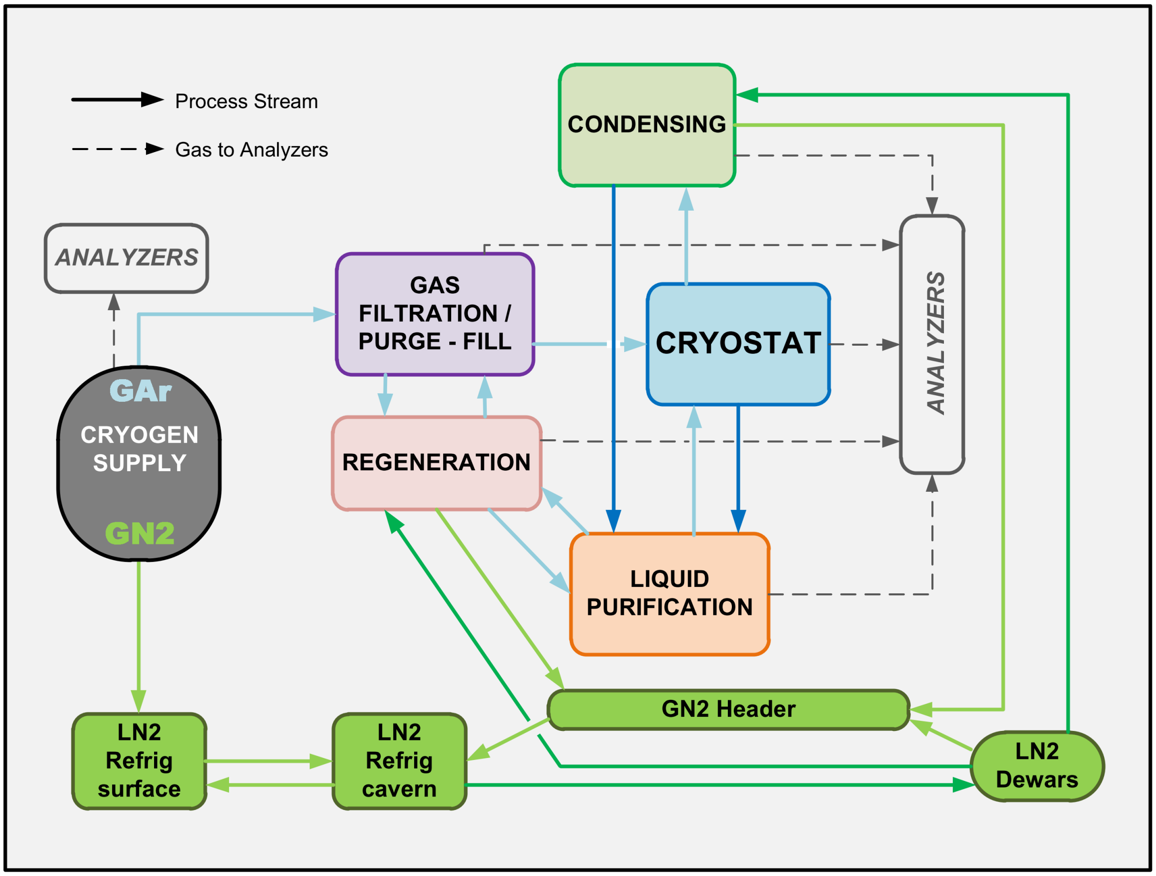
The LBNF Cryogenics Infrastructure at the Far Site

Oct 2015 Update to CDR Annex 3D



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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 LBNF Cryogenics Infrastructure

The scope of the LBNF Cryogenics Infrastructure includes the design, procurement, fabrication, testing, delivery and installation oversight of the following components:

- Four identical cryostats to contain the liquid argon (LAr) and the single-phase (or dual-phase) time projection chambers (TPCs)
- A comprehensive cryogenic system that meets the performance requirements for
  - purging, cooling down and filling the cryostats
  - acquiring and maintaining the LAr temperature within ±1 K range around nominal temperature (88.3 K)
  - purifying the LAr via constant filtration using recirculation pumps outside the cryostats

The reference design for the LBNF cryogenics infrastructure encompasses the following components:

- Four identical 10-metric-kiloton (fiducial mass) membrane cryostats
- Receiving facilities for LAr and LN_2 tanker trucks
- Transfer system to deliver argon gas for liquefaction and nitrogen gas for refrigeration system from the surface to the underground cavern area
- A closed loop LN_2 refrigeration system for condensing GAr
- Boil-off gas reliquefaction equipment

- LAr-purification facilities
- Cryostat-purge facilities

The conceptual reference design for the DUNE far detector (FD) specifies four rectangular cold vessels each measuring 15.1 m internal width, 14.0 m internal height and 62.0 m internal length - each vessel contains a total mass of approximately 17 kt of LAr and between 3 and 5% of Ar gas operating at a pressure of 75 mbarg, depending on the final TPC design. The membrane design is commonly used for liquefied natural gas (LNG) storage and transport tanker ships (Figure 1.1) and has been proven to be a viable option for LArTPC experiments. A membrane tank is made of 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 structural support which provides external support for the liner. The membrane liner is corrugated to provide strain relief resulting from temperature-related expansion and contraction (Figure 1.2).

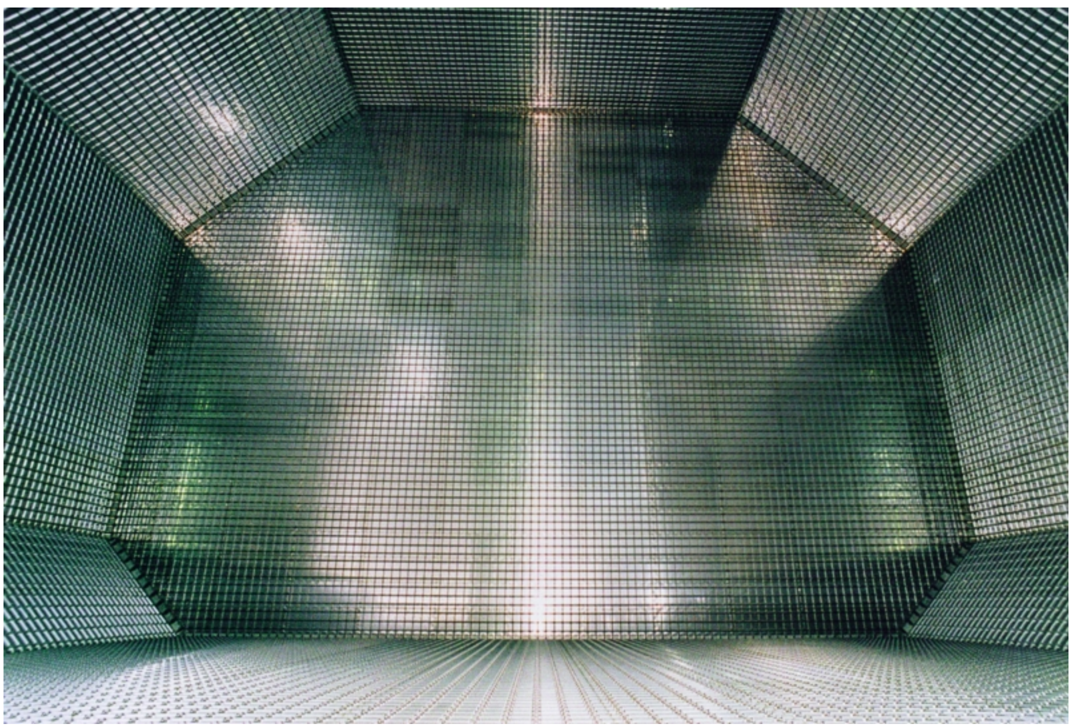

Figure 1.1: Interior of a LNG tanker ship. The tank shown is 24 m high by 35 m wide with interior grid-like corrugations on a 0.34 m pitch. By comparison, a single LBNF cryostat is 14.0 m high by 15.1 m wide.

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

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

Two membrane cryostat vendors have been identified. Those vendors are GTT (Gaztransport & Technigaz) and IHI (Ishikawajima-Harima Heavy Industries). Each is technically capable of

Figure 1.2: Primary membrane section (courtesy GTT)

delivering a membrane cryostat that meets the design requirements for the LBNF. To provide clarity, only one vendor is represented here (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.

1.2 Design Parameters

The requirements and parameters for the cryostat and cryogenics system design are within the LBNF requirement documentation [1] [2] and the parameter tables [3] and [4], 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 1.1 and 1.2 offer a brief overview of parameters for a single cryostat of LBNF.

Table 1.1: Design parameters for one LBNF Cryostat

Parameter	Value
Cryostat Internal Volume	13,107 m^3
Total LAr Mass	17.2 kt
Cryostat Inside Depth	14.0 m
Cryostat Inside Width	15.1 m
Cryostat Inside Length	62.0 m
Cryostat Outside Height	18.116 m
Cryostat Outside Width	19.216 m
Cryostat Outside Length	66.116 m
Insulation	Reinforced Polyurethane of 90 cm thickness; two (inner/outer) layers around secondary containment (30/60 cm per each layer)
Primary Membrane (GTT Design)	1.2 mm thick type 304L stainless steel with corrugations on 340 mm $\times$ 503 mm rectangular pitch
Secondary Containment (GTT Design)	$\approx$ 0.07 mm thick aluminum between fiberglass cloth; overall thickness is 0.8 mm located between insulation layers
External Vapor Barrier Thickness (Steel Plates)	10 mm
External Support Structure Thickness On Sides	1.148 m (Steel)
External Support Structure Thickness Top and Bottom	1.148 m (Steel)
LAr Temperature	88.3 $\pm$ 1 K
Minimum LAr Depth (Liquid Head)	13.2 m
Ullage Operating Pressure	130 mbarg (range: 50−200 mbarg)
Pressure at Bottom	1,948 mbarg
Cryostat Design Pressure	350 mbarg

Table 1.2: Summary of parameters for membrane cryostat at the 4850L (the bottom of the Ross shaft)

Property	Reference-Design Cryostat
Personnel Access to Cavern	Ross shaft
Equipment Transport to Cavern	Ross shaft (main transport), Yates shaft
Construction Access to Pit	From above highbay
Type of Crane in Cavern	Mobile construction
Base	Steel structure
Side Walls	Steel structure
Steel Beam Temperature Control	Active ventilation
Roof	Steel structure
Vapor Barrier	Steel plates
Insulation/Secondary Barrier/Membrane	GST system by GTT
TPC	Individual 2.3 m $\times$ 6.0 m frames lowered through a dedicated roof opening. Assembled within cryostat and suspended by hangers passing through the roof.
LAr Containment System	Stainless Steel Primary Membrane; Secondary Barrier

Chapter 2

Cryostat Configuration

2.1 Sides and Bottom of Cryostat

The membrane cryostat is a sealed container that relies on external support from the surrounding steel frame (outer warm vessel) to resist the hydrostatic load of the contents. From innermost to outermost layers, the side walls of the membrane cryostat consist of

- the stainless-steel primary membrane
- insulation (inner layer)
- a secondary barrier (thin aluminum membrane that contains the LAr in case of a leak in the primary membrane)
- more insulation (outer layer)
- a barrier to prevent water-vapor ingress to the cryostat insulation space
- the steel frame (outer warm vessel)

The basic components of the membrane cryostat are illustrated in Figure 2.1. The cryostat is positioned inside the rock pit with a forced air circulation mechanism to maintain rock temperatures above freezing and to prevent condensation on cryostat walls.

2.2 Steel Frame and Vapor Barrier

A vapor barrier is required on all internal surfaces of the steel frame (base, side walls, and end walls) and the roof to prevent the ingress of any water vapor into the insulation space. If water

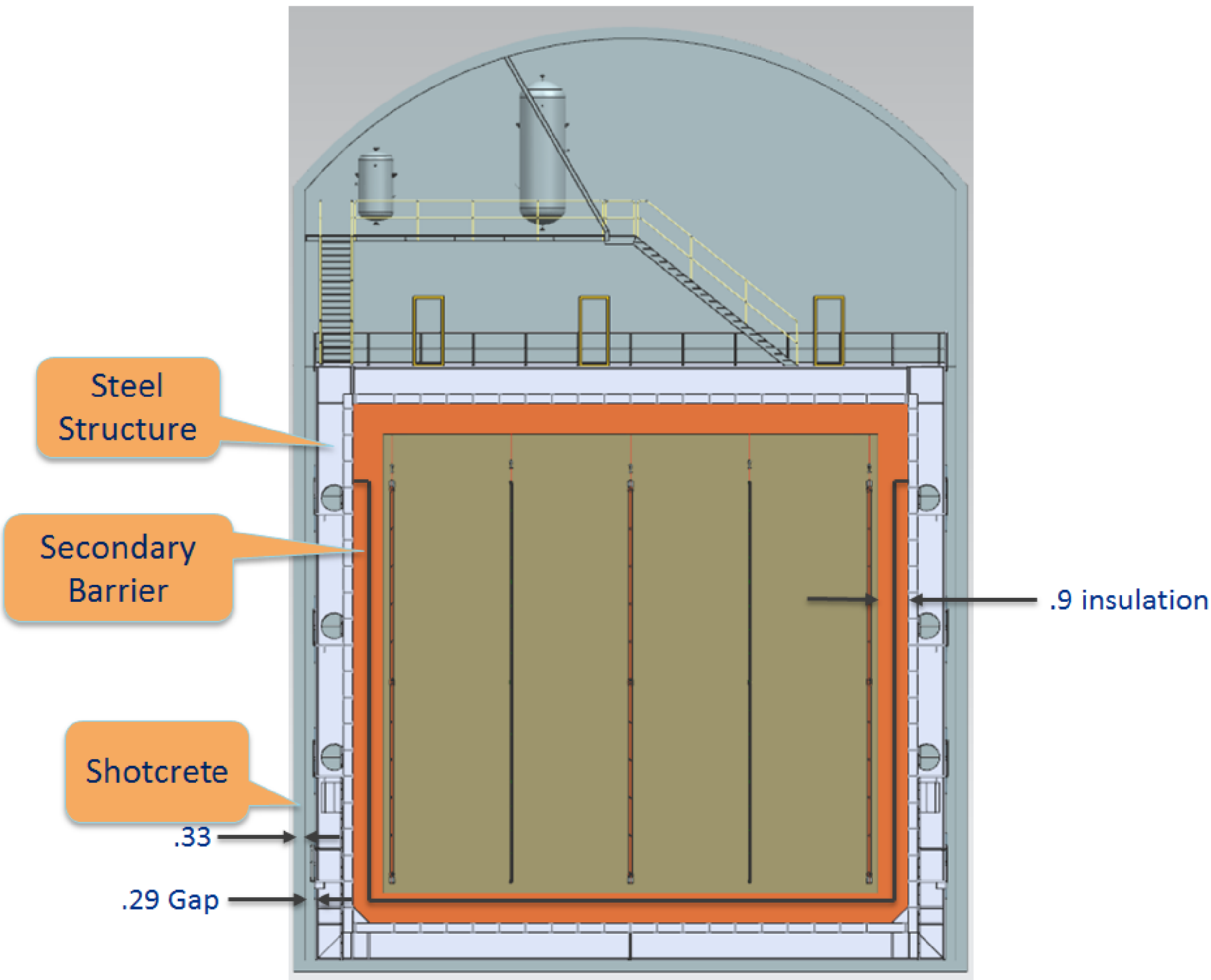

Figure 2.1: Composite system as installed for the LBNF reference design

vapor were permitted to migrate into the insulation 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 stainless steel plate of 10 mm applied to the side, top and bottom surfaces.

Each of the four identical cryostats will consist of two major components: a steel outer frame (warm vessel) and membrane (cold vessel). The membrane cold vessel is based on the technology used for liquefied natural gas (LNG) storage and transport ships. It consists of an inner stainless steel corrugated thin membrane in contact with the liquid and thermal insulation surrounding it. Details of this technology are presented in Chapter 1. The main idea behind this concept is that the cold membrane vessel represents a contained vessel with two independent barriers.

The function of the steel warm vessel is to contain the membrane vessel and provide mechanical support to it, while providing also a gas barrier towards the outside. Figure 2.2 below presents the layout of such an assembly which consists of a modular self-supporting steel structure.

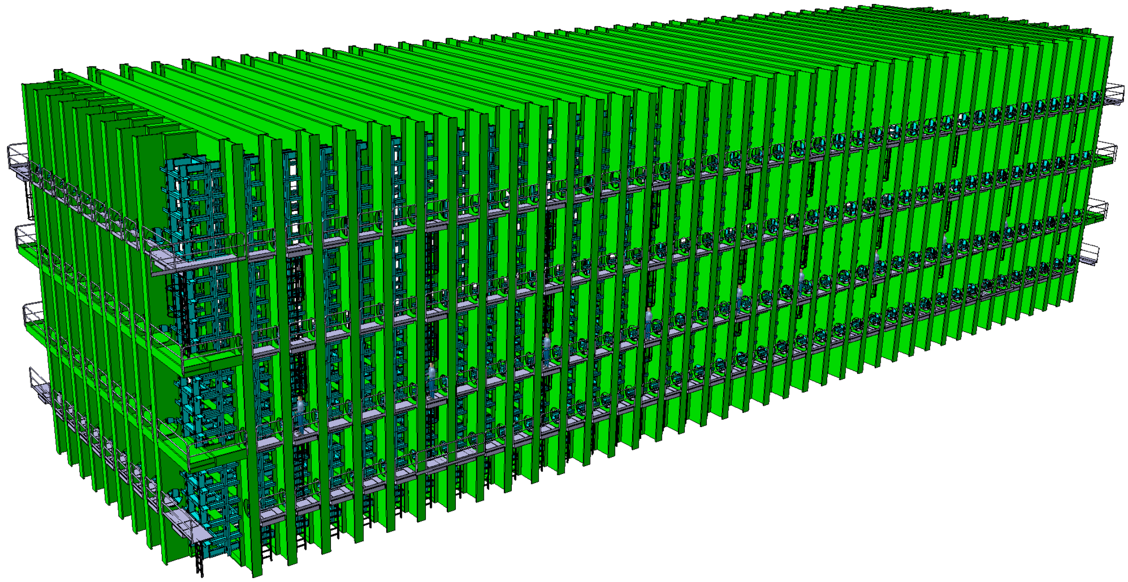

Figure 2.2: Outer layout of steel warm vessel

The structure will be positioned on a firm surface with no additional structural connections necessary for either the cavern floor or the cavern walls. The internal (external) dimensions of the structure are approximately 16.9 (19.2) m in width, 15.8 (18.1) m in height, and 63.8 (66.1) m in length.

The warm vessel consists of outer supporting profiles, interconnected through a steel grid and a 10 mm thick stainless steel (type 304L) continuous plate to the inside in contact with the membrane insulation. The material used is S460ML structural carbon steel, with yield strength of 430 MPa and tensile strength of 510 MPa. The main profile used is HL 1100×548 or its ASTM alternative W 44×16×368. Four profiles are bolted together, by four bolting connections, forming a structural "portal." Each bolting connection consists of 16 bolts (M42). The additional grid is made of the IPE300 profile. The total self-weight of the structure is approximately 2000 t.

The main advantage of this design is the fact that such a structure can be fully decoupled from the civil engineering work related to the excavation and finishing of the four caverns. All components can be procured and prepared on the surface, ready to be lowered through the shaft. Underground installation will take 4 months for each of the cryostats and can be done sequentially. The warm vessel will be fully accessible from outside and can be inspected at any moment. A net of stairs and gangways is included in the design at the allocated space. No requirements are put on the distance of the warm structure to the cavern walls. Typically this value might vary between 200 and 500 mm. The warm cryostat is positioned inside the cavern pit with a forced air circulation mechanism to maintain the rock temperatures above freezing and to prevent condensation on cryostat walls.

Finite Elements Analysis Methods using the commercial ANSYS code have been employed as the main design technique. The safety codes used are the Eurocode III and ASME Boiler and Pressure Vessel code Section VIII, Rules for Construction of Pressure Vessel, Division II. The most conservative requirements among the two codes have been adopted. The structure has been treated as a low pressure vessel (<500 mbarg).

Approximately 18,000 metric tons (t) of LAr is acting as load on the floor, i.e. around 20 t/m^2. Approximately 8,000 t of hydrostatic force is acting on each of the long walls, with triangular distribution over the height, and around 2000 t of hydrostatic force is acting on each of the short walls. Additionally a normal ullage operational pressure of 75 mbarg (0.75 t/m^2) is considered, acting in addition on every wall. The structure has been also verified to accidental overpressure of 350 mbarg (3.5 t/m^2), which is the maximum allowable working pressure of the cryostat. The weight of the detector itself, as well as seismic action, has been taken into account in the calculations.

The following models and analyses methods have been utilized:

- For evaluation of the global behavior of the entire structure, a beam model has been developed.
- Analytical models of a single portal, i.e. 4 main beams connected together (roof, floor and the side walls) have been used.
- To study in more details the main elements of the structure, an additional shell model of single cell, i.e. one portal and 8 additional grid beams, has been also developed.
- In order to evaluate the stability of the structure specific analyses, i.e. linear (eigenvalue) and nonlinear buckling, have been performed on the following parts of the structure:
  - A single portal by utilizing beams elements
  - A single cell (one portal and two additional grid beams, one on the left and the other on the right) on two different FE models:
    - One consisting of beam & shell (using ANSYS Workbench)
    - On another one containing only shell elements (using ANSYS APDL)

- Very detailed models on the connections (bolting and/or welding) on a single portal utilizing solid and contact elements have been further developed and used.

The maximum stress levels at the main profiles, at the location of the maximum moment, are in the range of 125 MPa, which allows a safety factor of 4 with respect to the tensile strength of the chosen material. Additional bracing of the main profiles increases the stability of the structure by factor 2.5, as verified with stability analyses. Additional optimization work aimed at reducing the global external dimensions as well as the self-weight of the structure is ongoing.

2.3 Insulation System and Secondary Membrane

The membrane cryostat requires insulation applied between the primary stainless steel membrane and the moisture barrier and roof in order to minimize the heat ingress and the required refrigeration load. Choosing a reasonable insulation thickness of 90 cm, given an average conductivity coefficient for the insulation material of $C \approx 0.0283$ W/m-K, the heat input is expected to be 28.8 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 (these will be filled with loose fiberglass) and fixed onto anchor bolts embedded into the steel outer structure at about $\sim$3 m 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. All seams are covered so that the secondary membrane is a continuous liner. A corner detail is shown in Figure 2.3.

The secondary membrane is composed 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 steel frame. This secondary membrane is connected to embedded metal plates in the vertical steel 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, the liquid cryogen will be contained in the secondary membrane volume.

2.4 Cryostat 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 2.4). Figure 2.1 illustrates how these layers would be used in the LBNF reference design.

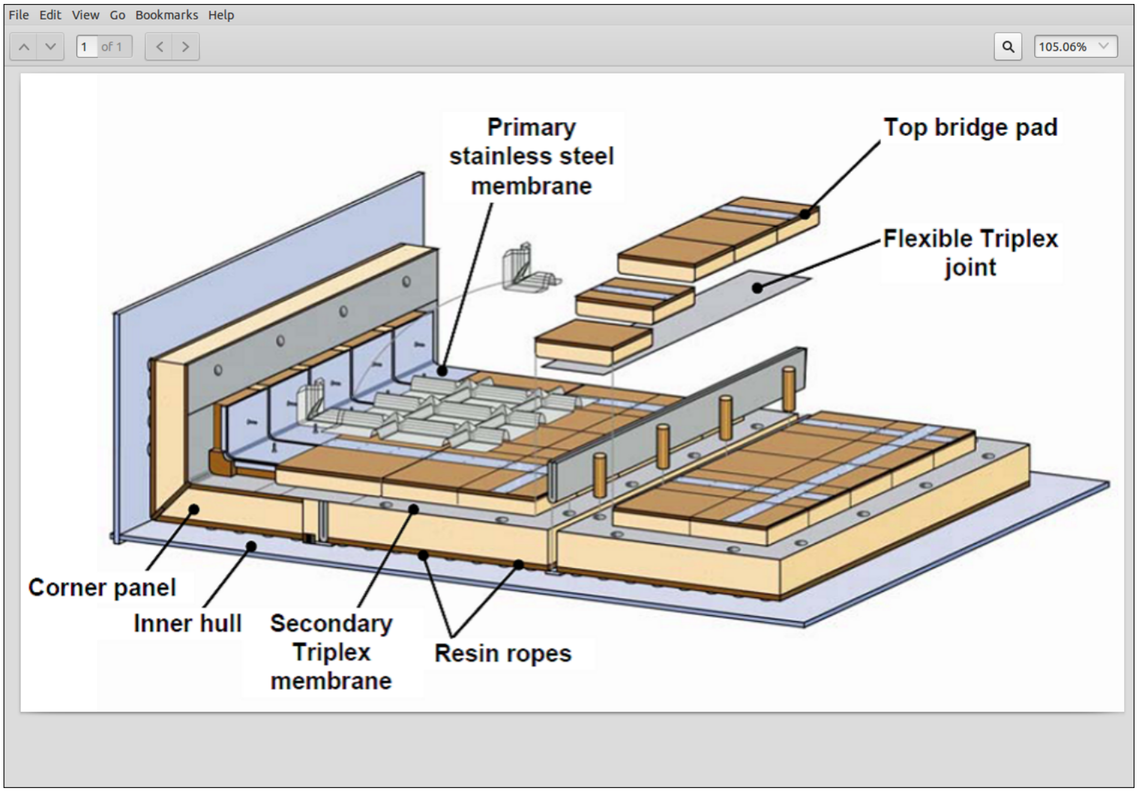

Figure 2.3: Membrane corner detail

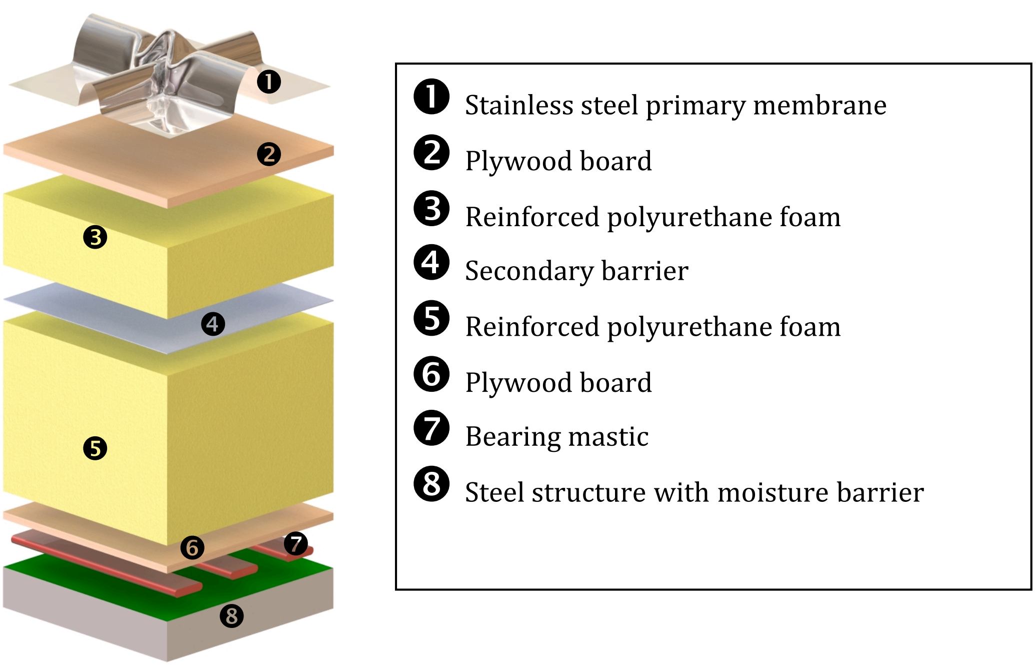

Figure 2.4: GST composite system from GTT

2.5 Top of Cryostat

The stainless-steel primary membrane and the intermediate layers of insulation and water-vapor barrier continue across the top of the cryostat, providing a vapor-tight seal. Note that no secondary membrane is required for the cryostat top.

The hydrostatic load of the LAr in the cryostat is carried by the steel frame on the sides and bottom. Everything else within the cryostat (TPC planes, electronics, sensors, cryogenic and gas connections) is supported by the top of the cryostat. All piping and electrical penetrations into the interior of the cryostat (except for sidewall penetrations from the external liquid argon recirculation pumps) 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 located at regular intervals within the corrugation pattern of the primary membrane to accommodate TPC hangers, electrical and fiber-optic cables, and piping are shown in Figure 2.5.

Some equipment, such as monitoring instrumentation, will be installed within wells extending through the roof structure. All connections into the cryostat (except for sidewall penetrations from the external liquid argon recirculation pumps) will be made via nozzles or penetrations above the maximum liquid level and mostly located on the roof of the cryostat. See figure 2.5 for a typical roof-port penetration.

Figure 2.5: Nozzles in the roof of membrane cryostat (Figure courtesy GTT)

Chapter 3

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 at least 5% ammonia into the bottom insulation space of the cryostat. Wherever the paint turns purple or blue, a leak is present. Any and all leaks will be repaired. The test will last more than 20 hours per cryostat 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.

The insulation space between the primary and secondary barriers will be maintained at 15 mbarg, slightly above atmospheric pressure. This space will be monitored for pressure 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 cryostat.

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 [5].

Chapter 4

Cryogenic System Layout

Cryogenic system components are located in and around the surface building, in the Ross shaft and within the underground caverns and drifts. Figure 4.1 illustrates the cryogenic system layout. On the surface near the Ross shaft there will be a cryogen receiving station. A 50 m^3 (69 tons of LAr capacity) vertical dewar will have two LAr truck connections to allow for receipt of LAr deliveries for the initial filling period. This liquid argon dewar serves as a buffer volume to accept liquid argon at a pace of about 5 LAr 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 and warm up the resulting gas to room temperature prior to the argon gas being transferred by uninsulated piping down the Ross shaft.

Another 50 m^3 vertical dewar and fill connection will be available near the liquid argon dewar. This 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 nearby converts liquid nitrogen to nitrogen gas and warm the gas to room temperature. This gas is used as the feed for the compressors of the nitrogen refrigerator. Four compressors are located in the cryogenics surface building near the Ross shaft and cryogen receiving area. The compressors require a set of nitrogen gas buffers as to regulate the nitrogen compressor low and high pressure loop, a set of oil separators and coalescers to clean the nitrogen gas after the pressurization loop, and a closed-loop water cooling circuit. The closed loop water-cooling circuit has recirculation pumps in the surface building and an evaporative cooling tower located outside near the vaporizers. The compressors are the only refrigeration-cycle components located on the surface. The compressors discharge high pressure (1.14 MPa) nitrogen gas into pipes that run down the Ross shaft. The reason why compressors were chosen to be on the surface is the electrical power and cooling supply are much cheaper to provide at the surface rather than at deep depth in the mine. Each compressor is an 1500 horsepower machine running at 4160 volts. Four running compressors will require a total of 4.5 MW of electrical power at the surface.

The Ross shaft contains the vertical pipelines connecting the surface equipment with the equipment in the cavern area. The vertical piping run is described in Chapter 5. The piping run consists of a GAr transfer line and the GN_2 compressor suction and discharge lines. At the bottom of the Ross

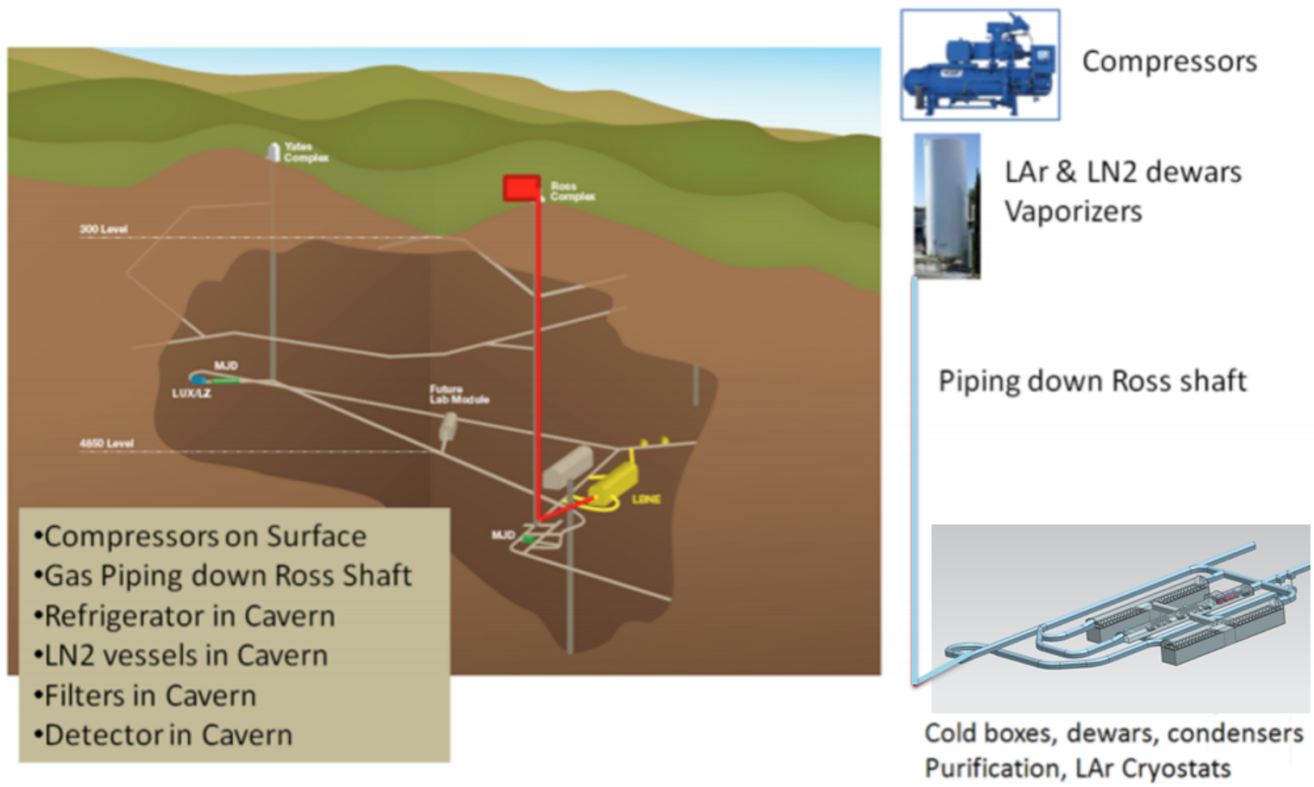

Figure 4.1: Graphical illustrations showing major pieces of equipment and their locations at the surface, piping down the Ross shaft, and in the cavern area

shaft at the 4850 level, the piping exits the shaft and runs along a drift to the cavern area.

The central utility cavern at the 4850 level contains the rest of the nitrogen refrigerator (cold boxes) and filtration equipment. The nitrogen refrigerator equipment is located at the far end of the central utility cavern, away from Ross shaft. The twenty-four liquid nitrogen storage vessels are distributed around drifts where the exits from all caverns intersect. Fresh ventilation air is supplied down the Ross and Yates shafts, enters the detector caverns and flows over the cryostats or the refrigerator equipment in the central utility cavern before being exhausted out via the Oro Hondo exhaust shaft.

There are four argon recondensers per cryostat. They are placed above each cryostat. Four 23 m^3/hr recirculation pumps per cryostat are used to circulate liquid from the bottom of the cryostat through the LAr filters and are set close to each cryostat as well. Each pump will have sidewall penetration to the membrane cryostat.

Chapter 5

Pipework between Surface and Cavern

The effort on pipework between surface and cavern is divided among the cryogenics infrastructure WBS and conventional facility (CF) WBS. The conceptualization of the piping has been done as part of cryogenic infrastructure, while the support system design as well as the construction of these piping system shall be carried out by CF.

The piping between the surface and cavern area is located in a utility chase down the Ross shaft. See Figure 5.1. The piping material is carbon steel coated with a corrosion barrier, a single layer of fusion epoxy. Table 5.1 lists the piping and its duty and size. The frictional pressure drop for the supply pipes matches the pressure gained due to the static head from elevation change. All the piping connections will be made with victaulic fittings. 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 the order of 0.05 MPa, whereas for the liquid transfer it is 20 MPa. If liquid were transferred it would require on the order of seven pressure reducing stations evenly spaced along the vertical drop. Using liquid cryogen delivery was considered in the March 2012 LBNE 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. With gas only transfer to the cavern, straight piping can be run 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 is a driving factor to determine the size of the refrigerator and condenser.

Table 5.1: Piping between surface and cavern area; description, duty, and size and pressure required

Description	Duty	[No. of Pipes] Size	Gas Pressure
Argon transfer	During filling and emptying	[1] 8” SCH. 40	0.24 MPa
N_2 compressor discharge	Continuous	[2] 8” SCH. 40	1.14 MPa
N_2 compressor suction	Continuous	[2] 16” SCH. 40	0.19 MPa (down); 0.11 MPa (up)

The facility is designed that the fresh air is drawn in through Ross and Yates shafts and the exhaust air is drawn out of the mine through the Oro Hondo shaft. The loss of mine ventilation for more than a few hours risks mine safety even without oxygen deficiency hazard (ODH) conditions. The response for unplanned loss of ventilation is to evacuate.

A preliminary ODH assessment for the piping in the Ross shaft has been done. If any of the pipes for the cryogenic system were to rupture in the shaft, they would only be able to reduce the oxygen content to a fraction of 20.5%, thus not being an oxygen deficiency concern. The ODH mapping of underground cavern area is given in Chapter 9.

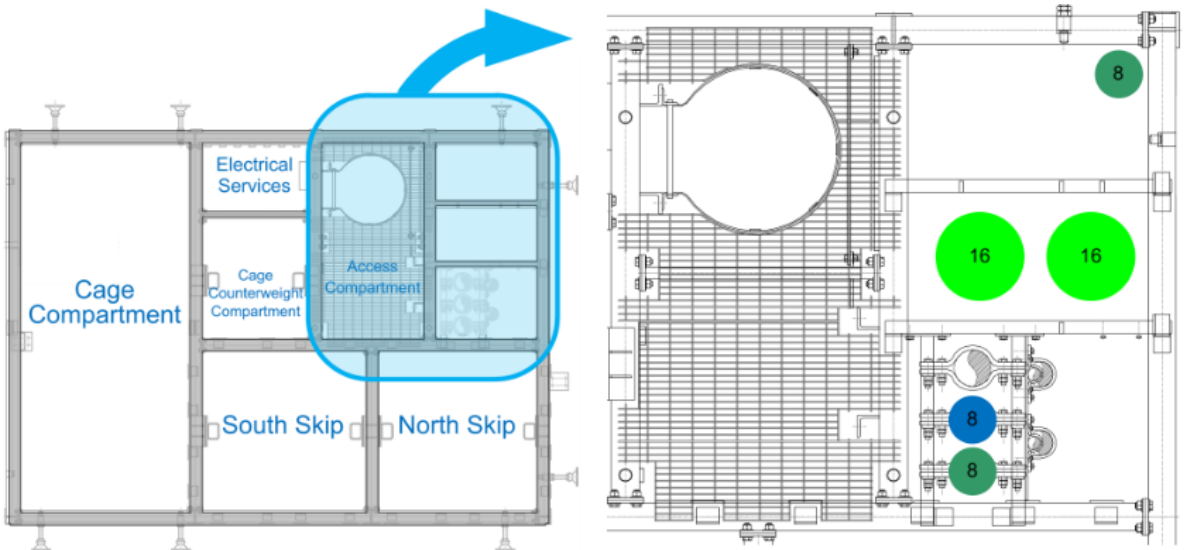

Figure 5.1: The framing of the Ross shaft is shown on the left. The utility area in the upper right corner contains the piping associated with the cryogenic system.

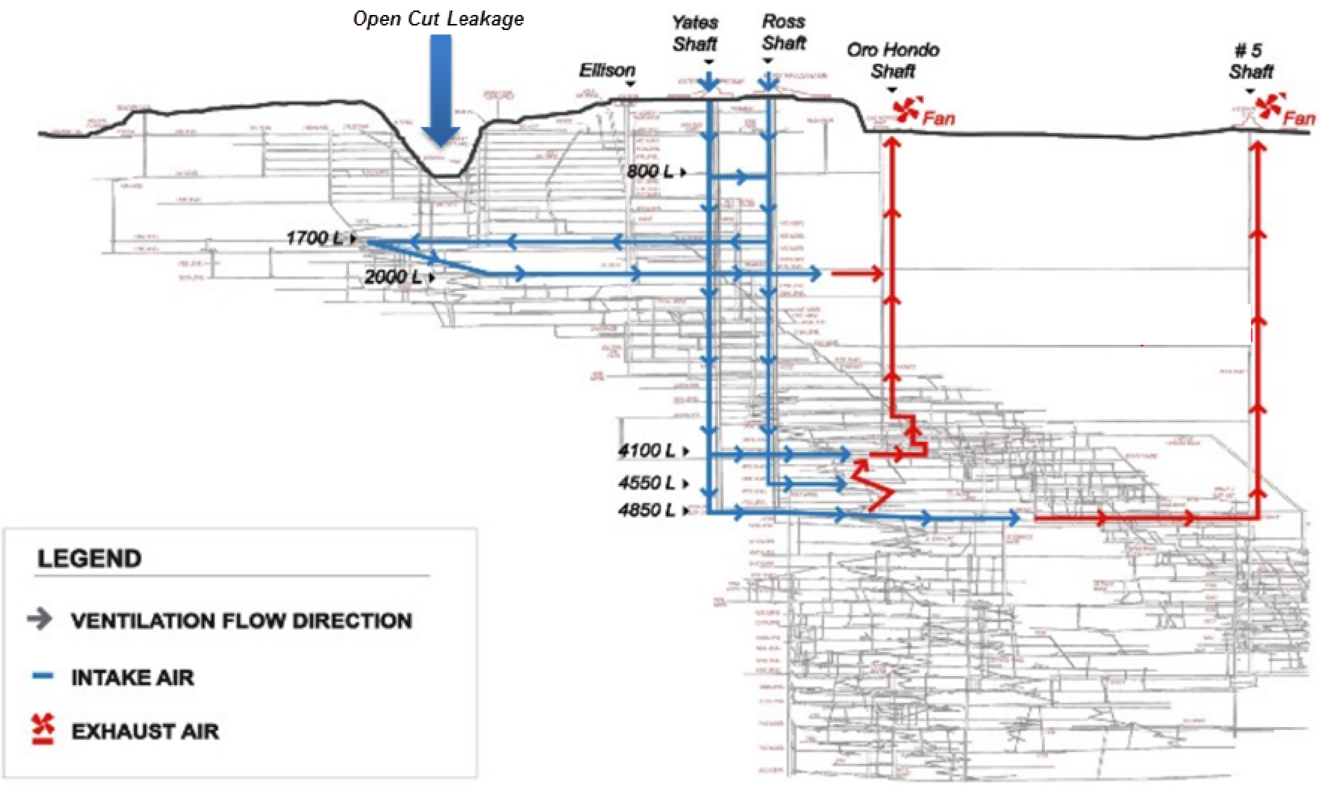

Figure 5.2: Homestake mine ventilation paths

Chapter 6

Equipment in the Cavern Area

There are four independent 85 kW (maximum capacity: 20% up above nominal rating of 71 kW) nitrogen refrigerators in the central utility cavern. The nitrogen refrigerator heat exchangers and expander sets are located at the east end of the central utility cavern. 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 six horizontal 8.3 m^3 (1.2 m diameter × 11 m long) liquid nitrogen vessels per cryostat that are mounted in the drifts. These liquid nitrogen vessels 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 independent 120 kW compressors located in the central utility cavern to 0.19 MPa and returned in the nitrogen suction piping in the Ross shaft.

Four argon condensers (0.8 m diameter × 2.0 m long) are located above each of the cryostats as shown in Figure 6.1. The full power of the argon condensers is used during the initial cooldown and filling phase of the cryostats in order to condense the gas argon transferred down the Ross shaft. The fill process is expected to take between 6 and 17 months. The fill time durations given here assume three refrigeration units available for the first and second cryostat fill and all four units available for the third and fourth cryostats (where steady state operations are maintaining liquid in the full cryostats). Additional information about the filling process is described in Chapter 7.

Purification filters are located in the central utility cavern as shown in Figure 6.2. The filters (1.0 m diameter × 4.3 m high) contain dual media, a molecular sieve for removal of water and a copper coated catalyst media for oxygen removal. There are four gas filters used during the argon filling phase and four liquid filters for each cryostat. Associated with the filters, there will be regeneration equipment such as heaters, gas blowers, and a hydrogen generator also located in the central utility cavern.

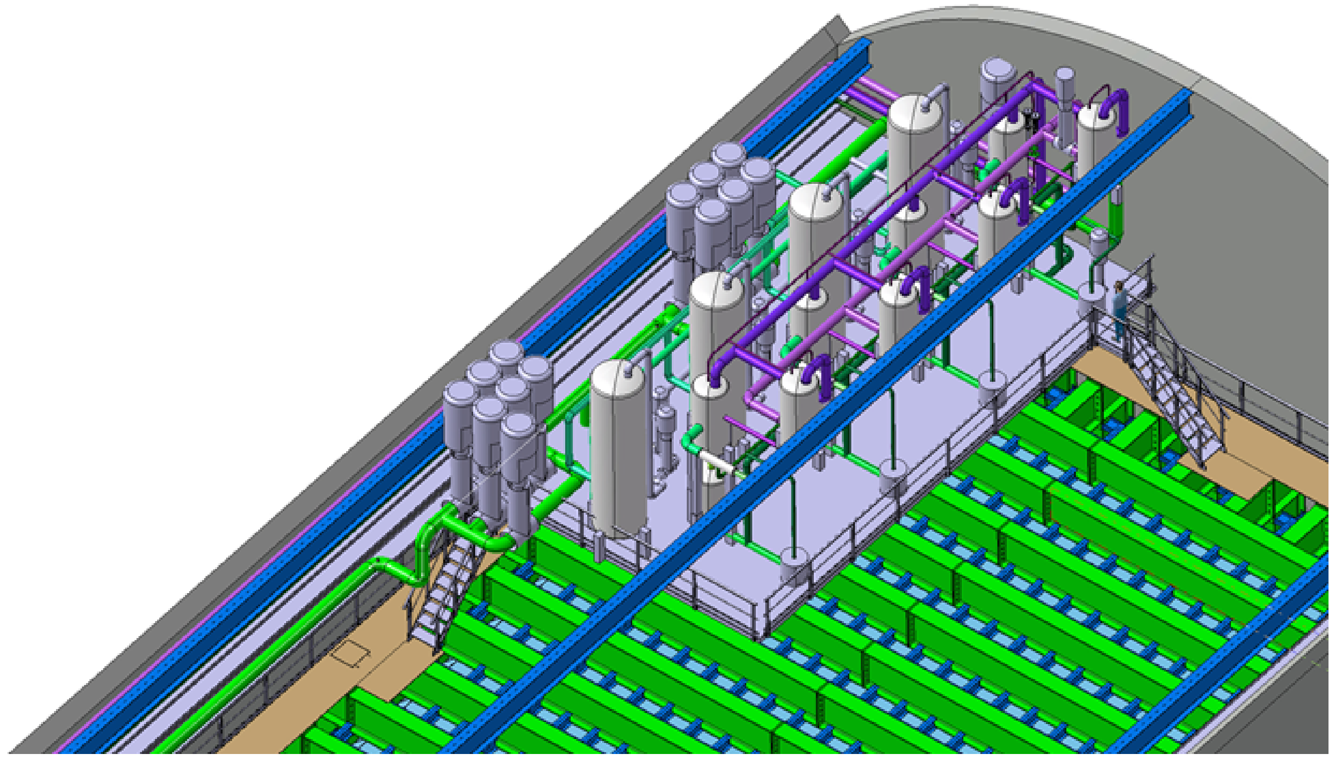

Figure 6.1: Cryogenic equipment on the top of cryostat (not to scale)

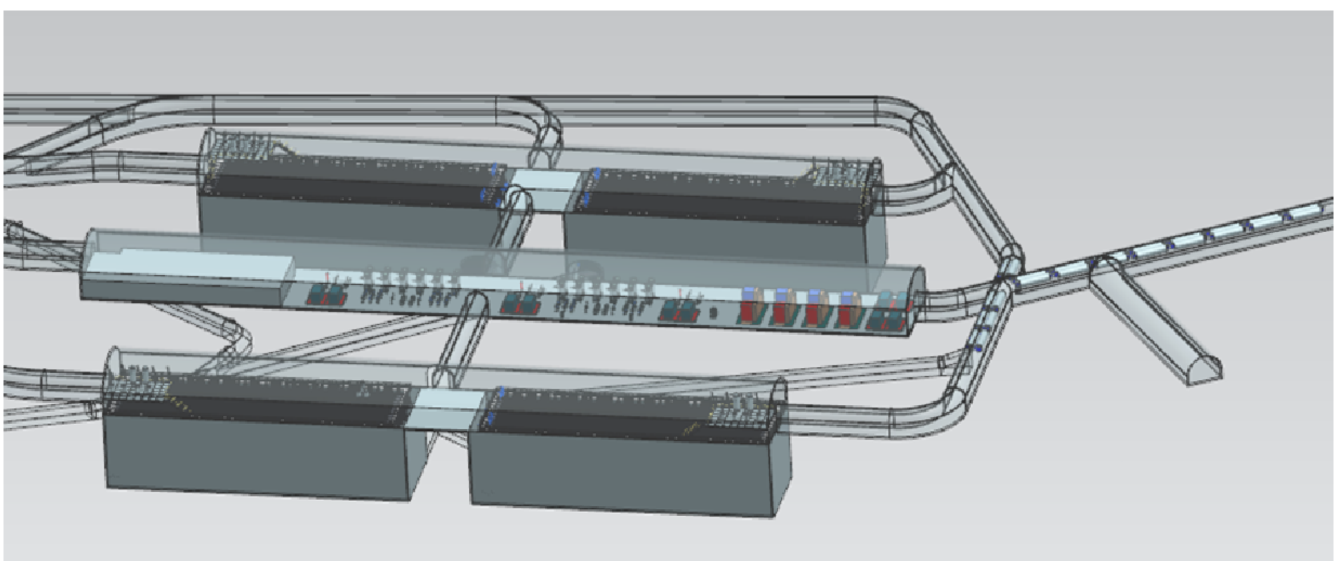

Figure 6.2: Isometric view of the underground caverns (not to scale)

Chapter 7

Cryogenic System Process

The entire cryogenic system process is summarized with functions of every cryogenic system component in Figure 7.1. The major functions serving the cryostat are cryogen supply for cooldown and fill, gas filtration, argon condensing, liquid circulation and filtration, and argon-purity analysis. The methods presented in this section are motivated by experience from the cryogenic systems of other LArTPC experiments, such as ICARUS, LAPD and prototype 35 ton membrane cryostat. The piping connections between major cryogenic system components are shown in Figure 7.2.

7.1 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 contain debris and is free of all loose material that may contaminate the LAr.

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 cryostat 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 the air is expelled, except trace amounts, the gas returns will be routed to the recondensers and then to the filteration system before being returned to the cryostat. It is in this step that the cool down of the cryostat begins. The vent gas will be cooled down and returned to the cryostat in a temperature controlled scheme, allowing for the cool down requirements of the cryostat manufacturer and TPC to define these criteria. During this cool down the gaseous argon is continuously drawn into the condensers, liquefied, filtered and returned to the cryostat as purified argon. This recirculation further purifies the gas. As the temperature of the cryostat/TPC mass approaches the liquid temperature of LAr, the fill process of the cryostat will begin.

7.1.1 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 in the piping to the ppm level. The reference-design choice for removing air from the membrane cryostat is argon flow/piston-purge, introducing the heavier argon gas at the bottom of the cryostat 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, approximately 10 mm diameter at a 50 mm pitch, will provide a uniform flow.

The flow velocity of the advancing argon-gas volume will be set to 1.2 m/hour. This velocity is high enough to efficiently overcome the molecular diffusion 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 Computational Fluid Dynamics (CFD) simulation of the purge process on the 5 kt fiducial-mass cryostat for LBNE 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. 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 in multiple arrangements: (1) in an instrumented cylinder of 1 m diameter by 2 m height, (2) Liquid Argon Purity Demonstrator (LAPD), a vertical cylindrical tank of 3 m diameter by 3 m height, taking gas-sampling measurements at varying heights and times during the purge process, (3) within the 35 ton membrane cryostat, a prototype vessel built for LBNE in 2013, of which the results are found at [6], and (4) within MicroBooNE cryostat, a horizontal cylindrical tank of 3.8 m diameter by 12.2 m length.

7.1.2 Water Removal via Gas Flow

Water and oxygen will continue to be removed from the system for several days following the initial purge. At this stage, the gas will be routed to the recondenser, filtered and recirculated to the cryostat. Each cryostat contains five tons of FR4 circuit-board material and a smaller inventory of

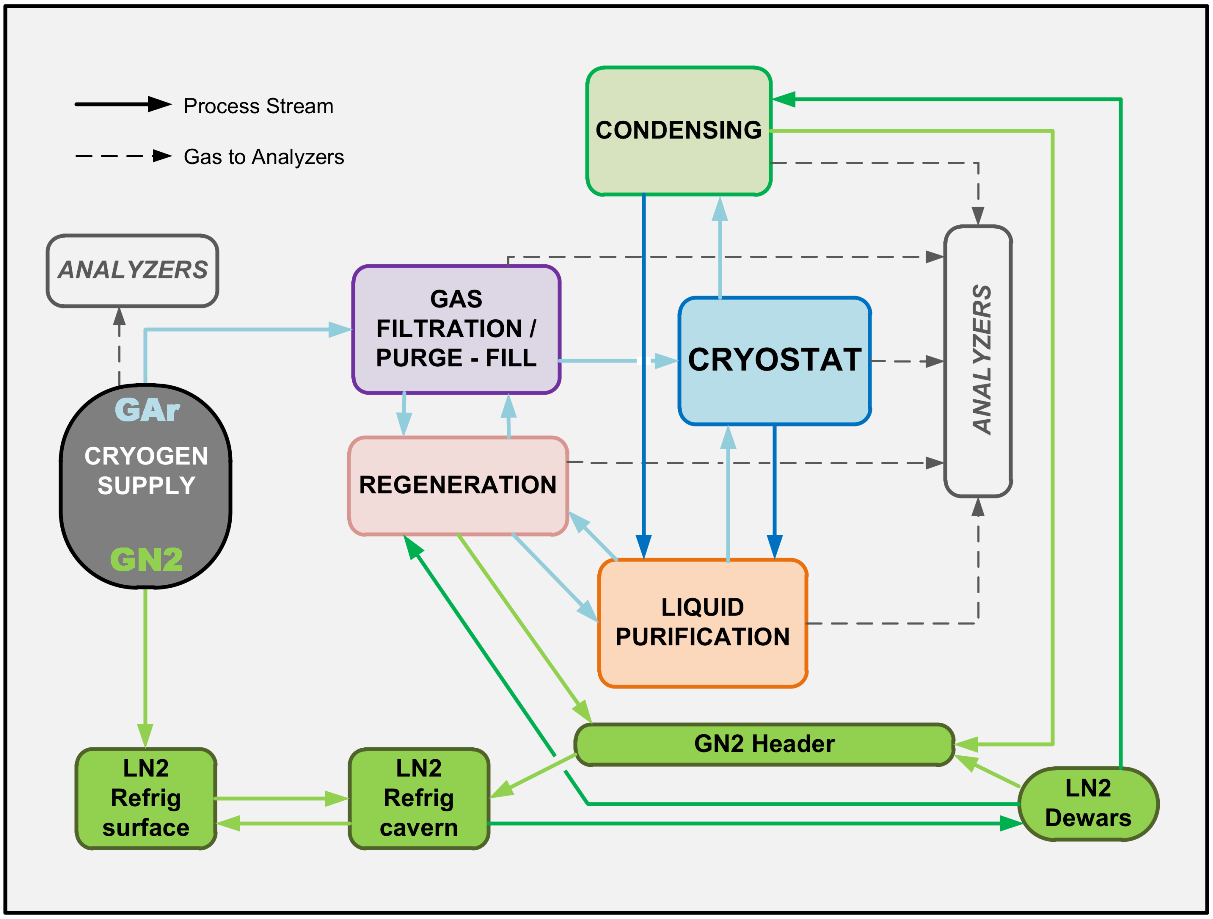

Figure 7.1: Cryogenic system functions

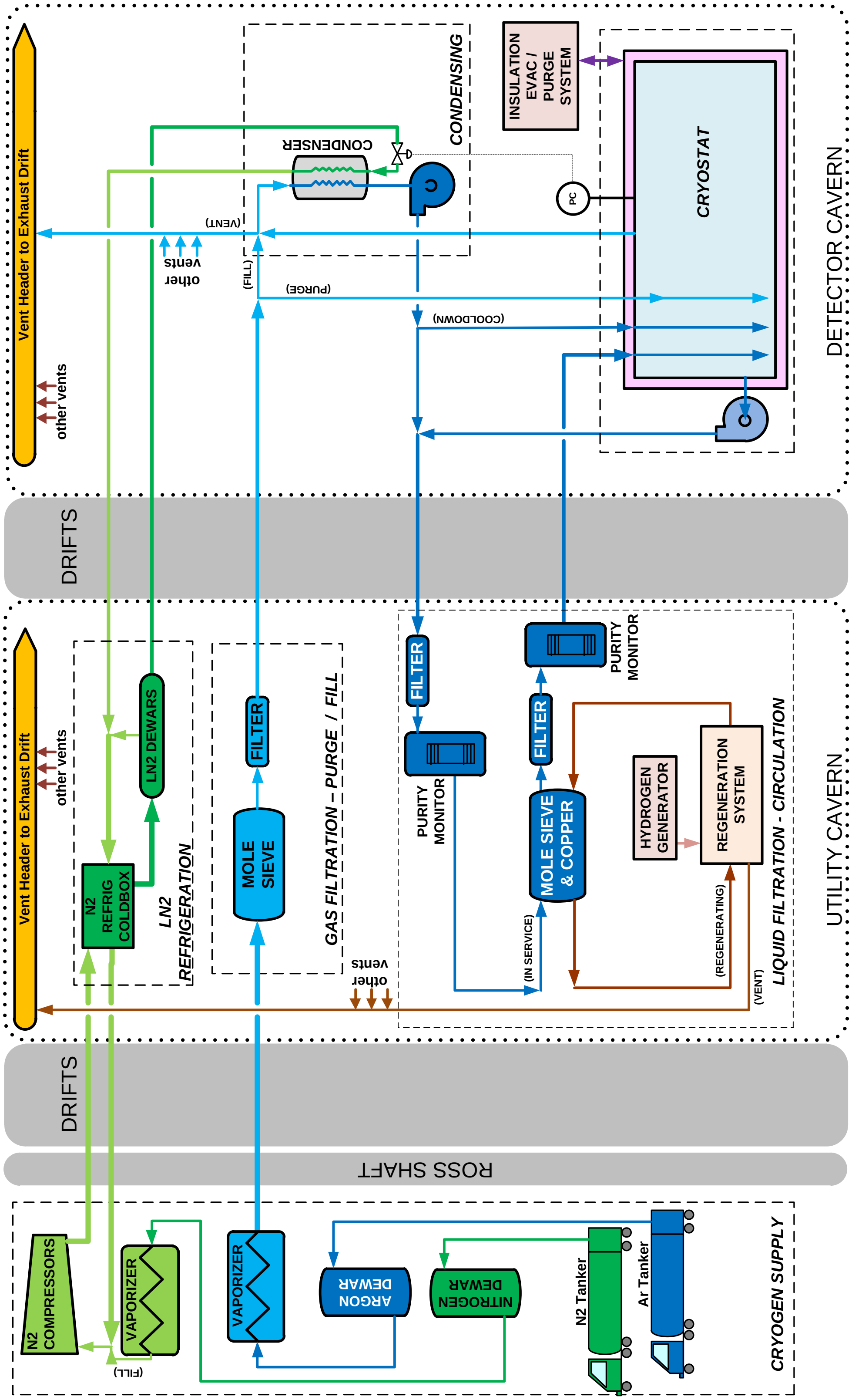

Figure 7.2: Cryogenic system flow block diagram

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 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).

7.1.3 Initial Cool-Down

The liquefaction rate in the recondenser is increased so that liquid argon can be returned to the cryostat. This purified LAr will be distributed near the bottom of the cryostat to cool down the cryostat in a controlled spray. The boil-off gas will flow through the volume of the cryostat, recondensers 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.

7.2 Liquid Argon Receipt

Each 10 kt fiducial mass membrane cryostat will hold an inventory of 17.2 kt of liquid argon. Considering that some quantities will be lost in transit, as a start (17.2+α) kt of LAr will need to be procured to fill the first cryostat. Planning the supply and logistics of LAr delivery 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 (that is the biggest contribution to determine α)
- 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

The current total argon capacity in the United States is approximately 5.2 kt/day, whereas the demand is about 4.7 kt/day, which means 90% capacity utilization in 2015. Argon demand slowed down during recession (2008−2009), but has been recovering strongly since 2010, especially in electronics and welding industries, in a pace faster than capacity growth. Some capacity was taken offline in recession and has not come back. The trend of growing demand at a rate of 3.4% per year, faster than capacity, is expected to continue for at least the next five years and will cause argon supply to be tight and prices to rise. Therefore, creating clusters of existing argon capacity that can provide argon to LBNF, rather than using one supplier, or identifying new argon capacity (preferrably closer to the SURF site) can be options to consider for economic and reliable supply. At the time of market research, air separation plants (ASPs) in Chicago and the Gulf Coast were identified as the most important supply source, but this option will require significant delivery cost.

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, it is likely that standard product will be procured from multiple vendors.

The most efficient mode of argon delivery seems to be over-the-road tank truck with a maximum capacity of 18.7 metric ton. The expected number of such deliveries per cryostat is about 1000 over six to seventeen months (Find more details in Chapter 6 and Section 7.8). Rail delivery is not cost-effective as there are no rail spurs leading to the SURF site. This mode would require transfer of product from rail tanker to a tank truck, introducing cost that exceeds the benefit.

Surface facilities for offloading LN_2 and LAr road tankers are required. It will be necessary to procure approximately four trailer loads of liquid nitrogen (about 40 tons) for the initial filling of the LN_2 refrigeration dewar and charging of a single refrigeration plant. Vehicle access and hard-surfaced driving areas are required adjacent to the LN_2 and LAr dewars. An interim LAr storage dewar will hold the contents of a few road tankers 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.

7.3 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 months 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 0.5 m in the cryostat. At this depth, the recirculation pumps can be safely turned on and it will direct up to 94 m^3/hr (412 gpm) of liquid argon through the purification system.

7.4 Argon Reliquefaction and Pressure Control

The high-purity liquid argon stored in the cryostat will continuously be evaporating 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 to prevent the loss of the high-purity argon.

During normal operation the expected heat ingress of approximately 66.6 kW to the argon system will result in an evaporation rate of 1496 kg/hr and expanding in volume by a factor of 200 when it changes from the liquid to the vapor phase. This increase in volume within a closed system will, in the absence of a pressure-control system, raise the internal pressure.

In LBNF, argon vapor will be removed from the top of the cryostat through 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 7.3) 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 $\pm$ 0.008 MPa. The liquid nitrogen stream (serving as 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 7.1.

Table 7.1: Estimated heat loads within the cryostat

Item	Heat Load (kW)
Insulation heat loss	28.8
Electronics power	23.7
Recirculation-pump power	10.4
Misc. heat leaks (pipes, filters, etc.)	3.7
Total	**66.6**

Each cryostat has a dedicated nitrogen-refrigeration plant and all four will be used for the initial cooldown and filling of the cryostats if possible because of the large volume of gas which must be cooled from 300 K to liquid argon temperature (88.3$\pm$1 K). Further, each cryostat will have four 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 redundancy. This will ensure the high availability of the recondensing system and minimize the need for venting high-purity argon or allowing downtime for maintenance of the recondensers and the refrigeration plants.

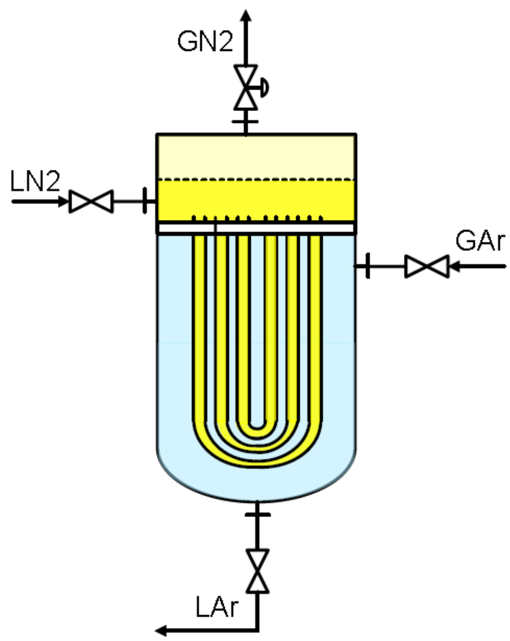

Figure 7.3: Liquid argon recondenser

7.5 Argon Purification

The cryostat is designed with side penetrations below the liquid level for external recirculation pumps used to continuously filter the cryostat's LAr. Figure 7.4 illustrates this mechanism. An Ebara model of vertical pump inserted into a vacuum insulated pump well, and external to the cryostat, is given as a typical example in Figure 7.5. The pump suction will be located at a distance below the lowest liquid level to prevent cavitation and vapour-entrapment. The base of the pump tower will be placed close to the cavern floor and below the inner floor of the cryostat. The pump suctions could be staggered at different elevations to allow flexibility in drawing liquid from different elevations. Vertical 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 94 m^3/hr (412 gpm). The liquid-argon volume in one cryostat will turn over every 5.5 days at this rate. Longer term the rate will decrease to 47 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 about ten days. See the Table 7.2 for a comparison of purification rates among other experiments and LBNF. The purification skids are located in the central utility cavern. 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 types of filter vessels containing molecular-sieve and copper media filters. The filter is 1.0 m in diameter by 4.3 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 type is for liquid filtration. After filling is complete, the gas filter can be repurposed for cryostat liquid filtration.

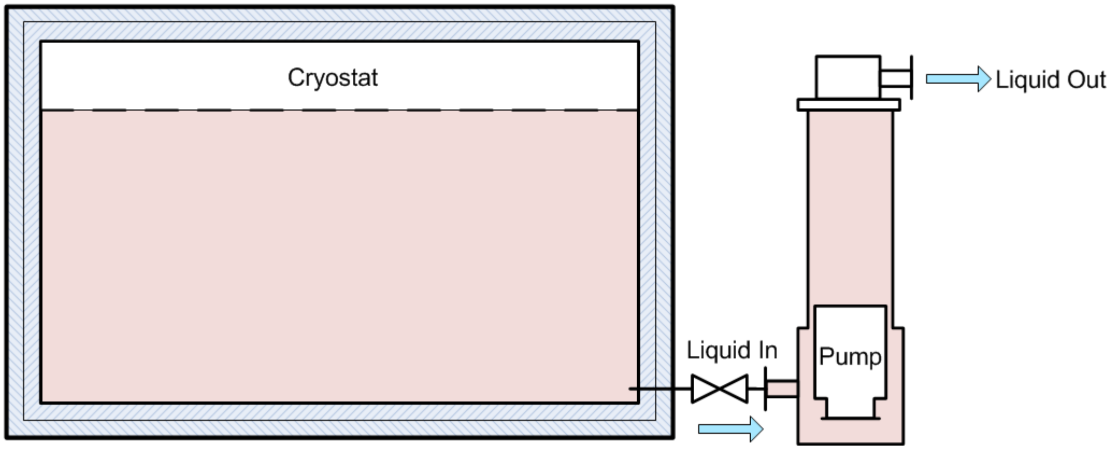

Figure 7.4: LAr recirculation mechanism using external pumps

The cryostat liquid argon inventory is circulated through a purification filter to achieve and maintain the required purity. The purification filter, containing 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 < 100 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 down to cryogenic temperatures by circulating argon gas chilled by a heat exchanger with 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.

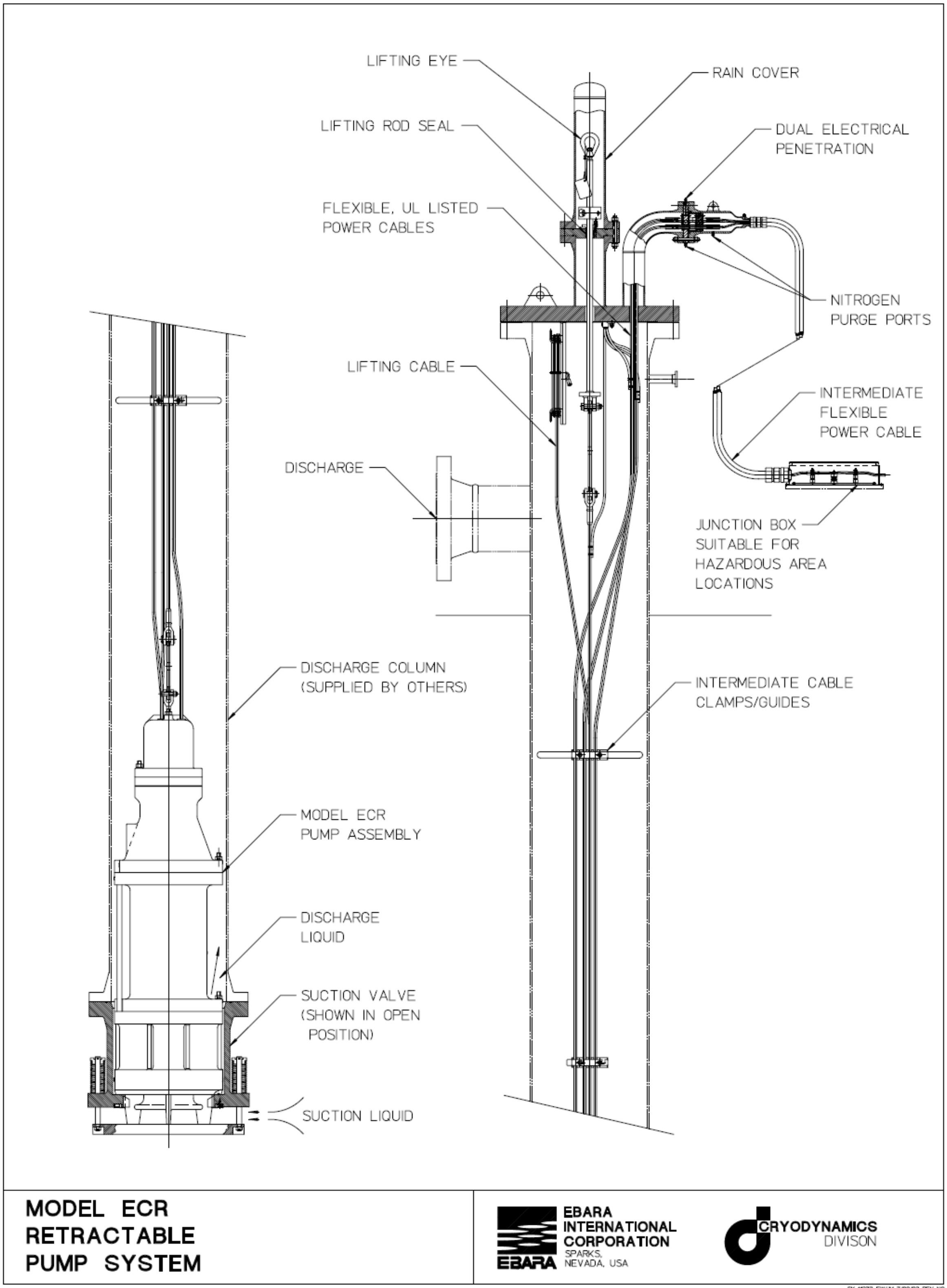

Figure 7.5: Concept of vertical pump and well

Table 7.2: Purification comparision data for LArTPCs

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-second)**
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 Cryostat Prototype	27.7	1900	27	0.7	> 2.5
LBNF (Per Cryostat)	12452	129828	1328.26	5.5	> 3.0 required

7.6 Pressure Control

7.6.1 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 between 0.105 MPa (50 mbarg) and 0.121 MPa (200 mbarg) are intended to be the normal operating range. 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. Table 7.3 gives important pressure values.

Table 7.3: Important pressure values

Vessel ullage maximum operating pressure	0.121 MPa, 200 mbarg, 2.9 psig
Cryostat Design Pressure, Relief valve set pressure	0.135 MPa, 350 mbarg, 5.1 psig

The ability of the control system to maintain a set pressure is dependent on the size of pressure deviations (due to changes in flow, heat load, temperature, atmospheric pressure, etc.) and the volume of gas in the system. The reference design has 0.66 m 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 of 66.6 kW, and for an isolated or un-cooled cryostat, the rate of pressure rise would be 490 mbar (7.1 psi) per hour. Two redundant pressure control valves will maintain the required pressure range, each sized to handle at least 1300 kg/hr of argon flow to the recondenser to handle the cooling and reliquefaction of warm GAr during cryostat filling.

7.6.2 Overpressure Control

In addition to the normal-operation pressure-control system, it is planned to provide a cryostat overpressure-protection system. This must 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 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 deviation and/or shutdown scenarios. The PRVs are self-contained devices provided specially for cryostat 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.

7.6.3 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.

7.7 LN_2 Refrigeration System

Four commercial LN_2-refrigeration plants will be procured for LBNF. After achieving the required purity and completing the initial fill, each cryostat will have a dedicated LN_2 plant for steady-state operations. The plants will be located in the central utility cavern at the 4850L. 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 71 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 per cryostat. Pure liquid is supplied from the LN_2 storage vessels via transfer lines to the phase-separator tanks located within the detector caverns. LN_2 is then withdrawn from the bottom of the phase-separator tank, at a pressure of 2.0 bar and temperature of 84 K, and directed to the recondenser. This results in a 5 K temperature difference relative to the 89 K argon recondenser temperature. The six 8.3 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 7.6, 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 system so that no operator will be required during normal operation. Estimated maximum power requirement is 1500 hp (1119 kVA), not taking into account the power generated by the expanders. The LBNF 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, as illustrated in Figure 7.7. 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 reference design cold box weighs 5670 kg. The compressors are located at the surface inside an equipment building. The compressor skid (frame) is 4.3 m long, 1.8 m wide and 2.7 m tall and weighs approximately 3630 kg.

7.8 Refrigeration Load Scenarios

In order to determine the optimal plant capacity and number of plants required, fourteen scenarios were forecasted for the LN_2 refrigeration loads and plant capacity. Those scenarios are described below and a summary is given in Table 7.4.

The conclusion points to the requirement of four 71 kW plants. Each of these plants can achieve a 20% turn up or turn down. Scenarios 1, 4, A and D impose the most severe requirements. In these scenarios, all plants available will be required to run at the maximum duty cycle to cool down and fill a cryostat, while maintaining purity for cryostat(s) filled and purified earlier. These scenarios will also require 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 40 kt module at 4850L using the Ross shaft. The refrigerators and condensers have been sized to accommodate

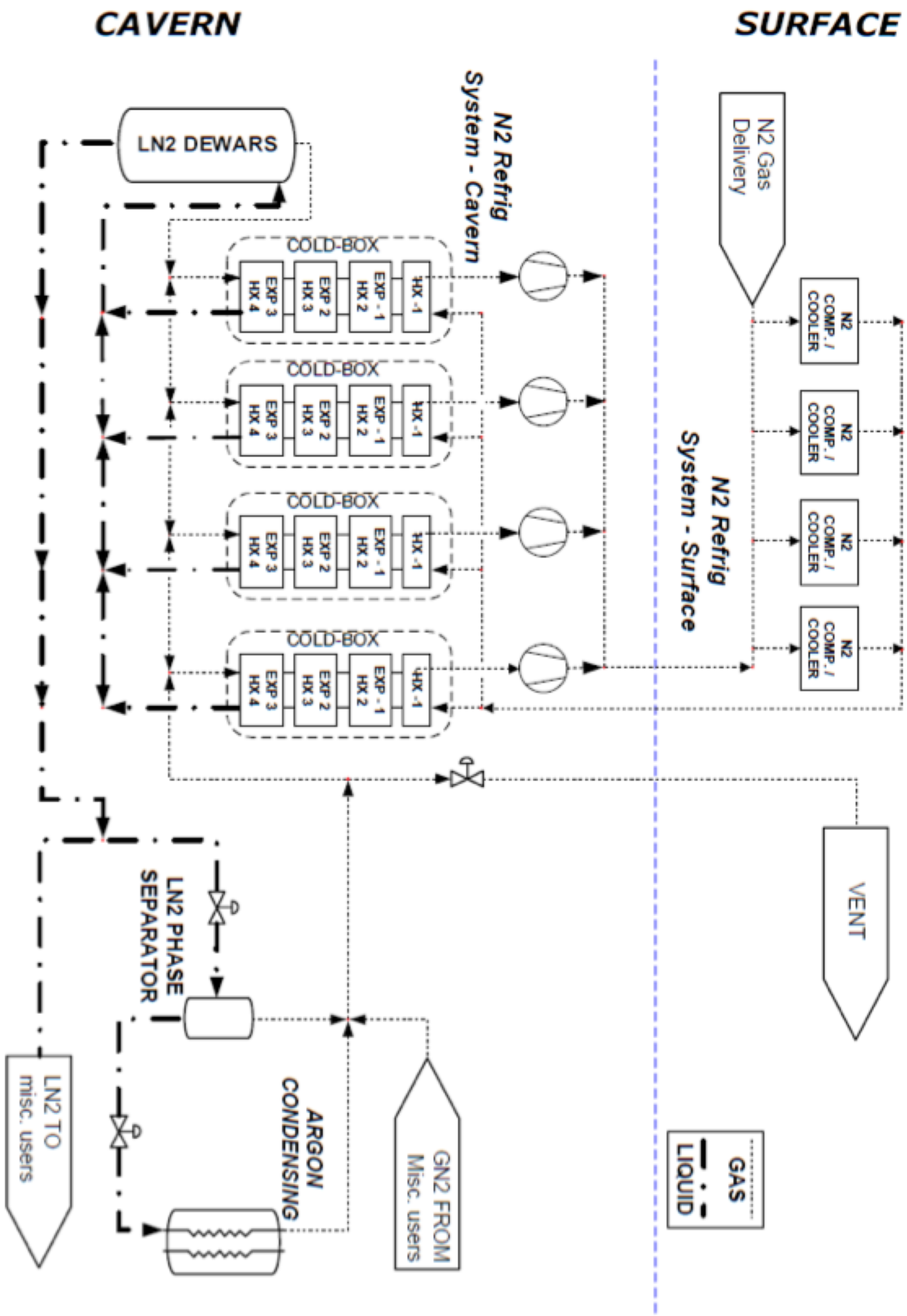

Figure 7.6: Nitrogen refrigeration-plant flow diagram

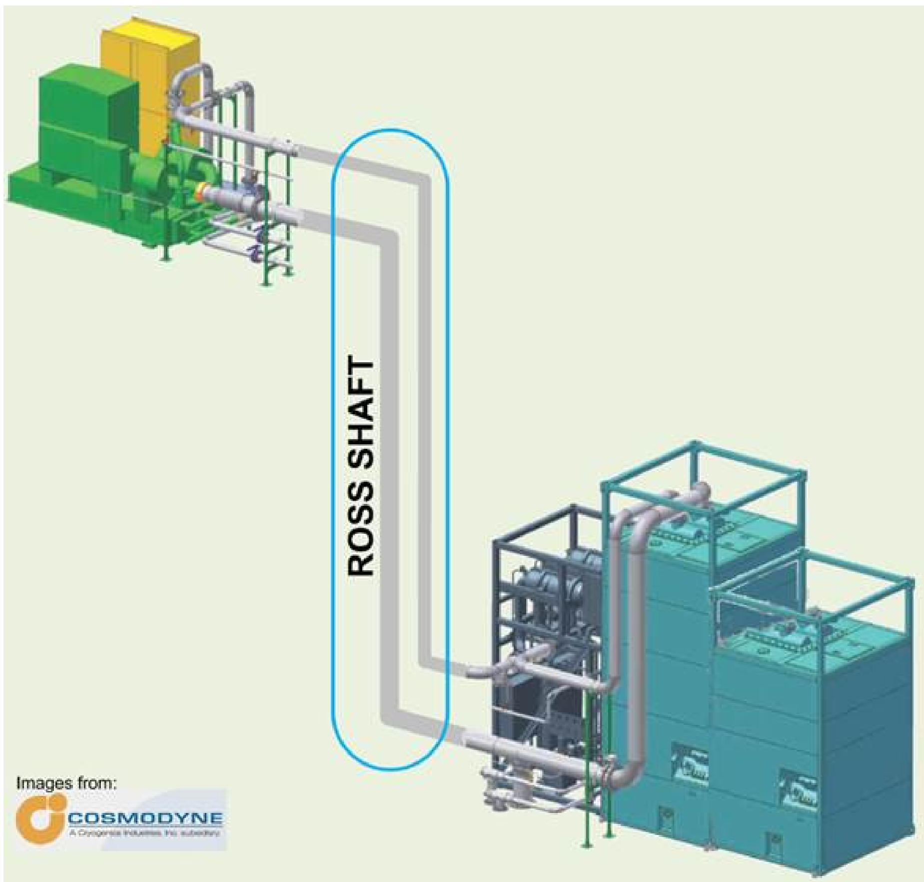

Figure 7.7: Nitrogen refrigeration plant (not to scale)

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 rest of 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 liquefaction.

Scenario 5 The second cryostat is full and LAr is circulated at high flow rate 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 LN_2 vessels in the central utility cavern 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 recirculation pumps and the purification plants are shut down.

Scenario A The first and second cryostats continue to operate in normal experimental mode while the third 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 liquefaction.

Scenario B The third cryostat is full and LAr is circulated at high flow rate through the purification plant. The first and second cryostats continue to operate as normally.

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

Scenario D The three cryostats continue to operate in normal experimental mode while the fourth 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 liquefaction.

Scenario E The fourth cryostat is full and LAr is circulated at high flow rate through the purification plant. The three cryostats previously filled continue to operate as normally.

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

Scenario G This is the same condition as Scenario 7, but now all four cryostats are in the LAr inventory protection mode.

7.9 Liquid Argon Removal

Although removal of the LAr from the cryostats at the end of life is not in the project scope, it is part of the final dispostion of the facility components. A method to accomplish this has been conceptualized here. The LAr is assumed to be resold to suppliers at half the supply cost.

It is expected that storage dewars sized for the task can be carried up and down the skip compartments of the shaft (initially used to haul up waste rock from the mine). Because there are two skip compartments, an empty vessel can simultaneously be lowered to the 4850L in one skip while a full vessel is raised to the surface in the other. The physical dimensions of skip compartment will accommodate a dewar size up to about 3000 L. If the vessel is pressurized to 50 psig, it will contain roughly 4.2 t of LAr. The pumps already present at the cryostats can be used to transfer the LAr from the cryostat to the storage dewar.

Assuming that crews work concurrently at the surface and at the 4850L, one optimized conveyance cycle can be fit in approximately 34 minutes, including 4 minutes of skip transit time up and down. This will allow for at least 31 cycles in an 18-hour day, corresponding to the delivery of 130.2 tons of LAr to the surface. Emptying each cryostat will require about 126 days.

It is expected that 15.6 kt of LAr per cryostat can be recovered in this process, i.e., over 91% of the total; this takes into account the quantity of liquid below a certain height that cannot be removed using pumps and a 5% loss in the transfer of remaining liquid to the dewars.

Heat Demand	Unit Loads (kW)	Scenarios 1	2	3	4	5	6	7	A	B	C	D	E	F	G
Recondenser Load, Cryostat #1															
Cryostat #1, Heat Ingress	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8
With 2 Recirculation Pumps	10.4			10.4	10.4	10.4	10.4		10.4	10.4	10.4	10.4	10.4	10.4	
With 4 Recirculation Pumps	20.7	20.7	20.7												
Piping & Purification Vessel Heat Ingress	3.7	3.7	3.7	3.7	3.7	3.7	3.7		3.7	3.7	3.7	3.7	3.7	3.7	
Detector Electronics in Cryostat	23.7			23.7	23.7	23.7	23.7		23.7	23.7	23.7	23.7	23.7	23.7	
Cryostat Fill - GAr Transfer/Recondense		183.8													
Number of Condensers in Operation		3	1	1	1	1	1	1	1	1	1	1	1	1	1
Condenser Load		237.0	53.2	66.6	66.6	66.6	66.6	28.8	66.6	66.6	66.6	66.6	66.6	66.6	28.8
Recondenser Load, Cryostat #2															
Cryostat #2, Heat Ingress	28.8				28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8
With 2 Recirculation Pumps	10.4						10.4		10.4	10.4	10.4	10.4	10.4	10.4	
With 4 Recirculation Pumps	20.7				20.7	20.7									
Piping & Purification Vessel Heat Ingress	3.7				3.7	3.7	3.7		3.7	3.7	3.7	3.7	3.7	3.7	
Detector Electronics in Cryostat	23.7						23.7		23.7	23.7	23.7	23.7	23.7	23.7	
Cryostat Fill - GAr Transfer/Recondense					117.2										
Number of Condensers in Operation					3	1	1	1	1	1	1	1	1	1	1
Condenser Load					170.4	53.2	66.6	28.8	66.6	66.6	66.6	66.6	66.6	66.6	28.8
Recondenser Load, Cryostat #3															
Cryostat #3, Heat Ingress	28.8								28.8	28.8	28.8	28.8	28.8	28.8	28.8
With 2 Recirculation Pumps	10.4										10.4	10.4	10.4	10.4	
With 4 Recirculation Pumps	20.7								20.7	20.7					
Piping & Purification Vessel Heat Ingress	3.7								3.7	3.7	3.7	3.7	3.7	3.7	
Detector Electronics in Cryostat	23.7										23.7	23.7	23.7	23.7	
Cryostat Fill - GAr Transfer/Recondense									129.7						
Number of Condensers in Operation									3	1	1	1	1	1	1
Condenser Load									182.9	53.2	66.6	66.6	66.6	66.6	28.8
Recondenser Load, Cryostat #4															
Cryostat #4, Heat Ingress	28.8											28.8	28.8	28.8	28.8
With 2 Recirculation Pumps	10.4													10.4	
With 4 Recirculation Pumps	20.7											20.7	20.7		
Piping & Purification Vessel Heat Ingress	3.7											3.7	3.7	3.7	
Detector Electronics in Cryostat	23.7													23.7	
Cryostat Fill - GAr Transfer/Recondense												63.10			
Number of Condensers in Operation												2	1	1	1
Condenser Load												116.3	53.2	66.6	28.8
LN_2 Dewar Heat Ingress (1 kW/each)	1	18	18	18	18	18	18		24	24	24	24	24	24	
Refrigeration Needed		255.0	71.2	84.6	255.0	137.8	151.1	57.6	340.0	210.3	223.7	340.0	276.9	290.2	115.2
Refrigeration Plants in Operation		3	3	3	3	3	3	0	4	4	4	4	4	4	0
Total Refrigeration Capacity Available		255	255	255	255	255	255		340	340	340	340	340	340	
Required Duty per Plant		85	60	60	85	60	60		85	60	60	85	69	73	
Electric Trim Heater Load		0.0	108.8	95.4	0.0	42.2	28.9		0.0	29.7	16.3	0.0	0.0	0.0	
Total Refrigeration Load		255	180	180	255	180	180	0	340	240	240	340	276.9	290.2	0
LAr Mass in Cryostat		17165040			17165040				17165040			17165040			kg
Fill Time Using Available Cooling Above		4157			6517				5892			12107			hr
(Units Listed on the right-most column		173.0			272.0				246.0			504.0			days
of table)		24.7			38.8				35.1			72.1			weeks
		5.7			8.9				8.1			16.6			months

Table 7.4: Refrigeration loads

Chapter 8

Prototyping Plans

The development of the LBNF cryogenics infrastructure from conceptual to preliminary design includes a prototyping program. The most significant issue to resolve is whether a membrane cryostat of the size planned for LBNF can achieve the required electron drift lifetime. The Liquid Argon Purity Demonstrator (LAPD) was an off-project prototype, built to study the concept of achieving LAr purity requirements in a non-evacuated vessel. The purge process accomplished in the LAPD was repeated on the 35 ton membrane-cryostat prototype developed as an LBNE effort, which confirmed that initial evacuation of the cryostat is unnecessary and that a LAr purity level sufficient to enable the electron lifetime required in a membrane cryostat can be achieved [6]. A further prototyping program aimed at testing and demonstrating this technology at the 1-kt scale is foreseen over the next two years as part of the CERN Neutrino Platform program.

Chapter 9

ES&H

Figure 9.1 shows the ODH classification for underground caverns. The detector and central utility caverns are Class 1 ODH areas [7], assessed by preliminary ODH analysis taking into account potential risks from undetected defects on materials and equipment, operational causes, etc. During an ODH event, workers must leave the area and head towards the Ross or Yates shaft.

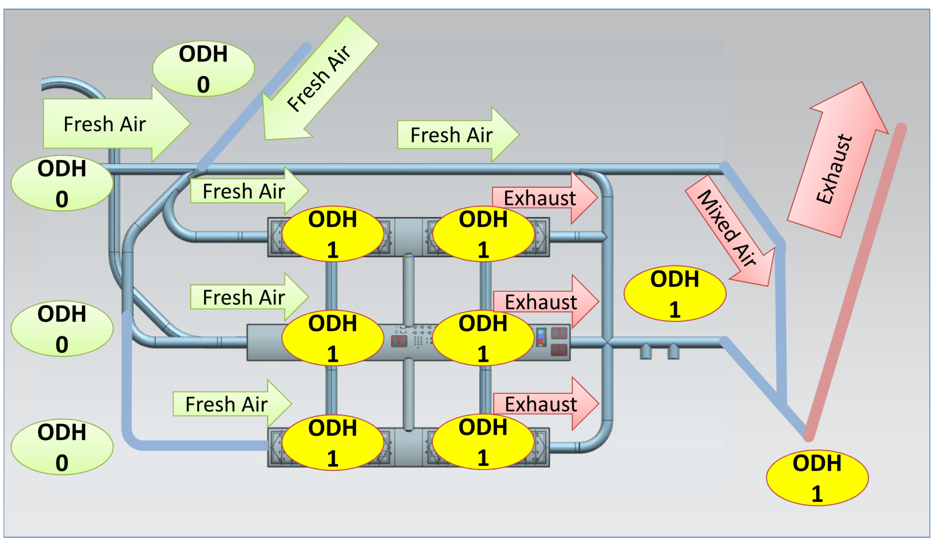

Figure 9.1: ODH mapping of the underground caverns at 4850L

During all phases of LBNF and the proposed prototypes, Fermilab ES&H standards and Sanford Underground Research Facility (SURF) 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 4240 [7] relating to ODH and Chapter 5000 [7] 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 requirements. Requirements on the membrane-cryostat materials and their fabrication will be strictly outlined in the specification documents. Close communication between the vendors, Fermilab and CERN's cryogenic and process engineers, and Fermilab and SURF ES&H personnel will be maintained at all times.

References

[1] LBNE LAr-FD L2 Project, "LAr-FD Requirements spreadsheets." LBNE Doc 3747.

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[3] DUNE Collaboration and Project, "LAr-FD Parameter Tables." DUNE Doc 158.

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[6] D. Montanari *et al.*, "First scientific application of the membrane cryostat technology.," 2013. `http://lss.fnal.gov/archive/2013/conf/fermilab-conf-13-076-ppd.pdf`.

[7] Fermilab, "Fermilab ES&H Manual ." `http://esh.fnal.gov/xms/FESHM`.