated purification filter is first warmed with heated argon gas to an elevated temperature driving the captured water into the gas. Hydrogen gas is generated and mixed with the circulating argon gas up to 1.5% hydrogen by volume. The hydrogen reacts with the oxygen and makes water that is also released into the circulating argon gas. Argon gas is vented to purge water from the hot circulating gas.

The hot filter full of regenerated media is cooled by circulating chilled argon gas. The circulating argon gas is chilled first with a heat exchanger using a commercial R-404A refrigeration unit until the filter is cold. The commercial refrigeration unit accumulates the R-404A liquid and shuts down. The filter is next cooled down to cryogenic temperatures by circulating argon gas chilled by a second heat exchanger with a liquid nitrogen coolant. This completes the regeneration steps for a purification filter. The filter is now ready to be switched into service or held cold until needed. Two spare purification filters are used with separate heating and cooling loops to reduce the usage rate of electricity and liquid nitrogen. This also reduces the stresses on heat exchangers by decreasing their temperature swings.

2.9.6 Pressure Control

:press-control

Normal Operations

The pressure-control valves are sized and set to control the internal cryostat pressure under normal operating conditions to the nominal design pressure of 0.113 MPa. Fluctuations within the range 0.105 MPa (50 mbarg) to 0.120 MPa (200 mbarg) will be allowed. Ten percent excursions above or below these levels will set off alarms to alert the operator to intervene. Further excursion may result in automatic (executive) actions. These actions may include stopping the LAr circulation pumps (to reduce the heat ingress to the cryostat), increasing the argon flow rate through the recondenser, increasing the LN_2 flow through the recondenser vessel, powering down heat sources within the cryostat (e.g., detector electronics). Eventually, if the pressure continues to rise, it will trigger the pressure-relief valves to operate.

Experiment	LAr Volume (m^3)	Max Liquid Purification Rate (kg/hr)	Boil off Gas Purification Rate (kg/hr)	LAr Volume Change rate (days)	Electron Lifetime (milli-sec.)
ICARUS T600 detector	550	2766	168	10.8	5
ICARUS prototype	10	692	0.69	0.8	1.1
Material Test Stand at FNAL	0.25	167	5.56	0.1	> 5
ArgoNeut	0.55	0	4.3	7.3	0.75
Microboone	123	6875	83	0.9	TBD
LAr Purity Demonstrator (LAPD)	22.2	3791	46.7	0.3	> 5
LBNE 35 ton membrane prototype	27.7	1900	27	0.7	>2.5
LBNE LAr-FD, one cryostat	6700	71040	1031	5.4	1.4 req'd

Figure 2.19: Purification comparision data for LArTPCs

fig:table:puri

Table 2.5: Important Pressure Values

table:pressure

Vessel ullage maximum operating pressure	0.121 MPa, 200 mbarg, 2.9 psig
Relief valve set pressure	0.125 MPa, 250 mbarg, 3.5 psig
Roof truss design working pressure	0.135 MPa, 350 mbarg, 5.1 psig

table:pressure-values

Table 2.5 gives important pressure values.

The ability of the control system to maintain a set pressure is dependent on the size of pressure upsets (due to changes in flow, heat load, temperature, atmospheric pressure, etc.) and the volume of gas in the system. The reference design has 0.8 meters of gas at the top of the cryostat. This is 5% of the total argon volume and is the typical vapor fraction used for cryogenic storage vessels. Reaction time to changes in the heat load is slow, on the order of an hour. At the expected heat-load rate of 52.6 kW, and for an isolated or un-cooled cryostat, the rate of pressure rise would be 168 mbar (2.43 psi) per hour. We plan to provide two redundant pressure control valves to maintain the required pressure range, each sized to handle at least 7700 kg/hr of argon flow to the recondenser to handle the cooling and reliquefaction of warm GAr during cryostat filling.

Overpressure Control

In addition to the normal-operation pressure-control system, it is planned to provide a cryostat overpressure-protection system. This will need to be a high-integrity, automatic, failsafe system capable of preventing catastrophic structural failure of the cryostat in the case of excessive internal pressure.

The key active components of the planned system are pressure-relief valves (PRVs) located on the roof of the cryostat that will monitor the differential pressure between the inside and the outside of the cryostat and open rapidly when the differential pressure exceeds a preset value. A pressure-sensing line is used to trigger a pilot valve which in turn opens the PRV. A pressurized reservoir of power fluid is provided to each valve to ensure that the valves will operate under all upset and/or shutdown scenarios. The PRVs are self-contained devices provided specially for tank protection; they are not normally part of the control system.

The installation of the PRVs will ensure that each valve can periodically be isolated and tested for correct operation. The valves must be removable from service for maintenance or replacement without impacting the overall containment envelope of the cryostat or the integrity of the over-pressure protection system. This normally requires the inclusion of isolation valves upstream and downstream of the pressure-relief valves and at least one spare installed relief valve ($n + 1$ provision).

When the valves open, argon is released, the pressure within the cryostat falls and argon gas discharges into the argon vent riser. The valves are designed to close when the pressure returns below the preset level.

Vacuum-Relief System

The cryostat vacuum-relief system is a high-integrity, automatic, failsafe system designed to prevent catastrophic structural failure of the cryostat due to low internal pressure. The vacuum-relief system protects the primary membrane tank. Activation of this system is a non-routine operation and is not anticipated to occur during the life of the cryostat.

Potential causes of reduced pressure in the cryostat include operation of discharge pumps while the liquid-return inlet valves are shut, gaseous argon condensing in the recondenser (a thermo-siphon effect) or a failure of the vent system when draining the cryostat. Vacuum-relief valves are provided on LNG/LPG storage tanks to protect the structure from these types of events.

The key active components of this additional protection system are vacuum-relief valves located on the roof of the cryostat that will monitor the differential pressure between the inside and the outside of the cryostat and open when the differential pressure exceeds a preset value, allowing cavern air to enter the cryostat to restore a safe pressure.

2.9.7 LN_2 Refrigeration System

Four commercial LN_2-refrigeration plants will be procured for LAr-FD. After achieving the required purity and completing initial fill, each cryostat will have a dedicated LN_2 plant for steady-state operations. The third and fourth plants will be used when the 30-kton detector is online. The plants will be located in the cavern in the 4850L configuration. Each will be a closed-loop system supplying LN_2 to the argon recondenser. The nominal rating of the quoted refrigerators is in the range of 85 kW.

Two-phase nitrogen is delivered from the cold end of the refrigerator into a farm of LN_2 storage vessels with a total capacity of 50 m^3. Pure liquid is withdrawn from the LN_2 storage vessels and is supplied via transfer line to a pressure-reducing valve and phase-separator tank also located within the cavern. LN_2 is then withdrawn from the bottom of the phase-separator tank, at a pressure of 2.0 bar and temperature of 84K, and directed to the recondenser. This results in a 5K temperature difference relative to the 89K argon recondenser temperature. The eight 12.5 m^3 LN_2 vessels will allow for greater than forty hours of refrigeration time. This time window is adequate to cover most power outages, refrigerator performance problems and refrigerator switch-overs.

The refrigeration system operation, illustrated in Figure 2.20, is based on a screw compressor package and three turbo expanders. This system is expected to be capable of running continuously for at least a year, and then require only minor servicing. The system will be equipped with automatic controls and a remote monitoring so that no operator will be required during normal operation. Estimated maximum power requirement is 850 hp (650 kVA) , not taking into account the power generated by the expanders. The LAr-FD reference design places the nitrogen compressor in a surface-level equipment building. A closed-loop water system with evaporative-cooling tower removes heat from the compressor. Compression is carried out at close-to-ambient temperature. A compressor aftercooler is provided to reject heat.

The fluid is next routed to a 'cold box' consisting of four heat exchangers. This series of exchangers provides staged heat transfer from a cooling nitrogen stream to a warming one. The expanders are connected between the heat exchangers to progressively reduce the pressure of the cooling nitrogen stream to isentropically reduce the pressure and temperature of the nitrogen stream, eventually leading to a large liquid-nitrogen fraction at the coldest end of the cold box.

The main cold box shell is 1.22 m (4 ft) in diameter and 8.2 m (27 ft) tall,

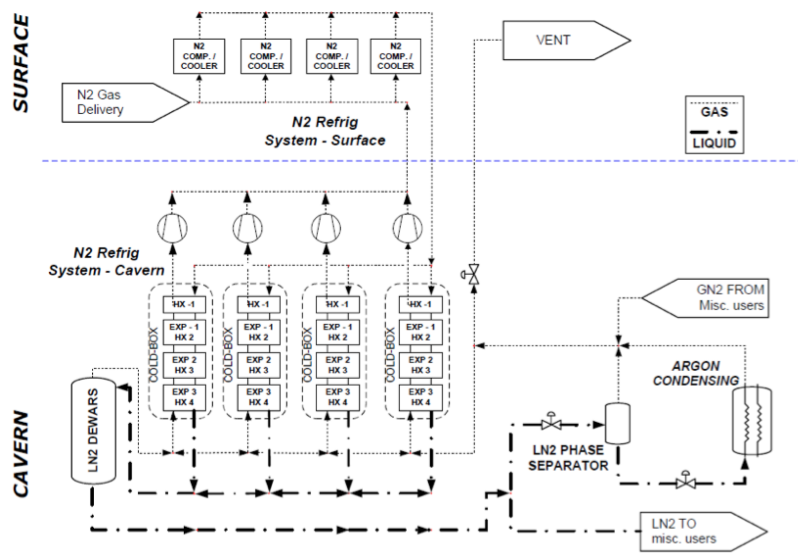

Figure 2.20: Nitrogen refrigeration-plant flow diagram

as illustrated in Figure 2.21. The expanders are adjacent to the cold box at three elevations and extend about 1 m to the side of the cold-box shell. The cold box will weigh 5670 kg. The compressors are located at the surface inside an equipment shed. The compressor skid (frame) is 4.3 m long, 1.8 m wide and 2.7 m tall and will weigh approximately 3630 kg.

2.9.8 Refrigeration Load Scenarios

> Editor's Note: The load scenario information contained in this section is relevant for a 34-kton fiducial mass detector made up of two 17-kton modules. As of late 2014, the refrigerator will need to serve the first 10-kton detector cavern and the 30-kt detector cavern.

In order to determine the optimal plant capacity and number of plants required, we forecast the LN_2 refrigeration loads and plant capacity needed over seven scenarios. Those scenarios are described below and a summary table is shown in Figure 2.22.

The conclusion points to the requirement of four 85-kW plants. Each of these plants can achieve a 20% turn up or turn down. Scenario 1 and 4 impose the most severe requirements. In this scenario, all four plants will be required to operate

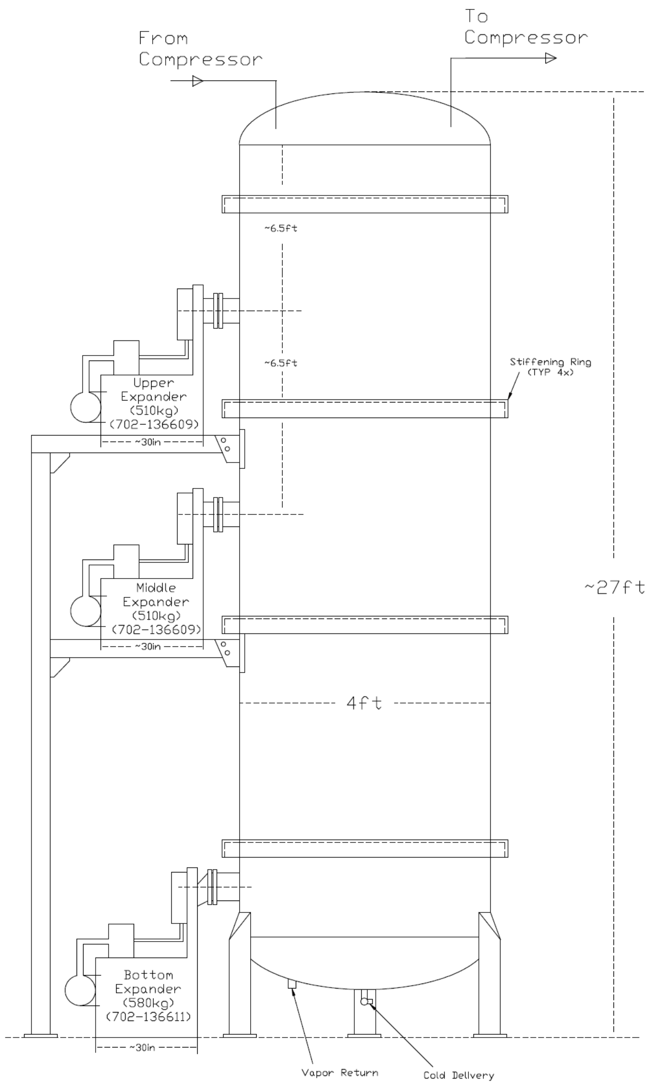

Figure 2.21: Nitrogen refrigeration plant

fig:nitrogrenat a duty cycle of approximately 85%. This scenario includes one completely filled and purified cryostat while the second is being purified and requiring frequent filter regeneration.

Scenario 1 The initial operation will be the purging, cooling and filling of the first cryostat, condensing gaseous argon in the cavern by heat exchange via the recondensers. The surface and cavern LAr and LN_2 dewars will be operational and the cooling load for the dewars will come directly from the refrigeration plant. The cavern pipework and vessels will be cold, the LAr in the cryostat will be circulating at high flow rate through the purification plant, and the cryostat will be cold. The cryostat cool-down rate is constrained by three variables: 1) The size of the piping from the surface to bottom of Ross Shaft, 2) The size of the LN_2 refrigeration units, and 3) the cooling power available via the recondensers. All three variables have been matched for the physical constraints of a 34 kton module at 4850 using the Ross shaft. The refrigerators and condensers have been sized to accommodate the long-term refrigeration load associated with the cryostats. As the LAr is circulated to achieve the operational purity the filtration plant will need to be regularly regenerated. This will mean that the associated refrigeration load will normally be present.

Scenario 2 Once the first cryostat is filled with LAr the cool-down load will reduce to zero and the cryogenic plant will run for several months purifying the LAr inventory.

Scenario 3 When the LAr in the cryostat reaches the required purity level, the circulation flow rate will be reduced and the detector electronics will be turned on. At this stage the recondenser refrigeration load falls such that only one recondenser is required and the second and third units can operate as spare units.

Scenario 4 The first cryostat continues to operate in normal experimental mode while the second cryostat is being purged, cooled down and filled with LAr. Again a very large burden is placed on the recondensers due to the gas condensation and rate of liquification.

Scenario 5 The second cryostat is full and LAr is circulated at high flowrate through the purification plant. The first cryostat continues to operate as normally.

Scenario 6 Both cryostats are operating in normal experimental mode. A spare recondenser is available on each cryostat to facilitate maintenance.

Scenario 7 It is assumed that a total failure of the refrigeration plant has occurred. All noncritical heat sources are isolated and liquid nitrogen from the cavern LN_2 vessels is utilized to recondense the inventory of high purity LAr. Nitrogen refrigeration must be reestablished before the liquid nitrogen reservoir is exhausted or the high purity argon will need to be vented. In the locked-down state the circulation pumps and the purification plants are shut down.

2.10 Prototyping Plans

> Editor's Note: LAPD has successfully achieved greater than 5 millisecond electron lifetime, and the LBNE 35t has also achieved greater than 2.5 milli-second electron lifetime.

The development of the LAr-FD from conceptual to preliminary design will include a prototyping program. The most significant issue to resolve is whether a membrane cryostat the size of LAr-FD can achieve the required electron-drift lifetime. The Liquid Argon Purity Demonstrator (LAPD), already in progress and introduced in Section **??**, is an off-project prototype being built as part of a development program at Fermilab to study the scaling of LArTPCs to kiloton sizes. In addition, a 35-ton membrane-cryostat prototype is being developed as an LBNE effort to confirm, among other things, that at larger scales the required LAr purity can still be achieved. It is scheduled for initial operation in late summer 2013. The prototype will be used to repeat the purge process accomplished in the LAPD to confirm that initial evacuation of the cryostat is unnecessary. This work will also seek to confirm that an LAr purity level sufficient to enable the required drift times in a membrane cryostat can be achieved.

2.11 ES&H

During all phases of LAr-FD and the proposed protoypes, Fermilab ES&H standards and Sanford Laboratory ES&H codes and standards will guide the design, procurement and installation phases of the project. Particular attention will be paid to critical sections of Chapter 5000 [**?**] relating to ODH, standards for piping construction and vessel design. The planned work process will provide for reviews throughout all phases of the project to guarantee stringent adherence to the safety

Heat Demand	Unit Loads (kW)	1	2	3	4	5	6	7
Recondenser Load, Cryostat #1								
Cryostat #1 - Heat Ingress	35.2	35.2	35.2	35.2	35.2	35.2	35.2	35.2
Recirculation Pump in cryostat with 1 pump	8.6	8.6		8.6	8.6	8.6	8.6	
Recirculation Pump in cryostat with 4 pumps	34.4		34.4					
Piping and Purification vessel Heat Ingress	3	3.0	3.0	3.0	3.0	3.0	3.0	
Detector Electronics	5.2			5.2	5.2	5.2	5.2	
Cryostat Cooldown & GAr Transfer-Fill	283.2	283.2						
Condensers in Operation		3	1	1	1	1	1	1
Condenser Load		**330.0**	**72.6**	**52.0**	**52.0**	**52.0**	**52.0**	**35.2**
Recondenser Load, Cryostat #2								
Cryostat #2 - Heat Ingress	35.2				35.2	35.2	35.2	35.2
Recirculation Pump in cryostat with 1 pump	8.6				8.6		8.6	
Recirculation Pump in cryostat with 4 pumps	34.4					34.4		
Piping and Purification vessel Heat Ingress	3				3.0	3.0	3.0	
Detector Electronics	5.2						5.2	
Cryostat Cooldown & GAr Transfer-Fill	231.2				231.2			
Condensers in Operation					3	3	1	1
Condenser Load					**278.0**	**72.6**	**52.0**	**35.2**
LN Storage dewar recondenser	2	2	2	2	2	2	2	
Refrigeration Needed		330.0	72.6	52.0	330.0	124.6	104.0	
Refrigeration Plants in Operation		**4**	**2**	**1**	**4**	**2**	**2**	**0**
Actual Duty per plant		83	50	52	83	62	52	
electric trim heater load		0.0	27.4	0.0	0.0	0.0	0.0	
Total Refrigeration Load		**330.0**	**100.0**	**52.0**	**330.0**	**124.6**	**104.0**	**0**

Figure 2.22: Refrigeration loads

fig:Refrigerat

requirements. Requirements on the membrane-cryostat materials and their fabrication will be strictly outlined in the specification documents. Close communication between the vendors, Fermilab's cryogenic and process engineers, and Fermilab and Sanford Laboratory ES&H personnel will be maintained at all times.