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Overview and status of the Long-Baseline Neutrino Facility Far Site cryogenics system

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Abstract. The Sanford Underground Research Facility (SURF) will host the Far Detector of the Deep Underground Neutrino Experiment (DUNE), an international multi-kiloton Long-Baseline neutrino experiment that will be installed about one and a half kilometers underground in Lead, SD. Detectors will be located inside four cryostats filled with almost 70,000 metric tons of ultrapure liquid argon, with a level of impurities lower than 100 parts per trillion of oxygen equivalent contamination. The cryogenics infrastructure supporting this experiment is provided by the Long-Baseline Neutrino Facility (LBNF). This contribution presents modes of operation, layout, and main features of the LBNF Far Site cryogenic system, which is composed of three subsystems: Infrastructure, Proximity, and Internal cryogenics. The Infrastructure cryogenics supports the needs of the cryostat and Proximity cryogenics. It includes the equipment to receive the argon in liquid phase, vaporize it and transfer it underground as a gas, the nitrogen system (composed of the refrigeration system, liquid nitrogen buffer tanks and liquid and gaseous nitrogen distribution), liquid and gaseous argon distribution and process controls. The Proximity cryogenics receives fluids from the Infrastructure cryogenics and delivers them to the Internal cryogenics at the required temperature, pressure, purity and mass flow rate. It includes the argon condensers, liquid and gaseous argon purification and regeneration systems, nitrogen and argon phase separators, piping, valves, and instrumentation. The Internal cryogenics comprises the liquid and gaseous argon distribution inside the cryostats for the commissioning, cool down, fill, and steady state operations of the cryostats and detectors. An international engineering team is designing these systems and will manufacture, install, commission, and qualify them. This contribution describes the main features, performance, functional requirements, and modes of operation of the LBNF Far Site cryogenics system. It also presents the status of the design, along with present and future needs to support the DUNE experiment.

1. Introduction

The Long-Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE) represents an international collaborative effort in neutrino physics. There are two project locations: a Near Site at Fermilab, where the neutrino beam is generated, analyzed with the Near Detectors, and accelerated through the earth towards the DUNE targets at the Far Site, approximately one and a half kilometers underground at the Sanford Underground Research Facility (SURF) in Lead, SD [1]. LBNF provides the infrastructure to support the Near Detectors at Fermilab and Far Detectors at SURF. At the

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Far Site, DUNE will employ four Time Project Chambers (TPCs), housed in cryostats requiring almost 70,000 metric tons of ultrapure liquid argon (LAr) total, about 17,400 metric tons for each cryostat, with impurities totaling less than 100 parts per trillion (ppt) of oxygen equivalent contamination. DUNE is expected to achieve transformative discoveries, making definitive determinations of neutrino properties, examining the dynamics of supernovae that produced the heavy elements necessary for life, and probing the possibility of proton decay [2]. This contribution focuses on the cryogenics system at the Far Site.

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

Membrane cryostat technology, widely used for transportation and storage of Liquified Natural Gas (LNG) is used for the cryostats. A 0.0012 m thick membrane contains the liquid and transfers the load to the insulation and support structure. Each cryostat has internal dimensions of 62.0 m long, 15.1 m wide, and 14.0 m tall, and is 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) [3].

Access to the underground site is very restricted: underground equipment must be transferred from the surface via a cage travelling down the Ross Shaft. The maximum dimensions of a load that can be transported down in the cage are: 3.8 m long x 3.9 m high x 1.4 m wide. The maximum weight is 6,123 kg. There are options to transport longer objects so long as they are narrow, either under the cage or in a nearby cargo compartment which is used for the removal of the rocks during the excavation phase. In this special compartment heavier loads are also possible.

To qualify the cryogenics system technology (as well as the membrane technology used for all but one of the cryostats) a strong prototyping effort is ongoing: several smaller detectors of increasing size with associated cryostats and cryogenics systems are in operation at Fermilab and CERN as part of the Short Baseline Neutrino (SBN) and ProtoDUNE programs, with an additional prototype under construction [4, 5].

This contribution describes the main features, performance, functional requirements, and modes of operation of the LBNF Far Site cryogenics system. It also presents the status of the design, along with present and future needs to support the DUNE experiment.

2. LBNF Cryogenics System

The LBNF cryogenics system is composed of three subsystems: Infrastructure, Proximity and Internal cryogenics. Fig. 1 shows a summary view of the scope.

The Infrastructure cryogenics supports the needs of the cryostat and the Proximity cryogenics. It includes the equipment to receive the argon in the liquid phase and transfer it underground in the gas phase, the nitrogen system (composed of the refrigeration system, the liquid nitrogen (LN_2) buffer tanks and the liquid and gaseous nitrogen (LN2/GN2) distribution), argon interconnecting piping and valves, the cryostat pressure control system, the GN2 supply to the cryostat insulation, and process controls. It is a United States Department of Energy (DOE) responsibility.

The Proximity cryogenics consists of all the systems that take the fluids from the infrastructure cryogenics and deliver them to the internal cryogenics 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 reliquefaction and purification sub-systems, and associated instrumentation and monitoring equipment, as well as the regeneration, and the nitrogen and argon phase separators. It is the responsibility of non-DOE collaborative partners, among which are Brazil, Switzerland (via CERN), and Poland.

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. The delivery is the responsibility of non-DOE collaborative partners, whereas the installation is a DOE 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 ProtoDUNE programs at CERN.

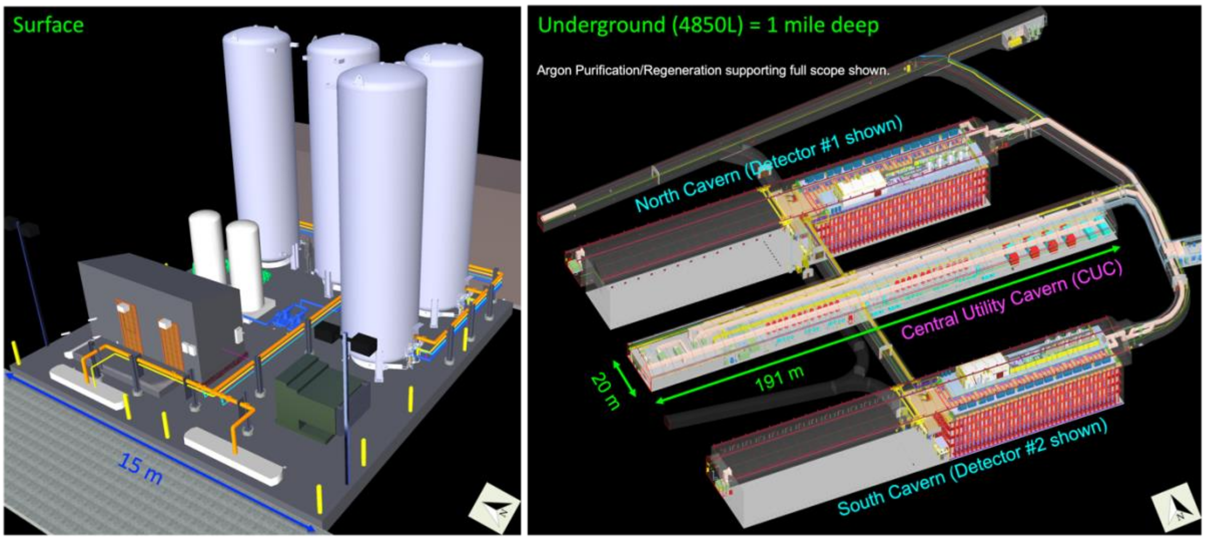

Figure 1. Far Site Cryogenics system scope (argon receiving on the surface on the left, underground installation on the right).

2.1. Process Flow Diagram

Fig. 2 shows the Process Flow Diagram (PFD) of the LBNF cryogenics system, which builds upon the successful LAr programs at Fermilab and CERN. 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. For convenience only one detector cryostat is shown, the full system supports four cryostats in total. The primary equipment locations and interconnecting areas are:

- **Surface.** The argon receiving facilities are located above ground.
- **Central Utility Cavern (CUC).** A central cavern area hosts the Nitrogen System, composed of the Nitrogen Refrigeration System (recycle compressors and cold boxes), LN2 storage and LN2/GN2 distribution, as well as the LAr and GAr purification systems, particulate filters, regeneration systems and argon interconnecting piping, valves, and instrumentation.
- **Detector caverns.** The four cryostats are housed two each in the North and South Caverns on either side of the CUC. Part of the Proximity cryogenics is local to each detector cryostat: argon condensers, LAr and LN2 phase separators, small and main LAr circulation pumps, interconnecting piping and valves for argon and nitrogen.
- **Ross Shaft.** This shaft connects the above and below ground areas to transfer GAr from the receiving facilities to underground (not shown on Figure 1).
- **Drifts.** The drifts connect the Ross Shaft, the CUC and the North and South Caverns. There are no major pieces of equipment in these areas, though they do contain some items, mainly interconnecting piping transporting argon and nitrogen.

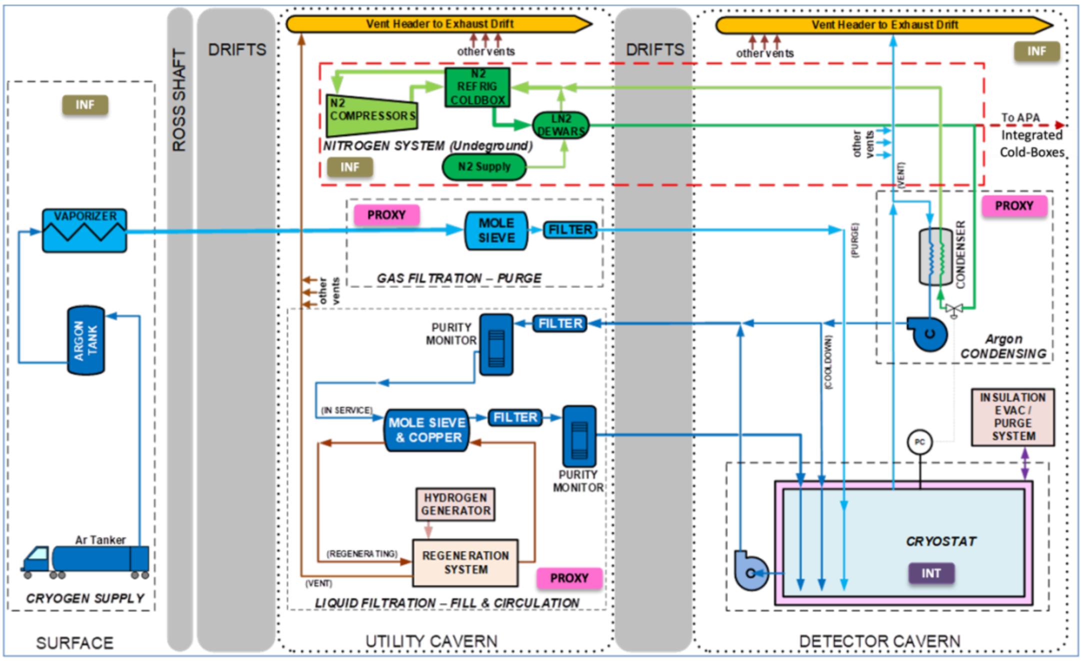

Figure 2. LBNF cryogenics system Process Flow Diagram (PFD).

2.2. Modes of Operations

The cryogenics system must fulfill the following modes of operations [6, 7, 8]:

- **Gaseous argon purge**. Initially, each cryostat is filled with air, which must be removed by means of a GAr "piston purge". A slow flow of argon is introduced 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, and water), drop to the parts per million (ppm) level, the argon is directed through the gas purification system in a closed loop before entering the cryostat 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 sprayed at the top of the cryostat using nozzles and vaporizes creating circulation cells that uniformly cool down the detector. The cooling power required to recondense argon in the condensers outside the cryostat is supplied by the vaporization of nitrogen from the nitrogen system. 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 system and is recondensed in the argon condensers by means of vaporization of LN2. It then flows through the LAr purification and is introduced in the cryostat as liquid. The filling of each cryostat varies in duration, from 8.5 to 15 months, depending on the available cooling power.
- **Steady state operations.** The LAr contained inside each cryostat is continuously purified through the LAr purification system using the main external LAr circulation pumps. In this step the purity goes down to 100 ppt. 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 and brought to the surface.

2.3. Relevant design and cryogenics parameters

Table 1 presents a selection of design and cryogenics parameters for the LBNF Far Site 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 multiple installations at Fermilab and CERN [5, 6, 7, 8]. The maximum cool-down rate of the detectors and the maximum temperature gradient between any two points are provided to ensure mechanical stability of the TPCs during cool-down [2]. The maximum available cooling power comes from the sum of the estimated heat loads during peak operation and some operational margin. The condensers size comes from the same considerations and the need to fill each cryostat in a reasonable time frame (1-1.5 year). The liquid argon purity is required for the TPCs to operate properly and drift electrons with a lifetime greater than 3 milliseconds (ms). The ProtoDUNE-Single Phase (ProtoDUNE-SP) at CERN exceeded 30 ms lifetime [5]. The maximum LAr turnover of 5 days for a full cryostat volume comes from the ICARUS experience, which has achieved and sustained a greater lifetime [9]. Since then, it has been verified by multiple installations at Fermilab and CERN, which also suggests that once purity has been achieved, a lower flow rate is enough to maintain purity. The estimated heat contributions come from the cryostat and detector designs and performance at ProtoDUNEs at CERN.

Table 1. Relevant design and cryogenics parameters.

Parameter	Value	Notes
GAr Purge flow rate	0.312 m^3/s	From 1.2 m/hr linear velocity.
Maximum cool-down rate	60 K/hr	Detector requirement.
Maximum temperature gradient between any two points	50 K	Detector requirement.
Maximum available cooling power	100 kW	Per detector, once in steady state (E.g., after filling).
Condenser size (per cryostat)	3 x 100 kW = 300 kW	3 LN2 refrigeration units for cryostats 1, 2. 4th unit added for cryostats 3, 4.
Required LAr purity	100 ppt (~3.2 ms lifetime)	Oxygen equivalent contamination (Oxygen and Water).
Maximum LAr circulation speed (assuming 5 days turnover)	0.029 m^3/s (40 kg/s)	All 4 LAr pumps in operation.
Nominal LAr circulation	0.43 m3/min (10 kg/s)	Only 1 LAr pump in operation.
LAr filling flow rate	0.788 / 0.465 kg/s	1st / 2nd cryostats only (With 3 LN2 refrigeration units).
Cryostat static heat leak	48.7 kW	Each cryostat.
Electronics heat leak	23.7 kW	Each cryostat.
Total estimated heat leak	87.1 / 98.2 kW	Each cryostat with 2/4 LAr pumps in operation.

2.4. Infrastructure cryogenics

The Infrastructure cryogenics includes the argon receiving facilities (above ground), the nitrogen system (underground), the Argon interconnecting piping and valves (underground), the cryostat pressure control system (underground), the GN2 supply to the cryostat insulation (underground), and process controls (above and below ground).

2.4.1. Argon receiving facilities. The argon receiving facilities consist of offloading stations for LAr, which is temporarily stored in up to four 50 m^3 storage tanks providing 280 metric tons of LAr storage, or up to 4 days at the delivery rate necessary for the fill of the first cryostat. LAr is vaporized before being sent underground as GAr. There is 2N redundancy on pumps and vaporizers to ensure continuity of the fill once deliveries start. Storage tanks, vaporizers, interconnecting piping, valves, pumps, and instrumentation to sample the liquid argon for purity are all included in this system.

2.4.2. Nitrogen system. The nitrogen system is composed of the nitrogen refrigeration system, the LN2 storage tanks, the LN2/GN2 distribution. The nitrogen refrigeration system includes the nitrogen compressors, the cold boxes and the GN2 to charge the system and makeup for the losses. 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 available as spare. LN_2 is distributed as needed from the storage tanks, with the still-cold spent GN2 returned to the cold boxes to close the cycle. The Nitrogen system also supplies LN2 to the APA cold boxes, a test facility where the TPCs are tested at cryogenic temperature (cold GN2) before being installed in the cryostat. The acquisition of this system is ongoing with a competitive multiphase approach with options started in March 2021, which includes a preliminary-Front End Engineering Design (pre-FEED), engineering, manufacturing, installation and commissioning. This system is primarily challenged by its installation underground, as well as associated concerns with its operation and reliability.

2.4.3. Argon interconnecting piping. The argon interconnecting piping consists of a series of vacuum and non-vacuum insulated pipes transporting LAr and GAr (cold and warm) between the CUC and the detector cryostats.

2.4.4. Process controls. The process controls architecture for the overall LBNF cryogenics system is in the Final Design stage. The nitrogen system will be delivered with its own standalone controls system, which will interface with the main LBNF control system. All other subsystems are developed in-house, including programming for the Programmable Logic Controllers (PLCs) and Human Machine Interface (HMI), the Oxygen Deficiency Hazard (ODH) system and overall integration.

2.5. Proximity cryogenics

The Proximity cryogenics includes reliquefaction and purification/regeneration subsystems, as well as the LAr circulation pumps, associated instrumentation and monitoring equipment. All items are located within the CUC and North and South caverns.

2.5.1. Proximity cryogenics in CUC. The argon purification system is composed of liquid and gas filtration elements and the associated equipment required for their regeneration, as well as particulate filters. It 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 of the filters is done with a hot (500 K) mixture of argon and a small percentage of hydrogen. This system is primarily challenging for its transportation underground (due to the large vessel sizes of the filters) and its installation.

2.5.2. Proximity cryogenics in North/South caverns. The bulk of cryogenic equipment within the North and South caverns sits atop a mezzanine about 2.3 m above each cryostat (details in Fig. 3 (left)). 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 LN2 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 sampling the GAr locally and measure the concentration of certain contaminants (oxygen and water). It is used during the GAr purge mode to verify progress and during steady state operations to ensure no contaminant 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 in case of emergency, loss of actuation, or another triggering event. Two of these safety valves are currently (and successfully) in use in the ProtoDUNE cryostats at CERN. The same devices will be used in LBNF (four per cryostat). Fig. 3 (right) shows the current configuration (only two LAr pumps shown for convenience, the other two are on the other side of the cryostat centerline). This system too is challenging for its transportation and installation underground.

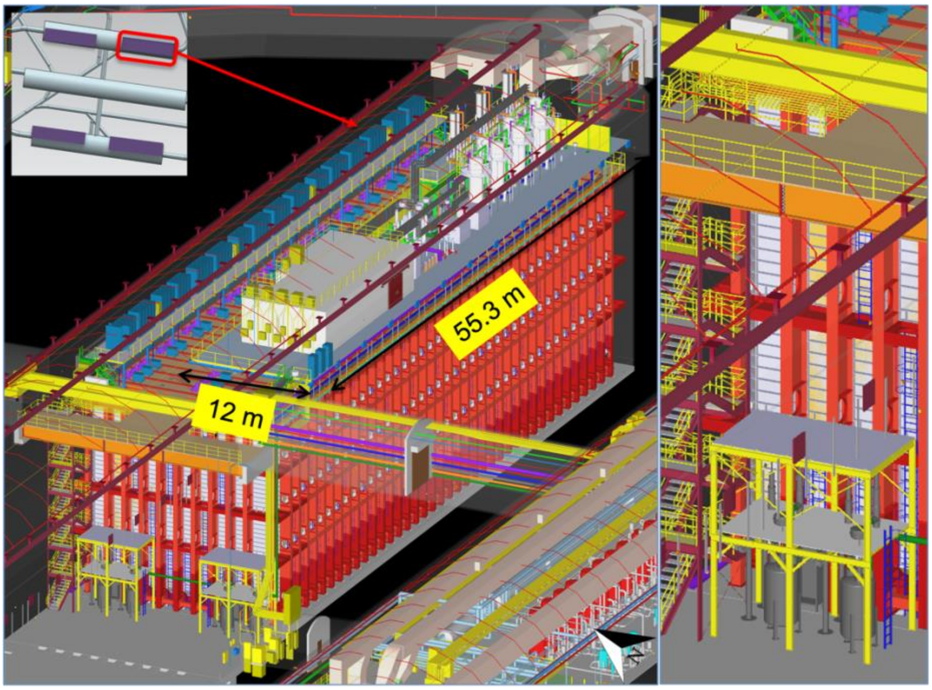

Figure 3. Proximity cryogenics in North/South Caverns (mezzanine on left, LAr pumps on right).

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, the LAr distribution, and cool-down nozzles. The purge manifold distributes GAr evenly at the cryostat floor with multiple pipes 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 with mixing. The cool-down nozzles are located at the top of the cryostat, at discrete points along either side of its middle line.

3. Liquid argon procurement

The procurement of LAr is a very large part of the scope. All liquid argon for the Far Site will be purchased from industry suppliers, for a total of 4 x 17,800 metric ton, plus losses. The highest anticipated delivery rate is 70 metric ton/day (roughly three to four tankers per day), for 10 months to support the purge, cooldown and fill of the first Cryostat. The requested grade is very standard: 5 ppm Oxygen and 10 ppm Nitrogen and Water contaminants. The project has been working with an experienced industry consultant and directly with argon suppliers since 2015 to develop a strategy for this procurement.

Challenges for this acquisition includes the average distance from the production (1,600 kilometers) and the tight supply/demand situation, with the demand being within 2-3% of the Maximum Deliverable Volume in the United States.

Deliveries to LBNF/DUNE are expected to start in 2028.

4. Summary

This contribution presented an overview of the main features of the LBNF Far Site cryogenics systems. The procurement process for the nitrogen system is underway at the time of writing. Design efforts on Proximity cryogenics are ongoing by non-DOE collaborative partners. Documentation packages for the acquisition of argon receiving facilities and internal cryogenics with functional specifications and interfaces are almost completed. Investigation on the LAr procurement acquisition is ongoing and will culminate in the submittal of the Acquisition Plan (AP) to DOE in either late 2021 or early 2022.

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