The LBNE 35 Ton Prototype Cryostat

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Abstract—The 35 Ton Prototype Cryostat was built to demonstrate that a commercial membrane-cryostat technology could achieve the performance necessary for the operation of a large multi-kiloton liquid argon detector for the Long-Baseline Neutrino Experiment (LBNE). A concluded Phase 1 run has confirmed both the thermal stability and leak tightness of this technology that is necessary to achieve extremely pure liquid argon. Measured electron drift times in excess of 2.5 ms infer impurity concentrations in the liquid argon of less than 140 ppt (O$_2$ equivalent). These purity levels were attained and held for sustained periods. Details of the cryostat operation, measurements, and analysis of the Phase 1 run are given. A future Phase 2 run, that will include a reduced-scale LBNE-style Time Projection Chamber with integral photon detectors is briefly described.

I. INTRODUCTION

The Long Baseline Neutrino Experiment (LBNE) is planning to construct a multi-kiloton liquid argon (LAr) detector at the 4850 foot level of the Homestake Gold Mine in Lead, South Dakota. Due to the large size of the cryostat that will hold this detector, LBNE has decided to employ a stainless steel membrane-cryostat technology that has been developed by industry for use in liquefied natural gas (LNG) tanker ships and land-based storage tanks.

Fig. 1. Cutaway drawing of the 35 Ton Cryostat showing construction details with exterior and interior dimensions.

The 35 Ton Prototype Cryostat (35T) is a small demonstration project to show the suitability of the membrane technology for LAr detectors. In particular that it can achieve and hold the needed purity levels and provide a stable environment for the TPC. A cutaway drawing of the 35T is shown in Figure 1.

The LBNE Far Detector is a Liquid Argon (LAr) Time Projection Chamber (TPC) that incorporates photon detectors for timing. Charged particles create ionized tracks and scintillation light in the LAr. Under the influence of an applied electric field, the electrons drift towards an Anode Plane Assembly (APA). The APA has a series of induction and collection wire planes that measure the spatial coordinates normal to the drift direction. The third coordinate is provided by the drift time of the electron in the LAr volume. For the electric fields considered for this detector (500 V/cm), the electron drift speed is 1.2 mm/µs. The starting time of the drift is provided by the photon detectors detection of the scintillation light.
The current LBNE Conceptual Design TPC has a drift distance of 3.45 m. If an electron attaches to an impurity molecule in the LAr during its drift, it is lost to detection since ion mobility is five orders of magnitude lower than the electron mobility. The TPC signal to noise requirement (9/1) for a minimum ionizing track at this distance sets the maximum level of electronegative impurities in the LAr to be less than 200 ppt ($O_2$ equivalent). At this purity level, approximately 20% of the electrons created at the 3.45 m drift distance would survive to reach the APA.

Table I gives the details of the construction materials and the dimensions for the 35T. More information can be found in [2].

### III. 35T INSTRUMENTATION

The 35T includes a full complement of standard commercial transducers and sensors that are used to monitor and control the cryogenic environment. They include temperature sensors, pressure transducers (absolute and gauge), flow meters, and level sensors. These devices are typically readout directly into the Control System and data logged.

A number of commercial gas analyzers are available that can measure trace impurity levels ($O_2$, $H_2O$, and $N_2$) in the argon. Some have sensitivities at the 100 ppt level. A gas distribution switchyard feeding the gas analyzers allows the sampling points in the 35T to be reconfigured.

There were also two purpose-built pieces of instrumentation for the monitoring of the high purity environment needed for a LAr detector. They are the purity monitors (PrMs) and the RTD Spoolers. The PrMs are used to measure electron lifetimes in the LAr, and the RTD Spooler is used to make precision measurements of the temperature profile of the cryostat as a function of depth. These instruments were originally constructed for the LAPD run and are described in depth in [1].

#### A. PrMs

The PrMs used in the 35 Ton run were developed at FNAL from designs that originated from ICARUS [3]. A total of five PrMs were used, four inside the cryostat, and one (the “inline”) inserted in a vessel just downstream from the LAr Purification

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**Table I. 35T Details and Dimensions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat Volume</td>
<td>29.16 m³</td>
</tr>
<tr>
<td>Liquid Argon total mass</td>
<td>38.6 metric tons</td>
</tr>
<tr>
<td>Inner dimensions</td>
<td>4.0 m (L) x 2.7 m (W) x 2.7 m (H)</td>
</tr>
<tr>
<td>Membrane</td>
<td>2.0 mm thick corrugated 304 SS</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.4 m polyurethane foam</td>
</tr>
<tr>
<td>Secondary barrier system</td>
<td>0.1 mm thick fiberglass</td>
</tr>
<tr>
<td>Vapor barrier</td>
<td>1.2 mm thick carbon steel</td>
</tr>
<tr>
<td>Steel reinforced concrete</td>
<td>0.3 m thick layer</td>
</tr>
</tbody>
</table>

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Fig. 3. Drawing of a short Purity Monitor. The drift distance (grid to grid) is 16 cm.
Filters system. This “inline” PrM sampled the LAr as it directly exited the Purification Filters.

The five PrMs are basically identical save for one feature, the length between the two grid planes. Two PrMs are “short” (16 cm drift from grid to grid) and three are “long” (47 cm drift from grid to grid). The “inline” is a long PrM. The four PrMs located inside the cryostat were attached to two support rods suspended under plate B of the cryostat. Each support rod held one long and one short PrM.

A drawing of a short PrM is shown in Fig. 3. Electrons are extracted from a Gold plated cathode (“C”) by the light produced from a Xe flash lamp. The light is transported into the cryostat and to the cathode via quartz fiber optic cables. Only photons with energy greater than 5.1 eV (< 250 nm) are energetic enough to extract an electron from the gold surface.

Under the influence of an applied electric field, the cloud of extracted electrons drifts towards the cathode grid (Cg), 1.78 cm away. During this period of drift, a current flows from C. The integral of this current is used to make the cathode signal, Qc in the PrM electronics. The current stops when the cloud passes through the Cg. The cloud continues to drift towards the anode grid (Ag), again due to an electric field between Cg and Ag. When the cloud passes through Ag, a current begins to flow in the anode (A). A is located 0.79 cm from Ag. The integral of the anode current is Qa.

If an electron attaches to an impurity, the new ion velocity is effectively zero compared to the electron mobility, so the current from that electron terminates. The lifetime measurement is comparing the charge, Qa arriving at the anode, to Qc that left the cathode. An electron lifetime τ is derived from the Qa and Qc using

\[ Q_a = Q_c e^{-t_{drift}/\tau}, \]

or

\[ \tau = \frac{t_{drift}}{\ln(Q_a/Q_c)}. \]

“t_{drift}” is the drift time between the grids, which is dependent on both the drift distance and the drift field. The derivation for τ is shown to explicitly point out the limits of the PrM lifetime calculation when \( Q_a/Q_c \rightarrow 1 \). The relationship between lifetime in milliseconds to the purity (in ppt of O₂ equivalents) is purity(ppt) = 300/τ(ms).

Generally short PrMs are useful to measure lifetimes of 100 μs to 4 ms since that lifetime is on the order of their drift time (300-600 μs). Conversely long PrMs are better matches for higher purity due their longer drift time (> 1ms).

A discussion of the PrM measurement systematics can be found in [1]. In this 35T run, these systematics were on the order of 3-4% in the ratio of \( Q_a/Q_c \).

Fig. 4. Photo of cryostat interior under Plate B showing RTD Spooler and the bottom short PrM. Also shown one of the two submersible LAr Pumps, the pump intake and the Condensate return line.

B. RTD Spooler

The RTD Spooler was designed to give precision measurements of the vertical temperature profile of the cryostat. Three Platinum RTDs (Resistive Temperature Detectors) are positioned at 23 cm intervals on a printed circuit board (pcb) that is
vertically suspended on a stainless steel chain. A stepper-motor drives the chain moving the pcb up or down in fixed steps in the cryostat. At each position measurements of the three RTDs are made.

A typical scan done during the Phase 1 run had sixty-four 3.2 cm steps for a total scan distance of 203 cm. Including the 46 cm separation between the top and bottom RTDs on the pcb, the total sampled height was 249 cm.

The LAr surface was 44.5 cm below the uppermost RTD position. This upper position was 27 cm below the lowest radiation baffles under Plate B (see Fig. 5).

The object of the RTD Spooler is to precisely measure the shape of the vertical temperature profile in the cryostat. The accuracy of the absolute temperature calibration of the RTD is not vital since it affects all the measurements in the scan but not the shape of the profile. The only caveat with this technique is that the cryostat temperature cannot have materially changed in the time it takes for the scan to occur. This issue will be brought up during the discussion of the measurement results.

IV. 35T OPERATIONS

In order to purify LAr, it is necessary to do three things: 1) remove the air from the cryostat, leaving only Ar gas, 2) clean the liquid Ar as it comes from the supplier, and 3) remove any impurities that are generated by materials outgassing within the cryostat.

LAPD has demonstrated that it is not necessary to evacuate a cryostat in order achieve LAr purity levels sufficient for LBNE. This is of paramount importance since the costs of multi-kiloton cryostats that could withstand evacuation is prohibitive. The 35T followed the procedure LAPD [1] established to obtain and maintain pure LAr.

A. Gas Phase

![Gas phase of removing impurities in the 35T. These quantities are being measured by various gas analyzers. The first stage of the purification is the “Piston Purge”. The second stage is “Recirculation with Filtering”. The gap between the two steps was due to troubleshooting a leak.](image)

Fig. 6. Gas phase of removing impurities in the 35T. These quantities are being measured by various gas analyzers. The first stage of the purification is the “Piston Purge”. The second stage is “Recirculation with Filtering”. The gap between the two steps was due to troubleshooting a leak.

The initial state of the 35T was that “dry” air had been purging the cryostat for approximately three weeks. The initial start values for oxygen, water, and nitrogen reflect this state.

The air in the cryostat is removed by a process called the “Piston Purge”. Argon gas is flooded into the bottom of the cryostat. As argon is heavier than air, the argon layer rises analogous to a mechanical piston, pushing the air up and out of the cryostat. This gas is vented to the outside atmosphere. The venting stage continues for 32 hours, approximately the equivalent of 12 volume changes.

At this point the exiting gas is re-routed to circulate through the filtration system which removes O₂ and H₂O. N₂ is not materially removed by the filters. Any leaks to the outside atmosphere can be detected during this step. As shown in the
Fig. 6, a leak was found and mitigated (the “Debugging” gap in the plot). Once leaks have been eliminated the recirculation continues until the O<sub>2</sub> level drops into the sub-ppm level. As can be seen in the plot, the H<sub>2</sub>O level plateaus at a much higher level than O<sub>2</sub>. This is due to the outgassing of materials inside the 35T, including the cryostat walls, which are at room temperature during the recirculation step.

**B. Cooldown & LAr filling**

We have adopted a gas/liquid spray method to cooldown the cryostat. This generates a turbulent mixing of cold gas in the cryostat and cools the entire surface. The cooldown rate was limited to be less than the maximum rate specified by the membrane cryostat manufacturer. The cooldown, as well as the initial filling is shown in Fig. 7. The temperature measurements (red traces) in this plot were made by RTDs that are glued to the membrane walls of the cryostat. The black dashed trace is the manufacturer specification for the cooldown rate.

Once the cool down was finished, the LAr transfer into the cryostat began. In the case of the 35T phase 1 run, the LAr came from LAPD, where it had been used by that system in its own recently completed second run [1].

LAPD contained about 30 tons of LAr, of which only 25 tons could be transferred to the 35T (~70% of the total possible 35T LAr volume). It was decided that we would begin the initial commissioning of the Phase 1 run with this level since several components of the 35 Ton could be commissioned with the partial LAr fill. After running with this partial fill for approximately eighteen days, additional LAr was added to bring the capacity to 100%.

**C. LAr Purification**

The Fermilab Material Test Stand (MTS) [4] has shown that contaminants released inside LAr filled cryostats are from materials outgassing in the warm ullage regions above the LAr surface. Typical detector materials located in the LAr have negligible impact of LAr purity levels.

Fig. 5 depicts how impurities generated by outgassing materials in the relatively warm ullage under Plate B are swept up by the normal Ar boil-off in the 35T. This impure vapor is condensed in the LN<sub>2</sub>-cooled LAr condensor. The impure condensate is returned to the 35T just inside the intake manifold of the interior submersible LAr pump. From there it is pumped to the filtration system where the impurities are removed.

![Fig. 7. Cooldown and filling the 35T. The measurements (red trace) are made from RTDs affixed to the cryostat walls. The black dashed curve is the manufacturer’s maximum allowed cooldown rate. The filling (blue trace) was from the transfer of LAr from LAPD. This quantity of LAr is less than the capacity of the 35T. The RTD traces drop to the LAr temperature when the level of the LAr covers reaches their mounting height.](image)

Of interest, the electron lifetime of the LAr exiting the filters, as measured by the inline PrM was always > 30 ms (purity ~ 10 ppt O<sub>2</sub> equivalent). This indicates that the filters are very efficient at removing all trace amounts of O<sub>2</sub> and H<sub>2</sub>O. This was true for the entire 35T phase 1 run, including the filling periods.

Fig. 8 shows the electron lifetime from the start of the LAr Pump operation until the Phase 1 run ended. In general the electron lifetime improved as a function of pump on-time, but there were several incidents that spoiled the lifetime. These will be discussed in the next section.

**V. STABILITY OF OPERATION**

The goals of the 35T Phase 1 run include not only achieving the required purity/lifetime levels, but to also hold those levels and provide a stable operation of the cryostat. The 35T Phase 1 run was a relatively short ~2 months of LAr running. We achieved electron lifetimes in the 2-3 ms range as can be seen in Fig. 8.
However the electron lifetimes were severely impacted whenever we would switch from one LAr pump to another. The drops in purity coincided with the turn on of the second pump (see annotations in Fig. 8). We believe the issue was with the procedure we used to start the pumps and plan to modify it for future operations in the 35T Phase 2 run.

A second stability question is keeping the temperature stable in the cryostat. Currently the 35T controls system regulates the gauge pressure of the cryostat, keeping the internal pressure to 6.69(02) kPa above ambient atmospheric pressure. However this leaves the thermodynamics of the LAr sensitive to normal atmospheric pressure changes.

Figure 9 is a plot over a nine day period of the Cryostat absolute pressure (blue trace), bulk LAr temperature (white dashed trace) and the normalized drift time of three PrMs, one short and long inside the cryostat, and the long inline PrM exterior to the cryostat. The temperature is taken from the RTD Spooler measurements by requiring that the RTDs be at least 15 cm below the LAr surface. The temperature curve lags the pressure changes (ΔP ~3.5 kPa over this period), due to the thermal inertial of the LAr. However the normalized drift time (= drift time/average drift time for this period) is directly correlated to the LAr temperature. The LAr temperature excursion range was ΔT ~0.3 °K. Fitting the normalized drift velocity (inverse of normalized drift time) gives the result

\[
\frac{\Delta \text{drift speed}}{\text{drift speed}} \cdot \Delta T = -0.022(001) \text{°K}.
\]

The electron drift velocities for these three PrMs varied from (0.3 to 0.4) mm/µs depending on the individual PrM’s drift field.

As described, The RTD Spooler was intended to give us a precision measurement of the vertical temperature profile. This measurement is a means of testing the Computational Fluid Dynamics Simulations [5] that are being made on the fluid motion in the cryostat. Experimentally measuring the actual motion does not appear to be feasible at this time. The CFD calculations are being used to understand whether there might be dead areas in the cryostat where impurities might collect. Fig. 10 (a and b) show the result of one RTD scan. This scan was taken from a period where the barometric pressure was relatively constant so that the temperature would remain constant during the scan. Since a scan takes up to 6 hours in one direction (up or down) and as can be seen in Fig. 9, pressure changes can impact the bulk temperature of the LAr. These profiles seen in Fig, 10 are in nominal agreement with the current CFD calculations [5].

VI. PHASE 2 RUN WITH PROTOTYPE DETECTOR.

We are planning a run in early 2015 that includes a functional prototype of the LBNE Conceptual Design Far Detector. This prototype includes many
of the design elements of the much larger Far Detector including 2048 channels of cold electronics with a digital readout, and functional photon detectors positioned within the APAs. The prototype will be installed under Plate A (see Fig. 1) since the cryo facilities will still be located under Plate B. Fig. 11 is a photograph of a trial assembly of this detector. This trial was done to convince ourselves that the detector could be successfully assembled in the 35T since the only access to the 35T interior is through the 76 cm (30”) access flange on Plate B. Currently this prototype detector has been disassembled and shipped to FNAL for installation in the 35T in early 2015.

VII. CONCLUSIONS

The 35T Phase 1 run has shown that the membrane cryostat technology has no innate difficulties with achieving the stated goals of the LBNE Conceptual Design Far Detector. Some of the 35T issues (e.g. loss of purity when pumps are switched) are most likely unique to the 35T. It also seems likely that in a future design, the pumps will be externally located, to avoid coupling acoustical vibrations into the Far Detector cryostat and to facilitate maintenance and repair.

A 35T Phase 2 run is prepared to start running in spring of 2015. This run will include a prototype detector. The Phase 1 run has helped us understand the cryogenic issues of the 35T and should enhance the probability of a successful Phase 2 run.

ACKNOWLEDGMENT

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REFERENCES