

Overview and Status of the Long-Baseline Neutrino Facility Cryogenics System

David MONTANARI^(a), Mark ADAMOWSKI^(a), Johan BREMER^(b), Michael DELANEY^(a), Roza DOUBNIK^(a), Justin FREITAG^(a), Kevin HAAF^(a), Trevor NICHOLS^(a), Adrien PARCHET^(b)

^(a) Fermi National Accelerator Laboratory (Fermilab)
PO Box 500, Batavia, IL 60510 Unites States dmontana@fnal.gov

^(b) Centre Européen Recherche Nucléaire (CERN)
1211 Geneva-23, Switzerland

ABSTRACT

The Sanford Underground Research Facility (SURF) will host the Deep Underground Neutrino Experiment (DUNE), an international multi-kiloton Long-Baseline neutrino experiment that will be installed about a mile underground in Lead, SD. Detectors will be located inside four cryostats filled with almost 70,000 ton of ultrapure liquid argon, with a level of impurities lower than 100 parts per trillion of oxygen equivalent contamination. The Long-Baseline Neutrino Facility (LBNF) provides the conventional facilities and cryogenics infrastructure supporting this experiment. The cryogenics system supplies and maintains the argon needed for DUNE, as it enables the study of neutrinos from a new and improved beamline from Fermilab, as well as the dynamics of supernovae and the possibility of proton decay. This contribution describes the main features, performance, functional requirements and modes of operations of the LBNF cryogenics system. It also details its current status, present and future needs to support the DUNE experiment.

Keywords: LBNF, Cryogenics, Liquid Argon, refrigeration, ultrapure.

1. INTRODUCTION

The Deep Underground Neutrino Experiment (DUNE) and Long-Baseline Neutrino Facility (LBNF) represent an international collaborative effort in neutrino physics. The combined project is developing the detectors and surrounding infrastructure for a massive neutrino experiment to be located at the Sanford Underground Research Facility (SURF) in Lead, SD, USA. The detectors, Time Projection Chambers (TPCs), reside in cryostats that will each be filled with some 17,400 tons of liquid argon (LAr) with impurities totaling less than 100 parts per trillion (ppt) of oxygen equivalent contamination. The DUNE detectors will ultimately enable the study of neutrinos from a new and improved beamline originating from Fermilab, as well as the dynamics of supernovae and the possibility of proton decay.

LBNF includes the four cryostats in which the DUNE detectors reside, as well as the surrounding conventional facilities and cryogenics necessary to receive, transfer, store, purify, and maintain the almost 70,000 tons of LAr required for the experiment.

Each cryostat has internal dimensions of 62.0 m long, 15.1 m wide, and 14.0 m tall, and are passively insulated by 0.8 m of polyurethane foam. The surrounding steel support structure for the cryostats include a 0.012 m thick stainless-steel plate serving as vapor barrier, as well as 1.1 m tall I-beams bearing the weight of the detector, cryostat and its contents, liquid and gaseous argon (GAr).

To qualify the cryogenics system technology (as well as the membrane technology used for all but one cryostats) a strong prototyping effort is also ongoing: several smaller detectors of increasing size with associated cryostats and cryogenics systems are being built at Fermilab and CERN as part of the Short Baseline Neutrino (SBN) Program and ProtoDUNE.

This paper describes the main features, functional requirements and expected performance of the LBNF cryogenics system. It also details its current status, present and future needs to support the DUNE experiment.

2. LBNF CRYOGENICS SYSTEM

The LBNF cryogenics system is comprised of three subsystems: Infrastructure, Proximity and Internal cryogenics.

The Infrastructure cryogenics supports the needs of the cryostat and the Proximity cryogenics. It includes the equipment to receive the argon and nitrogen in the liquid phase and transfer them underground in the gas phase, the nitrogen system (composed by the refrigeration system and the liquid nitrogen, LN₂, buffer tanks), interconnecting piping for gaseous argon and nitrogen and liquid nitrogen (and associated valves) and process controls. It is a DOE responsibility.

The Proximity cryogenics consists of all the systems that take the fluids from the infrastructure cryogenics and deliver them to the internal at the required temperature, pressure, purity and mass flow rate. It circulates and purifies LAr and GAr and condenses and purifies the boil-off GAr. It includes the condensers, the LAr and GAr purification systems and associated regeneration, the nitrogen and argon phase separators, LAr piping, valves and instrumentation. It is the responsibility of non-DOE collaborative partners.

The Internal cryogenics is located within the cryostats themselves and includes all items needed to distribute LAr and GAr and all features needed for the commissioning, cool down, fill and steady state operations of the cryostats and detectors. It is a DUNE responsibility.

An international engineering team will design, manufacture, commission, and qualify these systems, which benefit from the experience of the SBN program at Fermilab and the ProtoDUNEs at CERN.

2.1. Modes of Operations

The cryogenics system must fulfil the following modes of operations:

- **Gaseous argon purge.** Initially, each cryostat is filled with air, which must be removed by means of a slow GAr “piston purge”. A slow flow of argon is flown from the bottom and displaces the air by pushing it to the top of the cryostat where it is vented. Once the impurities, primarily nitrogen, oxygen, water, drop below the parts per million (ppm) level, the argon exhausted at the top of the cryostat is circulated in closed loop through the gas purification system and re-injected at the bottom. Once the contaminants drop below the ppm level, the cool-down can commence.
- **Cryostat and detector cool-down.** The detector elements must be cooled in a controlled and uniform manner. Purified LAr is flown into sprayers that atomize it. A second set of sprayers flowing purified GAr moves the mist of argon around to achieve a uniform cooling. The cooling power required for this mode is supplied by the vaporization of nitrogen from the nitrogen system in the argon condensers. Once the detector elements reach about 90 K, the filling can commence.
- **Cryostat filling.** Argon is vaporized and transferred underground as a gas from the receiving facilities on the surface. It first flows through the GAr purification and is recondensed in the argon condensers by means of vaporization of LN₂ from the nitrogen system. It then flows through the LAr purification and is introduced in the cryostat. The filling of each cryostat varies in duration, from 8 to 15 months, depending on the available cooling power.
- **Steady state operations.** The bulk of the LAr contained inside each cryostat is continuously purified through the LAr purification system using the main external LAr circulation pumps. The boil-off GAr is recondensed in the argon condensers and purified as liquid in the same LAr purification system as the bulk of the LAr.
- **Cryostat emptying.** At the conclusion of the experiment, each cryostat is emptied, and the LAr is removed from the system by means of the main circulation pumps.

2.2. Process Flow Diagram

Fig. 1 shows the Process Flow Diagram (PFD) of the LBNF cryogenics system. The PFD shows the physical location of the major equipment for each subsystem as well as boundaries and interfaces between them. There are three main areas, with the above ground and below ground areas connected by the Ross Shaft and the underground areas interconnected by drifts:

- **Surface.** It consists of the cryogenics receiving facilities and the nitrogen system compressors.
- **Central Utility Cavern (CUC).** It consists of the cold boxes, expanders and LN2 storage for the nitrogen system, as well as the LAr and GAr purification systems, particulate filters, regeneration systems and interconnecting piping, valves and instrumentation.
- **Detector caverns.** The four cryostats are housed in two detector caverns located north and south of the CUC. Part of the Proximity cryogenics is located in each detector cavern: argon condensers, phase separators, small LAr circulation pumps, interconnecting piping and valves.
- **Ross Shaft.** It connects the above and below ground areas and contains the GAr and GN2 piping.
- **Drifts.** They connect the Ross Shaft, the CUC and the detector caverns. There are no major pieces of equipment in these areas, mainly interconnecting piping transporting argon and nitrogen.

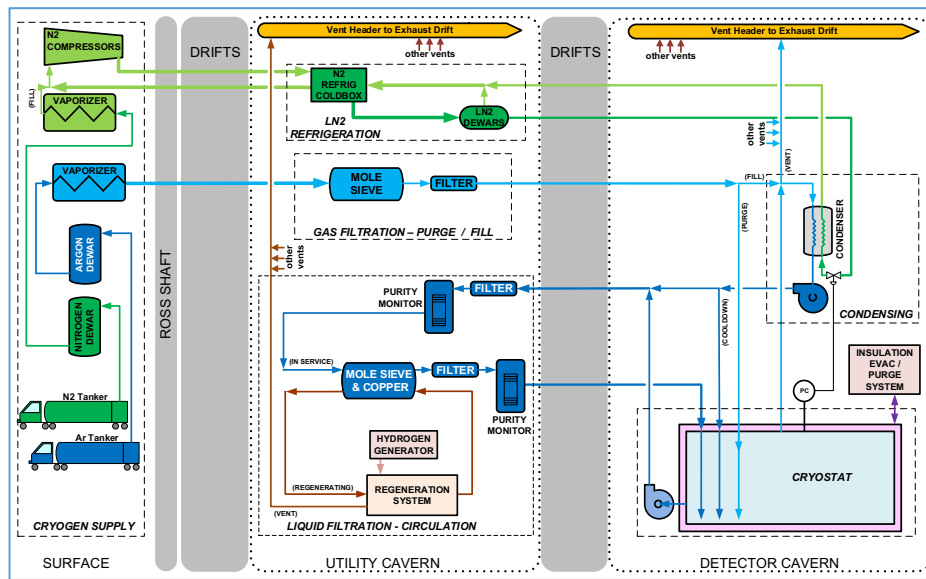


Figure 1: Process Flow Diagram for the LBNF cryogenics system

2.3. Relevant design parameters

Table 1 presents a selection of design parameters for the LBNF cryogenics system. The flow rate of the GAr during the piston purge mode has been calculated to avoid back diffusion of oxygen in argon. The chosen linear speed of 1.2 m/hr has been experimentally verified in the Liquid Argon Purity Demonstrator (LAPD), 35-ton prototype, MicroBooNE, 1x1x3 and ProtoDUNE-Single Phase (SP). The maximum cool-down rate of the detectors and the maximum temperature differential between any two points are provided to ensure mechanical stability of the TPCs during cool-down and normal operations. The maximum available cooling power comes from the sum of the estimated heat loads during peak operation and some operational margin. The liquid argon purity is required for the TPCs to operate properly and drift electrons with a lifetime greater than 3 millisecond (ms). The maximum LAr turnover of 5 days for a full cryostat volume comes from the ICARUS experience, where they were able to achieve and sustain a greater lifetime.

Table 1. Relevant design parameters

Parameter	Value (per cryostat)
Piston purge GAr flow rate (from 1.2 m/hr)	1,123 m ³ /hr
Maximum cool-down rate per detector	60 K/hr
Maximum temperature differential between any two points in detector	50 K
Maximum available cooling power	100 kW
Required LAr purity (Oxygen equivalent contamination)	< 100 ppt
Maximum LAr purification rate (from 5 days for a full volume turnover)	40 kg/s

2.4. Infrastructure cryogenics

The Infrastructure cryogenics is comprised of the cryogenics receiving facilities (above ground), the nitrogen system (above and below ground), the interconnecting piping (underground) and the process controls (above and below ground).

2.4.1. Cryogenics receiving facilities

The receiving facilities consist of offloading stations for liquid nitrogen and liquid argon, which are temporarily stored in 50 m³ storage tanks. LN₂ is vaporized and compressed in the adjacent compressors building before being sent underground as part of the nitrogen system, while LAr is only vaporized before being sent down the Ross Shaft. The storage tanks, vaporizers, interconnecting piping, valves, and instrumentation to sample the liquid argon for purity are all included in the receiving facilities.

2.4.2. Nitrogen system

The nitrogen system is comprised of the nitrogen refrigeration system and the LN₂ storage tanks. The nitrogen refrigeration system is split between above ground and underground. The surface nitrogen system equipment includes the large nitrogen compressors within the compressors building. The compressed nitrogen is transported down to the CUC via piping in the Ross Shaft and drifts and enters the nitrogen cold boxes. Each cold box will be capable of delivering 100 kW of nitrogen liquefaction to argon condensers via the nearby LN₂ storage tanks. Initially, three units (compressors and cold boxes) are needed to provide cooling for the operation of the first two cryostats, with a fourth unit added for the third and fourth vessels. During the cryostat cool-down and fill, all available units are employed to minimize the duration of each step. Once all four cryostats are filled and the required argon purity is achieved, three of the four units will be in use to re-condense boil-off argon, with the fourth being either held in reserve or actively under service. LN₂ is distributed as needed from the storage tanks, with the still-cold spent gas returned to the cold boxes. The cold gas is compressed in smaller booster compressors and sent back to the surface compressors in a closed cycle.

2.5. Proximity cryogenics

The Proximity cryogenics is comprised of the LAr and GAr purification systems, the argon condensing and the LAr circulation pumps. All items are located within the CUC and detector caverns.

2.5.1. Proximity cryogenics in CUC

The argon purification system is comprised of liquid and gas filtration elements and the associated equipment required to regenerate them, as well as particulate filters, and includes interconnecting piping and necessary valves and instrumentation. The argon purifiers themselves contain molecular sieve and copper pellets in order to remove water and oxygen respectively from the argon. Each of the filters, whether for gaseous or liquid argon, are sized to purify argon with contaminant levels of 5 ppm oxygen and 10 ppm water. The GAr purifiers are used during the argon purge phase, with shared filters used for cryostats 1 and 2, with another set of gaseous filters for cryostats 3 and 4. By contrast, the LAr filters are actively used throughout the experiment to achieve and maintain the required 100 ppt contamination level, with each cryostat given a set of liquid filters of its own. During operations, the LAr filters will switch between active filtration and regenerative modes, with one half of the set either actively filtering or being regenerated, so that the argon filtration process is uninterrupted. The regeneration is done with a hot (200 C) mix of a few percentages of hydrogen in argon.

2.5.2. Proximity cryogenics in detector caverns

The bulk of cryogenic equipment within the detector caverns sits atop a mezzanine about 2.3 m above each cryostat. The mezzanines are each 12 m wide and 55.3 m long, and contain the LAr phase separators, through which LAr is passed and conditioned before returning to the cryostat, the condensers, in which boiloff argon is re-liquefied before being pumped to the LAr purification system, and the nitrogen phase separators. Additionally, the mezzanine holds the cryostat overpressure and under-pressure protection system with the pressure controls and safety valves, along with PLC racks and the GAr sampling and measuring system, a set of lines connected to each cryostat feedthrough and piped to a gas manifold that allows to sample the GAr locally and measure the concentration of contaminants (oxygen and water). It is used during the GAr purge mode to verify progress and during steady state operations to ensure no pollution is entering the cryostat.

On the opposite end of the cryostat and on the lowest level are the four large LAr pumps that circulate the bulk of the LAr to the CUC for filtration. Argon is withdrawn by the pumps through the four side penetrations near the bottom of the cryostat, each equipped with an in-line safety valve with its seal located within the cryostat

itself. The safety valves normally remain open via actuators, but will close down in case of emergency, loss of actuation, or another triggering event. One of these safety valves is being successfully used in ProtoDUNE-SP. The same device will be used in LBNF (four each cryostat).

2.6. Internal cryogenics

The internal cryogenics distributes LAr and GAr inside each cryostat during all modes of operations. It consists of manifolds for the GAr purge and the liquid distribution, and cool-down sprayers. The purge manifold distributes GAr evenly at the cryostat floor with multiple pipe runs extending along the length of the cryostat. The liquid distribution manifold distributes LAr along the long edges of the cryostat during fill and steady state operation. The pipes have calibrated holes along the length to distribute the LAr evenly. This is very important to obtain a uniform LAr purity, in association with the LAr being returned warmer than the bulk of the liquid to help the mixing. The cool-down sprayers are located at the top of the cryostat, in discrete points along the long edges and at different elevations. A set of sprayers flows LAr only and atomizes it. Another set flows GAr only and moves the mist of LAr droplets within the cryostat to cool down the detector uniformly.

3. SUMMARY

This contribution presented a current look at the main features of the LBNF cryogenics systems. The procurement process for the nitrogen system is underway at the time of writing, with a Request for Proposals (RFP) issued in November 2018 and proposals due at the end of March 2019. Design efforts on Proximity and Internal cryogenics subsystems continue to inform requirements for the conventional facilities, helping to identify power and instrumentation requirements throughout the facility, and DUNE. Documentation packages for the Proximity and Internal cryogenics and the receiving facilities on the surface are being written to describe the systems, document functions, requirements and interfaces, and inform potential partners.

ACKNOWLEDGEMENTS

Fermilab is operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

REFERENCES

- Acciarri, R. et al., 2016. The Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 1: The LBNF and DUNE Projects. *ArXiv: 1601.05471*.
- Acciarri, R. et al., 2016. The Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 4: The DUNE Detectors. *ArXiv: 1601.02984*.
- Acciarri, R. et al., 2016. The Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 3: Long-Baseline Neutrino Facility for DUNE Jun 24 2015. *ArXiv: 1601.05823*.
- Bremer, J. et al., 2016. Overview of the development and prototyping of the cryostats and cryogenics systems for the LBNF/DUNE project. *Proceedings of the 14th Cryogenics 2017 IIR International Conference*.
- Montanari, D. et al., 2015. Performance and results of the LBNE 35-ton Membrane Cryostat Prototype. *Phys. Procedia Volume 67C pp. 308-313*.
- Geynisman, M. et al., 2017. Design of the cryogenic systems for the Near and Far LAr-TPC detectors of the Short-Baseline Neutrino program (SBN) at Fermilab. *Advances in Cryogenics Engineering: Proceedings of the Cryogenic Engineering Conference (CEC) 2017*.
- Adamowski M. et al., 2014. The Liquid Argon Purity Demonstrator. *JINST 9 P07005*.
- Zuckerbrot M et al., 2016. Purge, cool down and filling of MicroBooNE Cryostat. *Workshop on Cryogenics Operations, October 2016, Fermilab*. <http://microboone-docdb.fnal.gov/cgi-bin/ShowDocument?docid=6671>

Bettini A et al., 1991. A study of factors affecting the electron lifetime in ultra-pure liquid argon. *Nuclear Instruments and Methods in Physics Research A* (305 pp 177-186).

Andrews R et al., 2009 A system to test the effects of materials on the electron drift lifetime in liquid argon and observations on the effect of water. *Nuclear Instruments and Methods in Physics Research A* (608 pp 251-258).