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LBNF/DUNE Liquid Argon Roadmap

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Abstract. The Deep Underground Neutrino Experiment (DUNE) is an international flagship venture to unlock the mysteries of neutrinos. Hosted at the Sanford Underground Research Facility (SURF) and supported by the Long-Baseline Neutrino Facility (LBNF), DUNE relies on nearly 75,000 tonnes of ultrapure liquid argon (LAr) housed in state-of-the-art cryostats. Transporting such vast quantities of LAr to its destination a mile underground in Lead, SD, is a logistical and engineering challenge. The process begins with securing large quantities of liquid argon from suppliers located far from the site, with major sources situated near Houston, TX and Chicago, IL. The receiving facility, located atop a mountain with steep, often snow-covered access roads, provides limited maneuverability for trucks and can only handle two deliveries simultaneously. The facility serves as an entry point for argon to the greater LBNF cryogenic system. It is furnished with truck unloading stations, limited buffer storage of some 280 tonnes capacity, and vaporizers. The last are crucial for converting liquid argon into gas for transfer down the Ross Shaft, eliminating the need for cryogens in the vertical pipeline. These constraints, along with other operational factors, cap the delivery rate at 70 tonnes per day. Once underground, the argon is purified and recondensed before filling the cryostats. This roadmap outlines the integrated supply chain and cryogenic systems that enable the delivery of LAr to support DUNE's groundbreaking physics research.

1. Introduction

The Deep Underground Neutrino Experiment (DUNE), hosted by the Long-Baseline Neutrino Facility (LBNF), represents one of the most ambitious neutrino physics programs in the world. Its mission is to answer fundamental questions about the nature of matter and the evolution of the universe. Specifically, DUNE aims to uncover the origin of matter-antimatter asymmetry, determine the ordering of neutrino masses, search for signs of proton decay, and observe neutrinos produced by supernovae - potentially offering a window into the formation of neutron stars and black holes.

To achieve these goals, DUNE relies on massive liquid argon time projection chambers (LArTPCs) located 1,500 meters underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota (Figure 1). Liquid argon serves as both the interaction medium and detection target, offering high-precision tracking and calorimetry through ionization and scintillation signals.

However, deploying and operating LArTPCs at this scale requires solving an array of engineering, logistics, and project management challenges. These include securing large volumes of liquid argon, ensuring ultra-high purity, and transferring cryogenics down a mile deep shaft in a safe and stable way. This paper presents the end-to-end liquid argon handling strategy developed for LBNF/DUNE, from procurement and delivery to purification, recondensation, and cryostat fill. The roadmap is designed to enable high-performance neutrino detection while prioritizing operational safety, system robustness, and long-term maintainability.

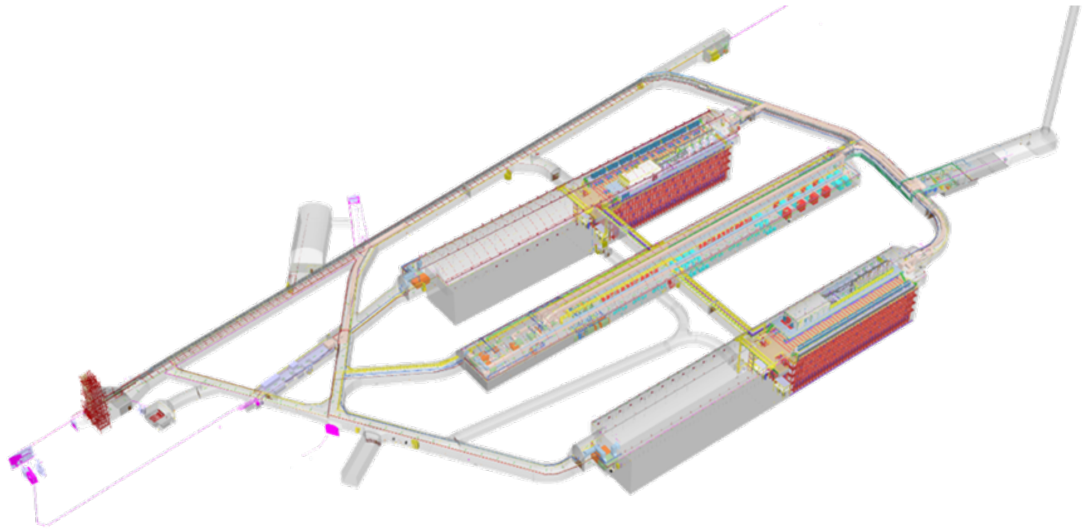

Figure 1. Underground LBNF complex.

2. Engineering Requirements and Challenges

The successful operation of DUNE relies on filling four large cryostats with approximately 75,000 metric tonnes of liquid argon. Beyond the volume required, the LBNF faces significant logistical challenges: the cryostats are located a mile underground in repurposed caverns of a former gold mine, while the facility itself sits atop a remote, often snow-covered mountain in South Dakota's Black Hills. Furthermore, the nearest liquid argon supply is over 1,000 miles away.

The LBNF houses four cryostats, each measuring approximately 66 meters by 19 meters by 18 meters (217 ft x 62 ft x 59 ft). Each cryostat holds 12,600 cubic meters of liquid argon at 87 K (18,600 tonnes) – equivalent to the volume of five Olympic swimming pools – and contains a modular neutrino detector.

Transporting such volume of liquid argon to the remote and elevated site introduces major logistical hurdles. The LBNF facility sits over 1,000 miles from the nearest large-scale argon production hubs, with no direct rail access and only limited road infrastructure. Access roads wind through mountainous terrain and include steep grades of up to 12%, which can complicate heavy tanker deliveries - especially during the long and severe winters common in the Black Hills. With only 280 tonnes of onsite argon storage, the system has little tolerance for delays, requiring highly reliable, high-frequency deliveries sustained over many months. Coordinating this effort

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across multiple suppliers and thousands of transport miles, while maintaining purity and minimizing losses, adds further complexity to an already high-stakes supply chain.

Finally, transferring liquid argon directly down the 1,500-meter shaft to the underground caverns poses serious engineering and safety challenges. The hydrostatic pressure from a liquid column of that height reaches approximately 20.6 MPa (around 3,000 psi), necessitating thick and robust piping capable of withstanding both static and dynamic stress. Any sudden pressure drop could result in flash boiling - causing violent vaporization and flow instability that would be difficult to control in such a confined, vertical geometry. Moreover, the liquid must remain cold and pressurized throughout the entire descent, demanding complex thermal management systems to prevent phase changes. These factors introduce high engineering risk, including thermal stress, oxygen deficiency hazards (ODH), and material fatigue over time. Given these challenges, maintaining cryogenic liquid conditions over such depth was deemed impractical, prompting a safer and more operationally flexible gas-phase transfer strategy.

3. From Source to Cryostat: Designing the Argon Delivery Pipeline

To meet the demanding cryogenic needs of the LBNF/DUNE far detectors, a comprehensive liquid argon delivery pipeline has been developed, spanning from commercial supply points to final cryostat fill nearly a mile underground. This end-to-end system is designed to ensure reliable, high-throughput delivery of ultra-pure argon while minimizing operational risk and complexity. Argon roadmap post delivery to the site can be followed in Figure 2.

3.1. Sourcing and Transport:

Bulk liquid argon is procured from commercial suppliers across the U.S., with supply chain planning coordinated to meet long-term delivery schedules. The argon is transported overland primarily by rail, leveraging high-capacity cryogenic tankers to reduce cost and delivery frequency. A key logistics node is the Argon Receiving Facility, located at the SURF site, which serves as the interface between overland supply and underground operations.

3.2. Argon Receiving Facility (Surface):

At the receiving facility, liquid argon is offloaded from tankers and vaporized in a controlled environment. This facility also handles staging, initial quality checks, and routing to the shaft transfer line. Vaporizing the liquid at this point enables a low-pressure, gas-phase transfer down the shaft, avoiding the hydrostatic and thermal hazards associated with transporting liquid over vertical distances.

3.3. Shaft Transfer (Gas Phase):

Argon gas is transferred down a dedicated vertical piping system into the underground cavern. This approach eliminates the need for pressurized liquid lines, significantly reducing system complexity and safety risk. The gas-phase transfer system is designed for low-pressure operation and includes safeguards against backflow, leaks, and contamination.

3.4. Underground Condensation and Purification:

Once underground, argon gas is recondensed into liquid using cryogenic refrigeration systems and passed through a multi-stage purification process. Achieving and maintaining ultra-high purity - below 100 ppt O_2 and 1 ppm N_2 - is essential for detector performance, specifically for ensuring long electron lifetimes and preserving scintillation light. Further design details and performance parameters of the underground purification systems are described in [1].

3.5. Cryostat Fill and Circulation:

Finally, purified liquid argon is transferred into the cryostats that house the DUNE time projection chambers. The cryogenic system supports steady-state operation with continuous recirculation and re-purification loops to maintain purity over the life of the experiment. The fill process marks the culmination of the cryogenic roadmap and is a key milestone before detector commissioning.

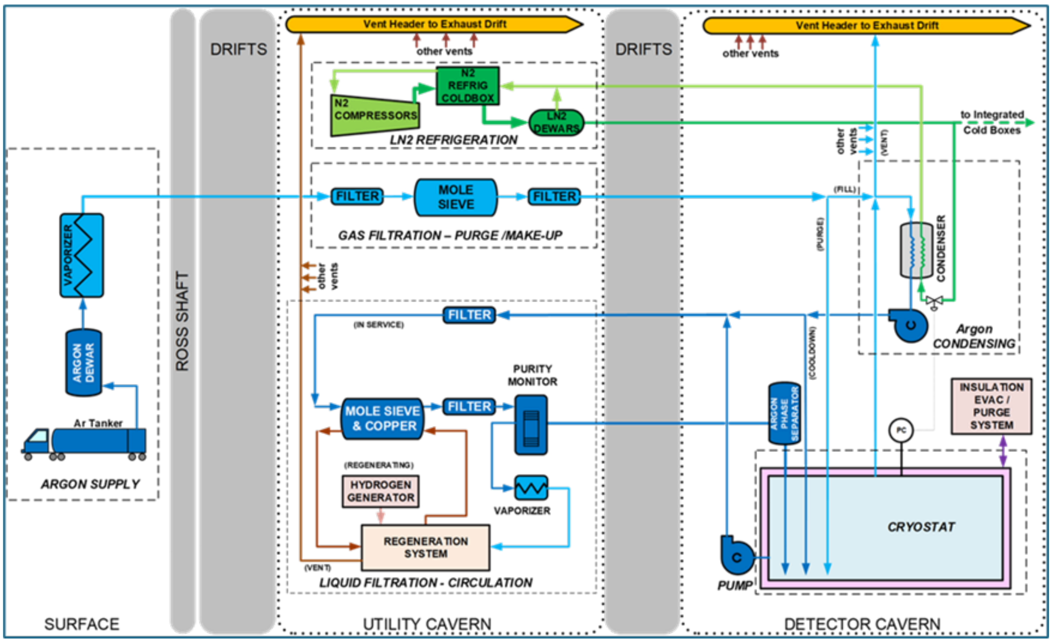

Figure 2. LBNF Process Flow Diagram showcasing the system for a single cryostat. Roadmap of Liquid Argon after being delivered to the Argon Receiving Facility can be followed in the picture. Starting from the surface receiving through Gar purification, recondensation, LAr purification to the cryostat.

4. Liquid Argon Supply Strategy for LBNF/DUNE

This section outlines the liquid argon sourcing strategy, defines the roles of key collaborators, and describes the approach to storage and delivery cadence - ensuring a robust supply chain capable of supporting the LBNF/DUNE.

The sourcing plan addresses the substantial volume required to fill four cryostats, each requiring approximately 18,600 tonnes of liquid argon to serve as both the interaction medium and detection target within the time projection chambers. To support detector filling operations, delivery must sustain rates of up to 70 tonnes per day, with each cryostat fill lasting between 8 and 18 months. The complete fill campaign is projected to span over five years. To meet these demands, a multi-supplier approach has been developed, leveraging the capacity of major U.S. industrial gas producers. A rail-based supply model was chosen for its scalability and cost-efficiency, sourcing primarily from the Houston and Chicago regions. This supply chain terminates at a transfill station in Upton, Wyoming, approximately 100 miles west of the detector site in Lead, South Dakota. From there, liquid argon is transferred to road tankers for the final leg, operated by drivers experienced in the local mountainous and often harsh environmental conditions.

Key collaborators are central to this strategy. John Campbell of J.R. Campbell & Associates, Inc. authored the 2021 LAr Procurement Supply Plan & Report, which included a comprehensive assessment of U.S. argon supply and demand dynamics, plant capacities, and transportation logistics. The firm engaged with stakeholders such as Tiger Transfer in Upton, WY, to evaluate transfill operations and advocate for a combined rail-road supply model supported by a centralized coordination and tracking system. The report also incorporated supplier responses to a 2021 request for information (RFI), synthesizing data from five major producers into a cohesive supply chain plan integrating railcars, tankers, and both on- and off-site storage strategies.

Storage and delivery cadence planning is shaped by the unique logistical challenges of the remote SURF site. Situated atop a mountain with limited road access and no direct rail line, on-site storage at LBNF is restricted to 280 tonnes - enough for less than four days of peak operation. The storage area is equipped with vaporization systems capable of transferring up to 70 tonnes per day down the 1,500-meter shaft to underground condensers. Due to the tight buffer, additional offsite inventory is critical. At the Upton transfill facility, 3 to 6 railcars (each with around 100 tonnes capacity) will serve as semi-permanent storage, providing 300 to 600 tonnes of reserve capacity to decouple supplier delivery from daily usage. The cadence plan involves dedicated railcars departing Houston on Mondays, Wednesdays, and Fridays via BNSF, completing a 30-day round-trip to Upton. There, the argon is offloaded into 20-tonne road tankers for the final 100-mile delivery to Lead, initially requiring 2 to 4 trips per day to meet fill demand, tapering to 40 - 50 tonnes per day in later phases. A parallel strategy is in development for deliveries originating from Chicago.

5. Argon Receiving Facility Design

The Argon Receiving Facility (ARF) serves as the critical interface between external liquid argon deliveries and the underground cryogenic infrastructure of the LBNF project. Located near the Ross Shaft Headframe at the SURF site in Lead, South Dakota, the ARF functions as the initial point of entry for all argon delivered to the experiment. Its core responsibilities include testing and verifying the purity of incoming shipments, accepting or rejecting deliveries based on specification compliance, and providing short-term storage and vaporization to support downstream gas-phase transfer operations.

The facility is designed to operate on a 24/7 basis during four planned cryostat fill cycles, each lasting 8 to 18 months, with approximately one year of downtime between cycles. Following completion of the fill campaign, operational demand at the ARF is expected to decrease substantially - limited to less than one day of activity per month for maintenance or contingency support.

A key design objective for the ARF is to maximize reliability and automation. The system is built for 99% availability, with high levels of automation in delivery handling and quality assurance. Every delivery is sampled, tested, and either accepted or rejected prior to offloading. Purity measurements are performed in a dedicated on-site purity shed, using instrumentation capable of detecting contaminants at levels below 10 ppm for water, 5 ppm for oxygen, and 1 ppm for nitrogen.

The facility (Figures 3 and 4) includes two cryogenic storage tanks with a combined total capacity of 200 m^3 (approximately 280 tonnes), of which 265 tonnes is effectively usable. At a maximum draw rate of 70 tonnes per day to support fill of a cryostat, the average available storage time under peak conditions is approximately 3.5 days. The tanks are rated for a maximum allowable working pressure (MAWP) of 18 barg, while the downstream process operates at a maximum of 3.45 barg. The system accommodates a wide temperature range - from ambient conditions (300 K) down to cryogenic levels (88 K) - to support both fill and vaporization operations.

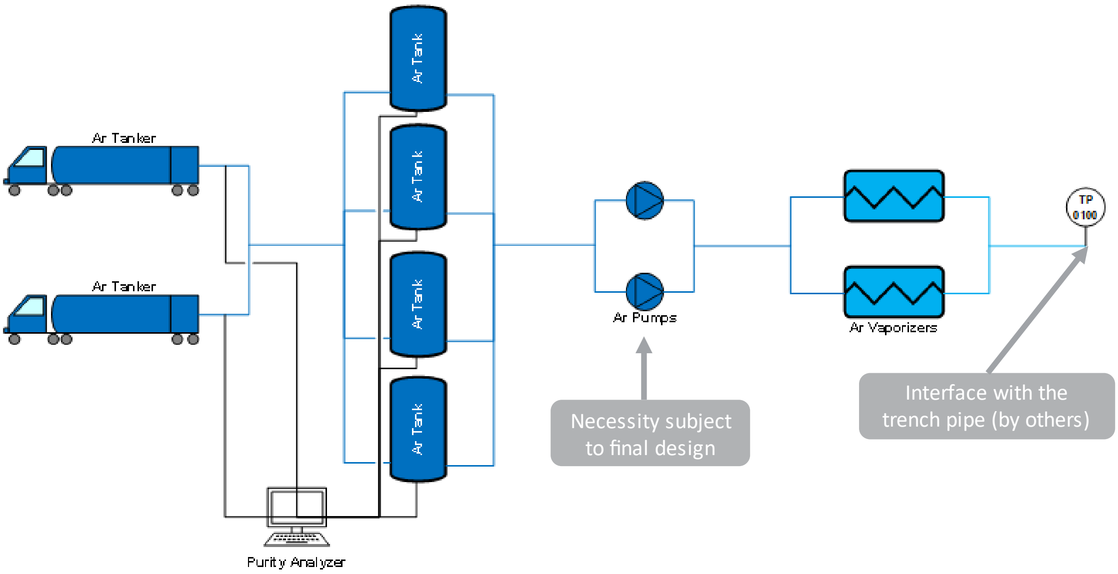

Figure 3. Argon Receiving Facility Process Flow Diagram.

Once accepted and stored, liquid argon is vaporized and transferred as gas through a dedicated pipeline down the Ross Shaft to the underground facility. This vapor-phase transfer eliminates the challenges associated with hydrostatic pressure and phase stability, enabling safer and more manageable delivery to the recondensation and purification systems underground. The conceptual 3D model of the Argon Receiving Facility is presented in Figure 4.

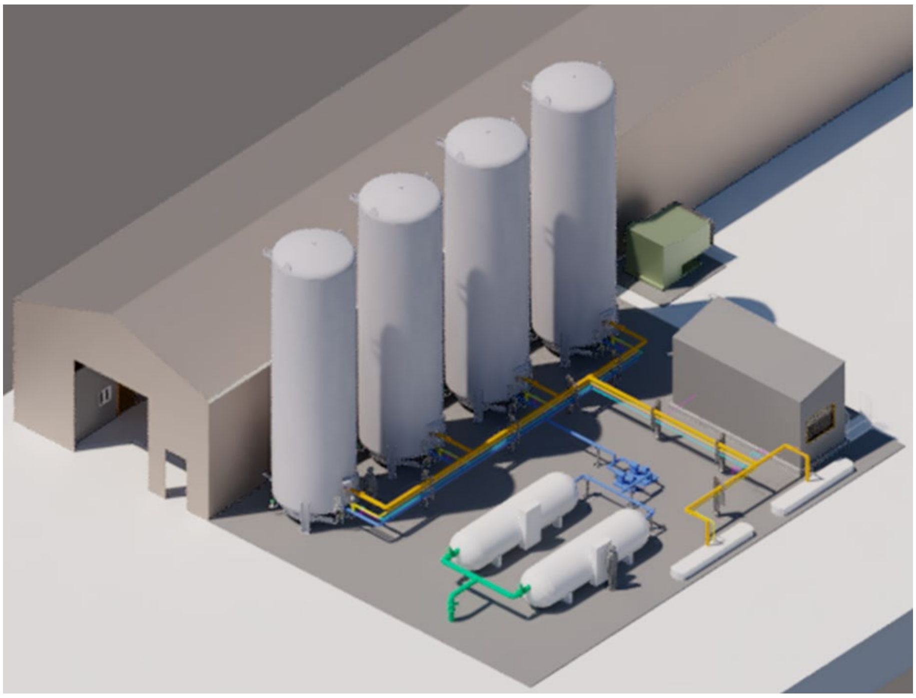

Figure 4. Conceptual design of the Argon Receiving Facility.

6. Underground Purification and Recondensation

After being transferred down the Ross Shaft as a gas, the argon is first purified to remove contaminants such as oxygen, water, and nitrogen to levels suitable for recondensation. The gas is then delivered to the Argon Condenser System, which cools and condenses it into a liquid. Following condensation, the liquid argon undergoes a second purification stage to reach the ultra-high purity required for detector performance. Specifically, electron lifetimes must exceed 3 ms for horizontal drift (<100 ppt O_2) and 6 ms for vertical drift (<50 ppt O_2), while nitrogen concentrations must remain below 1 ppm to preserve scintillation light. The detailed purification strategy, system design, and performance targets are described in [1]. The following section describes the Argon Condenser System and its role in enabling stable, high-purity liquid argon production underground.

The Argon Condenser System plays a central role in the underground cryogenic infrastructure by enabling the transition from purified gaseous argon to liquid argon suitable for final purification and cryostat delivery. The system condenses GAr using evaporative cooling of liquid nitrogen supplied by the underground refrigeration system. The condenser system ensures stable and efficient thermal exchange even at the high flow rates required during cryostat filling. Proven in prior smaller-scale neutrino detector projects—including ProtoDUNE and SBND—the design draws heavily on successful implementations developed by CERN, which is also responsible for the design of this system.

The system supports multiple operating modes, each aligned with a distinct operational phase of the experiment:

- Cryostat Cooldown/Fill: During initial cryostat commissioning, the condenser re-liquefies argon gas delivered from the surface through the gas-phase purification system. This enables a controlled cooldown and gradual filling of the cryostat with purified LAr.
- GAr Recovery: Once the cryostat is operational, some argon naturally evaporates. The condenser recaptures and re-liquefies this boil-off gas, minimizing losses and supporting closed-loop cryogenic operation.
- Desuperheater Mode: Incoming GAr is pre-cooled using LAr at the condenser inlet, reducing the thermal load on the condenser and improving liquefaction efficiency.
- Argon Phase Separator: This subsystem ensures that only fully condensed LAr is delivered to the cryostat, while directing any uncondensed GAr back to the condenser inlet for recondensation.
- Nitrogen Phase Separator: Liquid nitrogen from the refrigeration plant is routed through a separator to ensure that only LN_2 reaches the condenser. Gaseous nitrogen is redirected to a return manifold.
- GN_2 Return Manifold: All GN_2 streams from the condenser and separator systems are collected into a common return line, simplifying thermal management and pressure control within the nitrogen refrigeration loop.

While the final liquid purification step is performed downstream (via filters outside the condenser's scope), the Argon Condenser System regulates the flow and phase stability of the liquid argon delivered to both the purification skid and the cryostat itself. This multi-mode, modular design ensures high flexibility, efficiency, and redundancy throughout the full operational cycle - from cooldown to steady-state running.

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7. Cryostat Filling and Operational Readiness

The final step in the liquid argon delivery chain is the controlled filling of the cryostats with recondensed, ultra-pure liquid argon. This process marks a critical transition from cryogenic infrastructure commissioning to detector operation readiness.

For the horizontal drift detector modules, the filling process begins only after the cryostat has been uniformly cooled down to approximately 90 K. In contrast, the vertical drift modules are filled immediately following a gaseous argon purge, bypassing the dedicated cooldown phase. This procedural difference reflects the respective detector configurations and associated thermal constraints.

Each cryostat fill is expected to take between 8 and 18 months, depending primarily on the available refrigeration capacity. The filling is conducted through a manifold system installed at the base of each cryostat. These manifolds span the entire cryostat length and are fitted with a series of precision-calibrated orifices designed to ensure a uniform fill. This approach minimizes thermal gradients, reduces the risk of localized boiling or structural stress, and has been successfully validated in previous prototypes.

Once the cryostat is filled, the liquid argon is placed into continuous recirculation through the liquid argon purification systems. This recirculation loop is essential for maintaining the ultra-high purity levels required for physics operation, sustaining electron lifetimes exceeding 3–6 ms and preserving the integrity of scintillation signals throughout the lifetime of the experiment.

8. Conclusions and Outlook

The successful delivery of nearly 75,000 tonnes of ultra-pure liquid argon to the DUNE far detectors, located 1,500 meters underground at SURF, represents a significant cryogenic and logistical undertaking. The strategy developed by the LBNF/DUNE team addresses this challenge through a carefully engineered roadmap that integrates long-distance supply logistics, automated surface handling, low-risk gas-phase shaft transfer, dual-stage purification, and precision-controlled cryostat filling.

Key innovations—including the use of vapor-phase argon transfer to eliminate extreme hydrostatic pressure, the modular Argon Condenser System supporting multiple operating modes, and the validated fill manifolds designed for uniform thermal loading—demonstrate a mature reference design. These systems are now entering the execution and commissioning phases, with the first cryostat fill expected to span 8 months, and last 18 months depending on available refrigeration capacity.

Looking ahead, the focus will shift toward sustained operations and maintaining purity over the life of the detectors. This will involve continuous monitoring, recirculation, and optimization of purification performance to ensure compliance with the stringent electron lifetime and nitrogen contamination requirements that underpin DUNE's physics goals. The modularity and redundancy built into the system offer flexibility for future upgrades and will inform the design of next-generation detectors. As the cryogenic roadmap transitions from planning to practice, it will serve as a model for future large-scale liquid gas detectors in both particle physics and applied science domains.

9. References

[1] Doubnik R. et al. Ensuring High-Purity Liquid Argon for the LBNF FDC: Collaborative Cryogenics Research Between UNICAMP and FermilabC1Po3C-02, submitted to CEC/ICMC 2025.