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A MODEL FOR MANUSCRIPT SUBMITTED TO THE NTH IIR CONFERENCE ON OVERVIEW OF THE LONG-BASELINE NEUTRINO FACILITY CRYOGENIC SYSTEM

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ABSTRACT

The Deep Underground Neutrino Experiment (DUNE) collaboration is developing a multi-kiloton Long-Baseline neutrino experiment that will be located one mile underground at the Sanford Underground Research Facility (SURF) in Lead, SD. In the present design, detectors will be located inside four cryostats filled with a total of 68,400 ton of ultrapure liquid argon, at the level of impurities lower than 100 parts per trillion of oxygen equivalent contamination. The Long-Baseline Neutrino Facility (LBNF) is developing the conventional facilities and cryogenics infrastructure supporting this experiment. The cryogenics system is composed of several sub-systems: External/Infrastructure, Proximity, and Internal cryogenics. It will be engineered, manufactured, commissioned, and qualified by an international engineering team. This contribution highlights the main features of the LBNF cryogenic system. It presents its performance, functional requirements and modes of operations. It also details the status of the design, present and future needs.

Keywords: LBNF, Cryogenics, Liquid Argon, ultrapure.

1. INTRODUCTION

The Deep Underground Neutrino Experiment (DUNE) collaboration and the Long-Baseline Neutrino Facility (LBNF) are developing the detectors and infrastructure for a multi-kiloton Long-Baseline neutrino experiment that will be located at the Sanford Underground Research Facility (SURF) in Lead, SD. The detectors, Time Projection Chambers (TPCs), will be located about a mile underground inside large cryostats filled with a total of 68,400 ton of ultrapure liquid argon, at the level of impurities lower than 100 parts per trillion (ppt) of oxygen equivalent contamination.

The LBNF/DUNE installation includes four cryostats each one measuring 62.0 m in length, 15.1 m in width and 14.0 m in height (internal dimensions) and the associated cryogenic systems necessary to receive, transfer, store and purify the large quantity of liquid argon (LAr) required by the experiment, as well as the liquid nitrogen (LN2) refrigeration system to re-condense gaseous argon (GAr).

To qualify the cryogenic 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 side with associated cryostats and cryogenic systems are being designed and will be built in the next 1-2 years at Fermilab and CERN as part of the Short Baseline Neutrino (SBN) Program and ProtoDUNE. Details in contribution 076. Two detector technologies are being developed: Single Phase (SP), with the detector fully submerged in the liquid argon bath, and Dual Phase (DP), with a part of the detector in the gas phase as well.

2. DESCRIPTION OF THE SYSTEM

The LBNF cryogenics systems is comprised of the following sub-systems:

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- **External/Infrastructure (or LN2) Cryogenics.** It includes the equipment used to store and produce the cryogenic fluids needed for the operation of the Proximity Cryogenics: the surface receiving facilities for the liquid nitrogen and argon and the liquid nitrogen refrigeration system.

- **Proximity (or LAr) Cryogenics.** It consists of all the systems that take the cryogenic fluids from the External/Infrastructure Cryogenics and deliver them to the Internal at the required pressure, temperature, purity, quality and mass flow rate. It includes the purification systems for the liquid and gaseous argon and the equipment in the detector cavern (condensers, nitrogen and argon phase separators, and interconnecting piping).

- **Internal Cryogenics.** It is comprised of all the cryogenic equipment located within the cryostats themselves, including the liquid and gaseous argon distribution piping and the piping to cool down the cryostats.

2.1. Relevant design parameters

Table 1 presents a selection of the design parameters for the LBNF cryogenics systems.

Table 1. Relevant design parameters

Parameter	Value (per cryostat)
Piston purge gaseous argon flow rate (from 1.2 m/hr)	253.68 m3/hr
Maximum cool-down rate of the detector	40 K/hr
Maximum temperature differential between any two points in the detector	50 K
Maximum available cooling power	100 kW
Required liquid argon purity (oxygen equivalent contamination)	< 100 ppt
Maximum liquid argon turnover (5 days for a full volume)	36.12 kg/s

The rate of rise of the gaseous argon purge during the piston purge mode has been calculated based on the velocity of the back diffusion of oxygen in argon and the capability of the two to mix. The chosen linear speed of 1.2 m/hr is faster than the back-diffusion rate and has been experimentally verified in the Liquid Argon Purity Demonstrator (LAPD), 35-ton prototype and MicroBooNE. 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 required liquid argon purity is needed for the TPCs to operate properly and drift electrons with a lifetime greater than 3 millisecond (ms) according to the empirical correlation between electron lifetime and parts of oxygen equivalent contamination shown in Eq. (1). The maximum liquid argon turnover of 5 days for a full cryostat volume comes from the ICARUS experience, where they were able to achieve a greater lifetime.

$$Lifetime\,[s] = \frac{3\cdot 10^{-13}[s\cdot parts\ of\ Oxygen]}{\text{Contaminant}\,[parts\ of\ Oxygen]} \qquad \text{Eq. (1)}$$

2.2. Modes of operations and Process Flow Diagram

The cryogenic system must be able to fulfil the following modes of operations:

- **Gaseous argon purge.** This is the initial phase during which the contaminants are removed from the cryostat (which starts filled with air) by means of a slow gaseous argon flow that pushes the impurities from the vessels bottom to the top and out. During the first part, when the cryostat is full of air, argon is flown in open loop and vented. Once the contaminants (primarily oxygen, water and nitrogen) reach the parts per million (ppm) level, the argon is circulated in closed loop and sent to the gas purification system before being re-injected at the bottom of the cryostat. When the concentration of contaminants reaches the sub-ppm level, the cool-down can commence.

- **Cool-down.** Purified liquid argon is mixed with gaseous argon and distributed in dedicated sprayers near the roof of the cryostat to cool down the cryostat and the detector to their operating temperature in a controlled way. Additional sprayers provide momentum to move the mist of liquid and gas uniformly inside. The cooling power is provided by the vaporization of liquid nitrogen from the refrigeration system.

- **Filling.** We transfer gaseous argon from the receiving facilities from underground and recondense it locally. Once the cryostat and the TPCs are cold, liquid argon from the condensers above each cryostat flows into the vessel underneath, filling it with 17,100 tons of purified liquid argon, over a period of several months. The duration of the fill is between 5 and 10 months, depending on the available cooling power for each cryostat.

- **Steady state operations.** During this phase the liquid argon contained inside each cryostat is continuously recirculated thought the liquid filtration system by means of external pumps. The boil-off gaseous argon is re-condensed in the condensers and purified through the same liquid filtration system before being reintroduced as liquid inside the cryostat.

- **Emptying.** This is the final phase, following the completion of the experiment. The cryostat is emptied and the liquid argon removed from the system.

Fig. 1 shows the Process Flow Diagram (PFD) of the system that has been developed to satisfy these modes of operations. It details the scope of each sub-system, where it is located and boundaries between sub-systems. There are four main zones plus the drifts connecting the underground areas:

- **Surface.** It includes the cryogens receiving facilities and part of the liquid nitrogen refrigeration system (the gaseous nitrogen compressors).

- **Detector cavern.** It is underground and includes the cryostat and some of the proximity cryogenics (condensers, phase separators and liquid argon circulation pumps).

- **Central Utility Cavern** (CUC). It is underground and includes part of the liquid nitrogen refrigeration system (cold boxes and expanders) and the liquid and gaseous argon purification systems and associated equipment (particulate filters and regeneration system).

- **Ross shaft.** It includes the pipes to transfer the gaseous argon and nitrogen from the surface to underground.

- **Underground drifts.** They include the interconnecting pipes to transfer argon and nitrogen in liquid and gas phase.

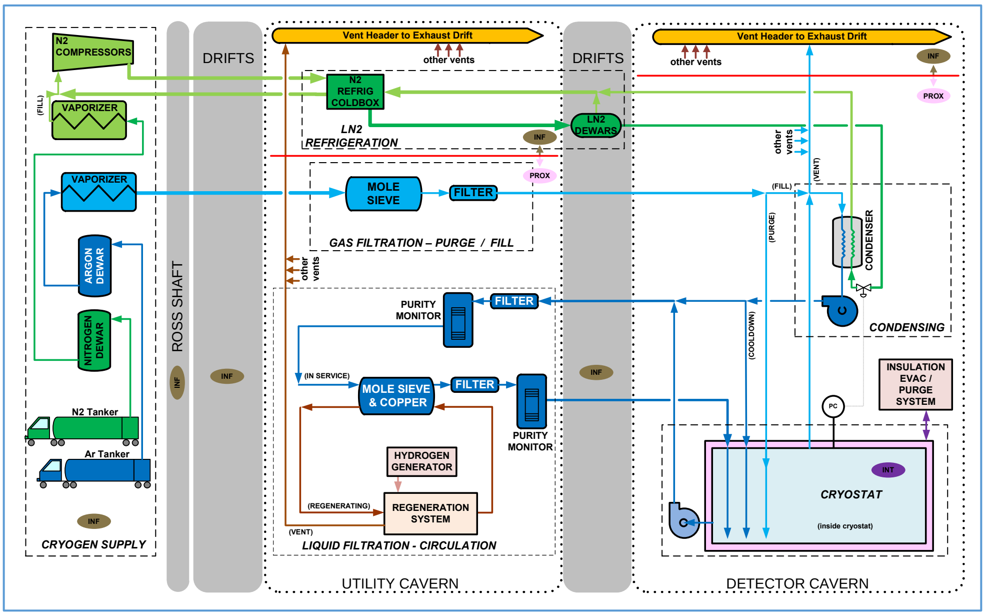


Figure 1: Process Flow Diagram

2.3. External/Infrastructure Cryogenics

2.3.1. Cryogens receiving facilities

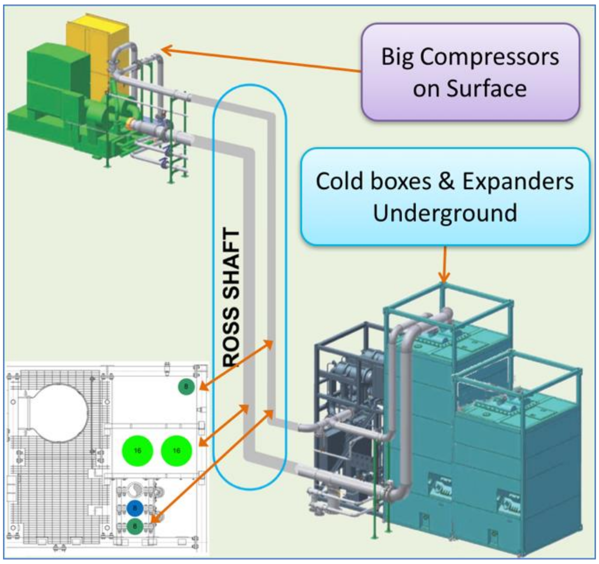
The cryogens receiving facilities are located on the surface, nearby the Ross Shaft. They consist of the offloading facilities for liquid argon and liquid nitrogen, the storage tanks, the vaporizers and the interconnecting pipes. We have chosen gaseous only delivery through the Ross shaft, mainly for safety reasons, but it is also a cost effective solution. Fig. 2 shows the current layout with the storage tanks and the vaporizers.

Figure 2: Layout of surface facilities

2.3.2. Liquid nitrogen refrigeration system

The liquid nitrogen refrigeration system includes four commercial units with cold boxes and return gas boosters in the CUC and gaseous nitrogen compressors above ground, in the compressors building, nearby the Ross Shaft. There are three units for cryostats 1 and 2 and a fourth unit is added for cryostats 3 and 4. During normal operations each cryostat has its own refrigeration unit; after achieving the required argon purity, only three units are needed to recondense the boil-off gaseous argon and a full unit is also available as spare to perform the recurrent maintenance. That is due to the reduction in the number of pumps needed to circulate the liquid argon. Each refrigeration unit as a nominal cooling power of 100 kW, enough to recondense the boil-off gaseous argon during normal operations, with some operational margin, and condense the gaseous argon during the cool-down and fill processes. Fig. 3 shows the layout of the system with actual-size components from one of the potential vendors that fit the available space and the modularity needed for the transportation in the shaft.

Figure 3. Layout of the liquid nitrogen refrigeration system



2.4. Proximity Cryogenics

2.4.1 Argon purification system

The argon purification system is composed of filters containing mol sieve and copper pellets to chemically adsorb water and oxygen respectively from gaseous and liquid argon, their regeneration equipment and particulate filters. Each cryostat has a dedicated set of liquid filters, regeneration equipment and particulate filters, while the gaseous argon filters are common for cryostats 1-2 and 3-4, since they are needed only during the purge phase. The liquid filters are used during the fill and during normal operations, once the cryostat is full, to achieve and maintain the required purity of 100 ppt. All filters are sized to accept and purify argon with the following initial contaminants: 5 ppm oxygen, 10 ppm water, 10 ppm nitrogen. To guarantee continuous operations, each cryostat has one set of liquid filters in operation and another set in regeneration. Once the first set saturates, it is regenerated and the regenerated set is put in operation. The regeneration is done with a hot (200-220 C) mix of few percentages hydrogen in argon.

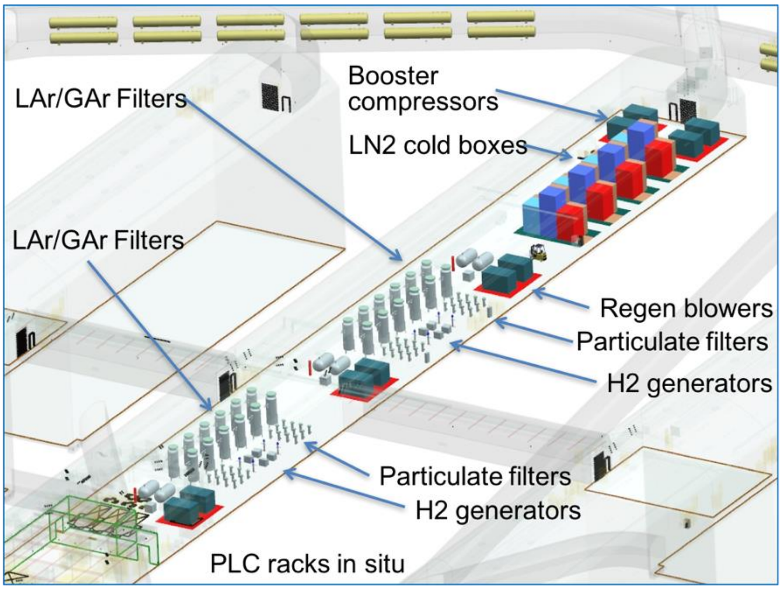


Figure 4. Layout of the cryogenics in the Central Utility Cavern

2.4.2 Proximity cryogenics in detector cavern

Each cryostat is equipped with a mezzanine level about 2.3 m over the roof. It spans almost half of the width and more than half of the length of the cryostat. All the pipes and equipment that connect to the cryostat are located here. The purified liquid argon from the CUC is returned to the cryostat through phase separators. The boil-off gaseous argon is re-condensed in condensers and sent to the liquid filtration system for purification through dedicated liquid pumps. The liquid nitrogen from the CUC passes through phase separators and provides the cooling power inside the heat exchangers of the condensers. The cryostat pressure and vacuum safety valves are also located here and their discharge lines collected into the main vent header.

At the opposite end of the cryostat are the liquid argon pumps to circulate the bulk of the argon. Argon is withdrawn through four side penetrations and sent to the liquid filtration system for continuous purification. Inline safety valves with the seal inside the cryostat are located on the side ports. They are normally closed and will shut close in case of emergency or another trigger event.

Fig. 5 shows the mezzanine area on the left and the liquid argon pumps area on the right.

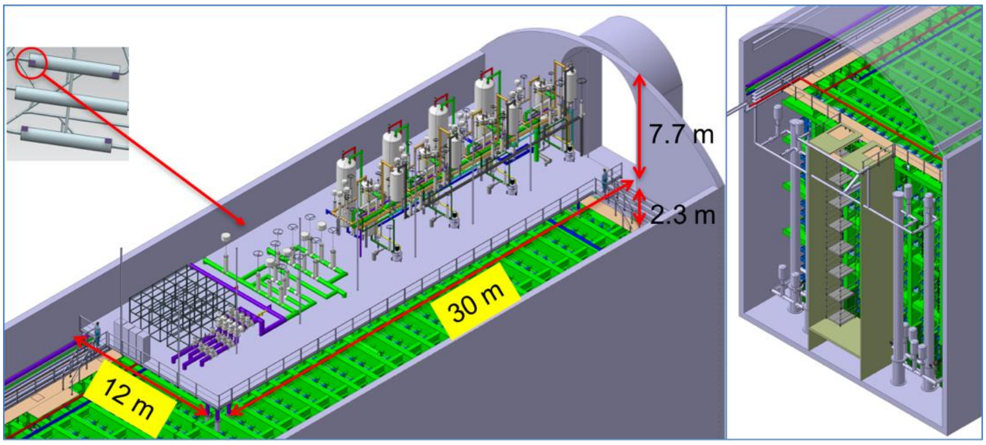


Figure 5. Proximity cryogenics in the detector cavern (mezzanine on the left and LAr pumps on the right)

2.5. Internal Cryogenics

The internal cryogenics distributes the liquid and gaseous argon inside the cryostat during all phases. It consists of several manifolds (e.g. gaseous purge, liquid distribution, cool down) and pipe stands to connect the inside to the outside (e.g. boil-off gaseous argon). The cryostat has passive polyurethane insulation. Vacuum insulated pipe stands are needed to transition from inside to outside in a way that does not affect the purity and does not introduce a significant heat load.

3. SUMMARY AND FUTURE STEPS

This paper presented the main features of the LBNF/DUNE cryogenics systems as currently designed. Through a consultant we have engaged with the potential liquid argon suppliers to understand the supply chain and economics of such a large procurement. We are preparing a Functional Requirements Specifications for the liquid nitrogen refrigeration system with the goal to award a contract for design and fabrication in mid 2018. We continue with the design of the proximity cryogenics in the detector cavern to inform the cryostat design.

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