Design of the DUNE APATF cryogenic system

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Abstract. Fermi National Accelerator Laboratory (FNAL) is developing the international Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) to advance neutrino science. The flagship of the DUNE project consists of a large particle detector constructed one-mile (1.6 km) beneath the surface at the Sanford Underground Research Facility (SURF) in Lead, SD. The SURF detector is the largest of its type ever built and is comprised of four cryostats totaling 70,000 tons of liquid argon (LAr) to record neutrino interactions with unprecedented precision. Each cryostat houses a detector, the first includes 150 Anode Panel Assemblies (APA) submersed within 17,500 tons of LAr. Before installing 150 APA within the SURF detector they will be cryogenically cooled to nominally 90 K at the APA Test Facility (APATF) utilizing nitrogen flows. The APATF cryogenic system is entirely located one-mile underground at the SURF facility and includes nominally 13 kW of refrigeration at 80 K, cryogenic transfer lines, APA test cryostats, a cryogenic control system, and various control and pressure safety elements to ensure performance and safety requirements are achieved. The APATF preliminary design is in progress and major considerations include an efficient, cost-effective mechanism to deliver the required refrigeration to the APATF underground, support of rigid testing intervals to support the DUNE operating schedule, temperature stability of the APA and electronics within cryostats, efficient cryogenic system operation to minimize heat leak and/or liquid nitrogen consumption, thermo-mechanical stability and flexibility of components, and pressure safety of the APATF cryogenic system. Installation and integration of the APATF cryogenic system within the footprint and to adjacent sub-systems is also discussed.

1. Introduction
The Deep Underground Neutrino Experiment (DUNE) Anode Panel Assembly Test Facility (APATF) cryogenic system is in preliminary design for development of facilities and infrastructure capable of testing a total of 150 APAs in pairs of two for 75 total tests of dual APAs. Current plans include 3 APATF coldboxes with each coldbox supporting 25 tests of dual-connected APA pairs to maintain the DUNE project and Detector installation on schedule. It is estimated that each APA coldbox test has a 4 day (96 hour) thermal cycle and the turnaround time between tests is such that all 75 pairs are tested within approximately a 1-year time span, with cryogenic APATF operations beginning in early 2026 [1].
2. Cryogenic System Scope

The primary scope of the DUNE APATF cryogenic system includes the design and development of a source of underground refrigeration capable of supporting up to 13 kW at 80 K and the control and distribution of refrigeration from the source to the coldbox test load [2]. Most notably the design of the three test coldboxes are outside of the scope of the cryogenic system (and also this paper) but careful iteration between cryogenic system and coldbox design is essential since they share several mechanical and electrical interfaces and both systems come together to form an integrated cryogenic test stand. Additional cryogenic system scope includes the pressure safety and stability of the overall cryogenic system, including the coldboxes, and the development of commissioning, testing, and management plans for the APATF cryogenic operations. The scope of this paper is principally focused on the design and development of the underground cryogenic system for supporting low temperature operation of the APATF coldboxes.

3. Cryogenic System Process Design

The APATF cryogenic system utilizes several key components to provide sufficient refrigeration in the underground DUNE cavern for each APA test which are identified and described in this paragraph. A simplified process schematic of the DUNE APATF cryogenic system is presented in figure 1.

The APATF cryogenic system is designed to support a variety of operating modes, but conceptually the overall cryogenic system can be broken down in three basic sub-systems [1]:

1. The supply side cryogenics to the APATF coldboxes supply nitrogen flows to support the various operating modes. These include liquid nitrogen (LN2) flows used for cooldown and cold testing of the APAs, and N2 vapor flows used for purging and warmup of the APAs. The supply side cryogenics are ‘upstream’ of the coldboxes.
2. The APATF cold boxes house the APAs during testing and provide the majority of the system thermal loads.
3. The exhaust side of the cryogenic system is where spent N2 vents from the coldboxes to the DUNE cryogenic exhaust header or into the DUNE cavern itself. The exhaust side cryogenics are ‘downstream’ of the coldboxes.

3.1. Liquid nitrogen storage vessel

The source of all nitrogen (both liquid and gas) used in the APATF cryogenic system and coldboxes is a 11000 L LN2 storage vessel. The LN2 storage vessel operates nominally at 2 bara with a 6.9 bara design pressure.

3.2. Refrigeration and transport of LN2

Provisions are in preliminary discussions and estimation for a mechanical nitrogen liquefier to provide up to 13 kW of refrigeration at 80 K to the APATF cryogenic system to support the peak required cryogenic load for three coldboxes of up to 2975 kg LN2 per test or at peak operation with three coldboxes running approximately 4150 L/day, including design margin of 50%. As contingency for this mechanical liquefier, preparations are being investigated to allow the transport of LN2 via portable dewar(s) on the elevator cage. It is confirmed that a transport dewar with 2000 L of saturated LN2 will fit on the elevator cage and not exceed the weight limit. The total roundtrip time to fill, withdraw, and refill the 2000 L transport dewar is 7 hours, or approximately three refills per day which provides between 4500 – 6000 L of saturated LN2 per day depending on thermal efficiency and vapor flashing of nitrogen during transport and withdrawal [2].
Figure 1. Preliminary Process Schematic of the APATF Cryogenic System [3].
3.3. Heaters
There are multiple electrical heaters planned for installation in the APATF cryogenic system which principally serve one of two purposes. Heaters on the supply side of the cryogenic system vaporize LN2 to create nitrogen gas for purging coldboxes and assisting with warmup, while heaters on the exhaust side of the cryogenic system warm vent flows to room temperature to prevent icing and condensation on downstream piping.

3.4. Cryogenic supply lines
The cryogenic supply piping brings flows to each coldbox to support the range of operating flows and modes required per thermal cycle of dual APAs tested. There are two supply lines to each coldbox: one for supplying LN2 and another for supplying N2 vapor. The LN2 supply line flows saturated LN2 into the coldbox through small orifice diameter nozzles at the top each coldbox to take advantage of buoyant forces to help circulate fluid flow throughout the APAs. The LN2 nozzles are designed to atomize the LN2 to maximize the heat rejection from APAs by utilizing the heat of vaporization of the atomized LN2 and reducing overall supply mass flow rates. The N2 vapor supply line flows N2 vapor heated by a 15 kW electrical heater on the discharge from the 11000 L LN2 storage vessel and injects the warm gas into the bottom of each coldbox to take advantage of buoyant forces to help generate a piston-type purge of the coldbox to remove moisture contamination prior to cooldown [2].

3.5. Cryogenic exhaust lines
The cryogenic vent piping exhausts N2 flows from the coldboxes to the DUNE detector cryogenic exhaust header to safely and effectively remove a potential oxygen deficiency hazard from the cavern cleanroom and Detector hall. The vent lines are sized to maintain a total pressure drop ≤ 20% of relief set pressure (100 mbarg set pressure) to prevent accidental venting of coldbox flows into the Detector hall. Each coldbox vent pipe includes double isolation valves to allow for Lock Out Tag Out (LOTO) of the coldbox, a 10 kW heater to warm the venting flows to ambient temperature, a check valve to mitigate backflow contamination from other coldboxes in operation, and a dual range pitot tube flow meter to monitor venting flows from the coldbox at ambient temperature during steady state operations to calibrate and monitor the LN2 consumption of each coldbox during APA testing [4].

4. Cryogenic System Operating Modes
Each APATF coldbox provides cryogenic refrigeration to dual APAs being tested over a 96-hour thermal cycle test period. The primary operating modes and durations per APATF coldbox thermal cycle are summarized in table 1, without contingency or design margin applied.

| Operating Mode | Duration (hr) | Temperature (K) | Operating Medium | Fluid Load (g s⁻¹) | Test Load (W) | LN2 Consumed (kg) |
|----------------|--------------|-----------------|------------------|-------------------|--------------|------------------|
| Purge          | 4            | 295             | N2 vapor         | 16                | -            | 235              |
| Cooldown Cold  | 24           | 295 - 90°       | LN2, saturated   | 6 - 17            | -            | 1015             |
| Operations     | 48           | 90°             | LN2, saturated   | 9                 | -            | 1580             |
| Warmup         | 20           | 90° - 295       | Electric heater  | ≤ 2               | 6000         | 145              |

* Operating requirements for the APATF cryogenic system allow for temperature uniformity of +60 / -0 K.
4.1. Purge
Purge of each dual APA test spans up to a 4-hour duration, with one coldbox volume change per hour, and is the first operating mode in the APATF coldbox and initiates a test thermal cycle. Purge mode is designed for one coldbox volume change per hour for a total of 4 volume changes during purge. Purge mode utilizes warm N2 vaporized from the 11000 L LN2 storage vessel with a 15 kW heater to provide 16 g s\(^{-1}\) of warm vapor at 295 K per coldbox to reduce the residual moisture contamination within the coldbox prior to cooldown [5]. Approximately 235 kg of LN2 is consumed during a typical coldbox purge. Moisture contamination is specified to be no more than 5 ppm of water before cooldown is initiated, and a plot of calculated moisture contamination is presented in figure 2.

![Figure 2. Calculated Water Contamination vs. Purge Duration and Coldbox Volume Changes at Various Elevations within the Coldbox [5].](image)

4.2. Cooldown
The next sequence in a coldbox thermal cycle following purge is cooldown which spans a duration of 24 hours from 295 K to 90 K with a temperature uniformity requirement of ± 60 / - 0 K [1]. Cooldown is accomplished by supplying LN2 from the LN2 storage vessel to liquid spray nozzle locations at the top of each coldbox with symmetry about the APA center axis to utilize buoyant forces within the coldbox to help circulate cooling flow.

To ensure effective liquid quality at the sprayer nozzles, a cooldown bypass valve is installed in each coldbox which bypasses saturated LN2 along the entire length of the liquid spray pipe and before flowing out of the coldbox vent line to be warmed up in the exhaust heater. The cooldown bypass valve helps to maintain sufficient liquid flow to the sprayer nozzles by helping to push more flow through the liquid spray pipe than the nozzles themselves could sustain due to the high impedance of the nozzles and allows more control over the temperature of the liquid spray pipe at the nozzles low enough temperature to ensure quality liquid at the nozzles.

The cooldown line also includes an integrated cold trap and liquid spray baffle which serves two unique purposes. The cold trap allows for residual moisture which is still present post-purge to freeze out on the cold trap since the cold trap represents the largest and coldest surface inside each coldbox. The cold trap also is designed to function as a physical barrier to inhibit any potential liquid droplets which are not converted to saturated vapor upon spraying to hit the back side of the cold trap and act as a baffle to prevent these potential liquid droplets to accumulate on the APA wires.
Cooldown mode utilizes a variable mass flow rate from 6 to 16 g s$^{-1}$ to help regulate temperature uniformity in the APAs which also minimizes LN2 consumption, compared to utilizing a fixed mass flow rate and approximately 1015 kg of LN2 is consumed from the cryogenic system LN2 storage vessel during a typical dual APA cooldown [2]. A plot of the estimated mass flow of saturated LN2 to the coldbox during cooldown is presented in figure 3.

![Plot of estimated mass flow of saturated LN2 to the coldbox during cooldown](image)

**Figure 3.** APATF Cooldown Mass Flow Rate to each Coldbox Test (a) vs. Time (left) and (b) vs. Coldbox Fluid Temperature (right) [5].

### 4.3. Cold testing

Following cooldown for each dual APA coldbox test to 90 K, within ± 60 K of temperature uniformity, the APATF proceeds to cold testing mode which span a duration up to 48 hours to test various electronics and APA performance at low temperature. Note that while the DUNE Detector will operate the APAs at 90 K within a bath of liquid argon rather than cold nitrogen vapor, this operating mode represents the first opportunity to run diagnostics and test the APAs at their nominal design temperature before installation into the Detector. A computational fluid dynamic (CFD) model is developed to analyze the temperature uniformity of the dual APA during cold operations and is presented in the two left-most graphics within figure 4 [5].

Cold testing is achieved utilizing the same piping and control devices as cooldown including the liquid sprayers, at a reduced flow rate since there is only minor heat leak and the primary thermal load is 300 W of electronics included with the dual APAs. Cold testing represents a steady-state operation of the dual APAs where they are maintained at 90 K throughout the duration of the test and as a result the mass flow rate to each coldbox remains uniform throughout the duration at approximately 9 g s$^{-1}$ and typical LN2 consumption is 1580 kg per test.
Figure 4. CFD Model of APATF Cryogenic System Operations (from left to right): (a) Cold Testing of All Coldbox Surfaces and N2 Vapor, (b) Cold Testing of APA Frame and Electronics Only, (c) Warmup of All Coldbox Surfaces and N2 Vapor at Peak dT dt\(^{-1}\), (d) Warmup of APA Frame and Electronics Only at Peak dT dt\(^{-1}\) [5].

4.4. Warmup

Once cold testing of each dual APA is concluded the final operating mode for the APATF cryogenic system is warmup to ambient temperature from 90 K to 295 K, which spans a duration of 20 hr and is achieved by applying 3000 W of electrical heat and circulating warm N2 vapor inside each coldbox. The assumption is that ≤ 2 g s\(^{-1}\) of N2 vapor is required to maintain uniform warming with the addition of electrical heat so the typical consumption for warmup is estimated at 145 kg from the LN2 storage vessel as presented in table 1. A CFD model of the temperature uniformity of the dual APA during warmup at peak temperature gradient is presented in the two right-most graphics within figure 4 [5].

During the 20 hrs warmup mode, 18 hrs is allotted for actively warming the internal coldbox surfaces and components with 2 hrs at the end allotted as a buffer period to allow internal temperatures to equalize. To maintain the coldbox internal dewpoint about 282 K during the warmup the supply flow is overheated to 316 K during the 18 hrs of active warmup. The APATF coldbox temperature profile over the entire thermal cycle is presented in figure 5 (left).

Of the requirements imposed on the APATF cryogenic system is to maintain temperature uniformity inside the coldbox within 60 K at all times during testing. During cooldown the maximum temperature spatial gradient is ≤ 30 K and during warmup the maximum gradient is ≤ 50 K, as presented in figure 5 (right).
5. Summary
The DUNE APATF cryogenic system development is underway and requirements are well understood. The cryogenic system design is sufficiently mature to begin programmatic design reviews and become a part of the DUNE/LBNF project, incorporated into the project WBS. The DUNE APATF Cryogenic System is well positioned to satisfy all functional and technical requirements of APA testing and is on schedule to complete a preliminary design review in 2019 and begin operations in 2026.

6. References
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