4.2. Cryostat, Cryogenics & Purification

4.2.1 Introduction

Two technical factors are critical in the design of the cryogenic systems for the MicroBooNE detector. The first is that a liquid argon TPC relies on the fact that ionization electrons can be drifted over distances of meters in liquid argon provided that the argon is free of electronegative contaminants to the 10's of parts per trillion (ppt). The second factor is that the electron drift-velocity is of the order of a meter per millisecond and depends on the argon temperature with dV/V ~ -3% dK. Since commercially available liquid argon has oxygen and water contamination at the part per million level, the first factor means that there has to be a powerful and effective purification facility to remove electronegative contaminants from the argon as supplied. Additionally, the whole cryogenic system has to meet cleanliness and vacuum requirements on all components, such as feedthroughs and valves, to avoid leakage of air. The second factor restricts the spread of the argon temperature within the cryostat to less than 1 K and limits the argon velocity to less than 1 meter per second. These constraints affect the design by limiting the allowable heat-leak.

The designs of the cryostat, cryogenics system, and purification system for MicroBooNE are intended to meet both the R&D and the scientific goals of the experiment. This chapter describes the conceptual design of these systems, as well as the alternatives considered., including alternatives under consideration.

4.2.2 The Recommended Design

4.2.2.1 MicroBooNE Cryostat

4.2.2.1.1 Vessel Construction

The cryostat is the vessel that contains the liquid argon and active detectors. It is a single walled vessel to be constructed from 304 stainless steel to the latest ASME Boiler Code requirements and stamped to indicate that it meets ASME code thus meeting the requirements of the Fermilab standards. The cryostat, shown in Fig. 4.2.1, is cylindrical in shape with an outer diameter of 152 inches (3.86 m) and has a wall thickness of 1 inch (2.54cm). This outside diameter is the maximum standard size for over the road transport and will require special planning for delivery to FNAL. The cryostat is capped at both ends with dished heads. The main body of the cryostat is 473 inches (12m); the dished heads are each approximately 28 inches (0.71 m). One end will be removable for detector installation and modification. The decision to attach it with welding or with a bolted flange will be made after evaluation of the expected opening frequency, sealing difficulty and costs.

The vessel is capable of being pumped to full vacuum. The safety reliefs will be set for 30 psig; in normal operation the vessel will be at a pressure of about 3 psig. It will contain ~4750 ft^3 (~135 m^3) of LAr, leaving a 9% ullage volume. The empty weight of the vessel is 73,700 pounds (33.4 metric tons), and the weight with detector and LAr is ~514,000 pounds (233 metric tons).

Penetrations into the cryostat for liquid and gaseous argon supply lines, argon purity monitors, safety relief valves, and instrumentation signal and high voltage cabling will be provided in the form of chimneys spaced along the top of the vessel; the high-voltage feed is an exception and will be brought in away from the top for convenience of connection to the TPC cathode. Since the chimneys are quite long and add to the overall size of the vessel as shipped, the present scheme is that the chimneys will be extended upon delivery to Fermilab. If necessary an ASME shop will be contracted to weld the extensions. The chimneys will be capped by the manufacturer to allow pressure testing at the manufacturer and to prevent contamination during shipping. Once at Fermilab the caps will be removed and extensions with flanges for the various signal and voltage feedthroughs will be butt welded to the chimney stubs to make the total extension of each chimney from the cryostat body 16 inches to accommodate the insulation. The vessel will then be tested to 1.1 times its maximum allowable working pressure as given by the setting of the safety relief valves. An alternate scheme would be to have a flange a short distance up the chimney to which an extension is attached at Fermilab. This scheme avoids the welding at the cost of an extra pair of flanges per chimney.

We have considered three schemes for supporting the cryostat. One is to hang the vessel, one is to support the vessel on steel cradles at each end, and the third is to use cradles made of high density foam which would act as the local insulation and have sufficient strength to support the vessel – the other techniques involve insulating around the support. We have found some promising materials [1] for this latter approach in which the cradles are each 36 inches long located about 11 ft from the ends and support the bottom of the cryostat 28 inches from the floor.

The cryostat will have mounting rails and brackets installed on the inside walls of the vessel for securing the TPC and photomultipliers. These will be installed at the manufacturer.

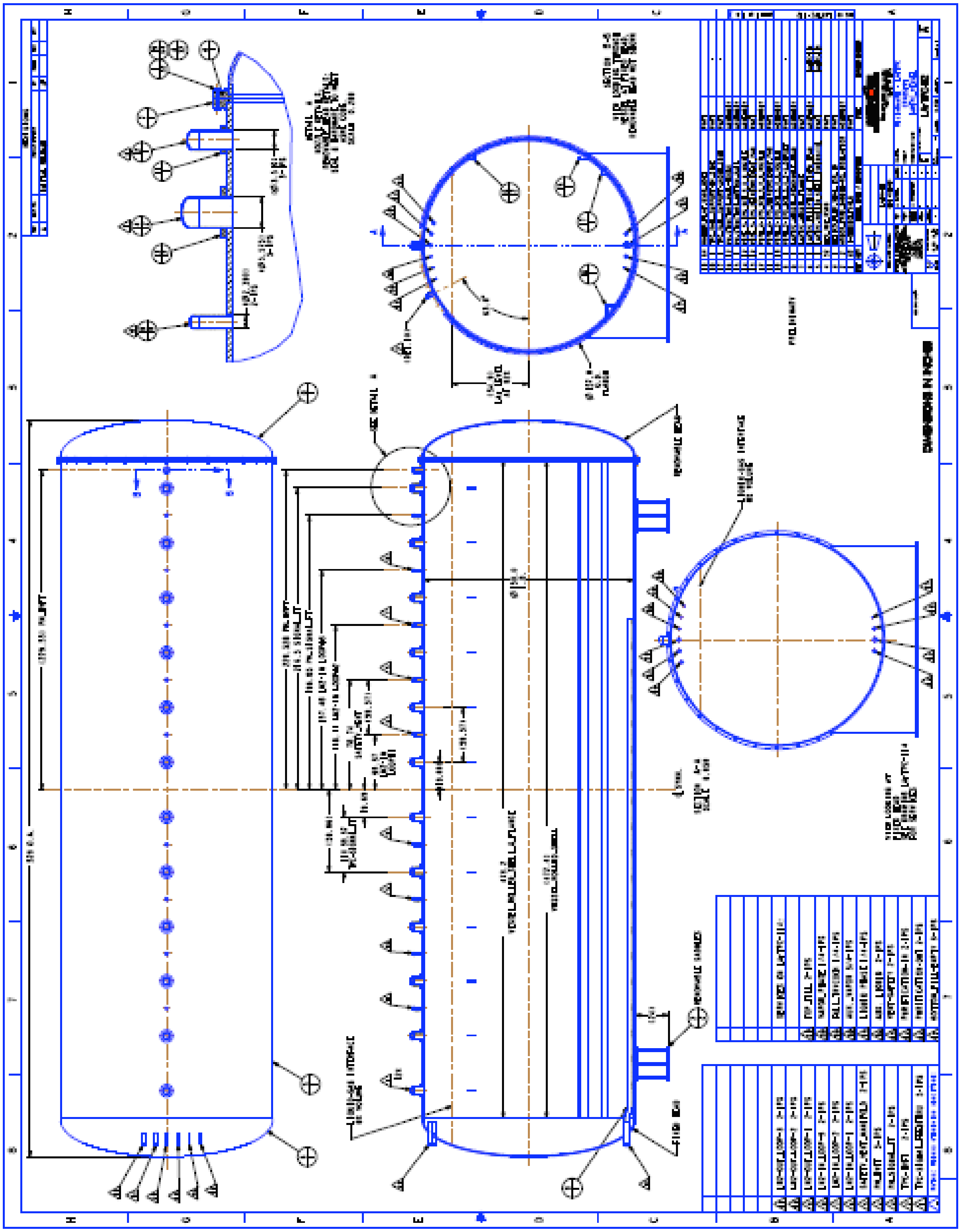

Figure 4.2.1 Cryostat conceptual design

4.2.2.1.2 Insulation

The liquid argon will be maintained at a temperature of about 88K (17.4 psiA, 3 psiG). To reduce the transmission of heat into the cryostat and maintain evaporation of the argon at an acceptable rate, the vessel must be adequately insulated. The insulation must allow for an acceptable operating cost of the cooling system and the heat leak through the insulation must be small enough that the temperature gradients and convective flow in the liquid argon do not significantly affect the spatial or energy resolution of the detector. The insulation must also prevent ice buildup and water condensation on the cryostat. These goals are achieved by a layer of 16 inches of polyurethane (PU) foam.

The heat leak through the 16 inch thick tank insulation will be 13 W/m^2, for a total heat input of 2.34 kW. The heat leak will be offset using 1300 L of liquid nitrogen per day, though this estimate does not account for penetrations or the purification system. The temperature and velocity of the liquid argon in the cryostat has been modeled using a finite element analysis assuming a heat load of 13 W/m^2, and the results of the calculations are shown in Fig. 4.2.2. These calculations show that the temperature difference of the liquid at various points in the vessel can be kept to ~0.01 K with the proposed insulation. Additionally, the velocity of the liquid will be less than 4.56 x 10^{-2} m/s with this insulation.

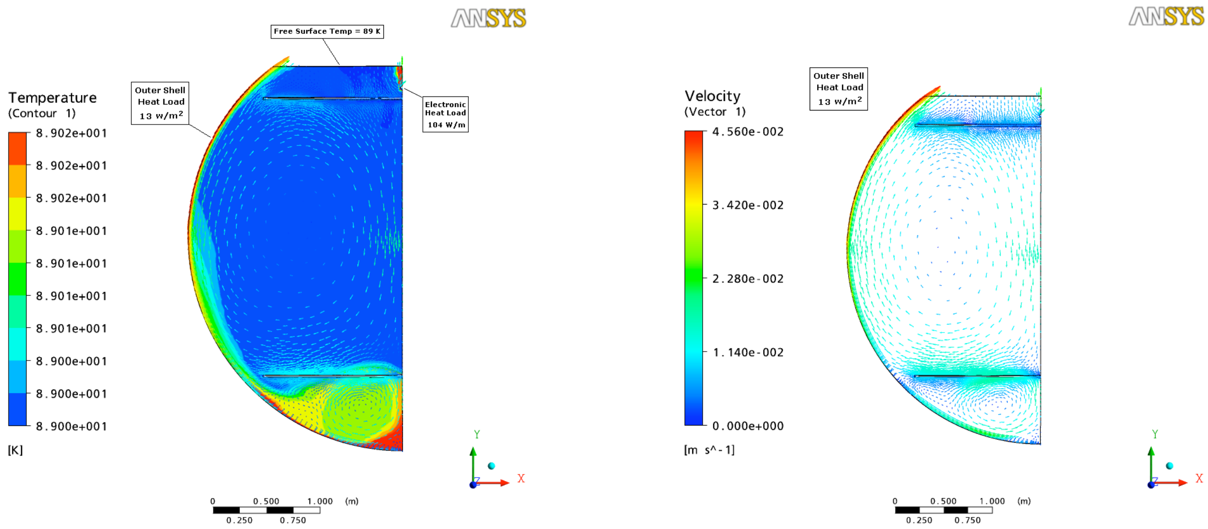

Figure 4.2.2 – Temperature (left) and velocity (right) of the liquid argon at various points inside the vessel assuming a heat load of 13 W/m^2.

Our plan is to contract a company which uses a technique called “foam in-place” that applies the PU foam directly to a surface; the most common application of this technique is to insulate buildings. The completed insulation must be protected from water vapor diffusion and must meet fire protection requirements. A non-flammable vapor barrier will be applied over the insulation. We have requested the Fermilab Fire Protection Engineer perform flammability tests on any possible coatings.

The differential thermal shrinkage between the PU insulation and the stainless steel tank raises the concern of the development of cracks in the insulation. We are studying this in detail. Our studies to date suggest that this is not a problem and as extra insurance we will be using additional strengthening of the foam in the form of three layers of fiberglass mesh. The first layer will be applied to the cryostat surface and the remaining layers applied after the first two 1.5 inch lifts. The mesh will help prevent propagation of any localized cracks that appear, as crack propagation could lead to foam de-lamination from the cryostat. The localized cracks have little impact on the insulating ability of the foam.

A clearance of 12 inches has been allowed between the bottom of the insulation and the floor; the overall height to the top of the flanges on the service chimneys will therefore be 16 feet 4 inches.

4.2.2.2 Cryogenics and Purification System

This section describes the delivery of the liquid argon, as well as the operation of the closed system for purifying the argon. The system to be implemented is shown in Fig. 4.2.3.

4.2.2.2.1 Liquid Argon Delivery

Liquid argon will be delivered to the MicroBooNE site via tanker truck. A total of 10 truck loads will be needed to fill the cryostat. Once each truck arrives a small sample of liquid argon will be taken from the truck and tested for impurities. These tests will check that the concentration of water and oxygen in the supply liquid argon meet specifications. The sample will then be purified to a level where the electron drift-lifetime of the argon can be measured. If the electron drift-lifetime is satisfactory, the truck will be connected to a pump and the liquid will be pumped into the cryogenics and purification system. The system will be capable of receiving one truck per day.

4.2.2.2.2 Filling and Purification

Before the cryostat is filled with liquid argon, its volume must first be purified. Previous cryostats, such as ArgoNeuT and the ICARUS series of detectors, were first evacuated and then filled with argon gas. While the MicroBooNE cryostat can be placed under vacuum, the initial attempts at purification will be made by purging the atmosphere inside the vessel with argon gas; this is part of the R&D program of MicroBooNE. The filling and purification procedures will be developed by the LAPD test stand at Fermilab [2]. A system of external heaters will be mounted directly on the cryostat vessel beneath the insulation. These heaters may be used to help reduce the water content – consistent with the temperatures that the detector inside the cryostat can tolerate. After the cryostat has been sufficiently purged to a level of 500 ppb oxygen and water, it will be exposed to cooled argon gas and eventually filled with liquid argon. The cool down rate must be controlled so as not to shock the inner detectors too severely.

The liquid argon is purified using a series of filters. The first filter is a molecular sieve to remove water. This is followed by an activated carbon filter to remove hydrocarbons and miscellaneous contaminents and a particulate filter to remove dust from the liquid. The final filter contains activated copper to remove oxygen. The oxygen and water levels of the argon emerging from the purifier will be monitored and the drift-lifetime measured with a custom built `purity monitor' [3]. If the drift lifetime is satisfactory, >3 milliseconds, the liquid argon will be delivered to the cryostat. There will be two identical purification systems located at the MicroBooNE site, each with enough capacity for the steady state operating condition. During normal operations one system will be active and the other will be a spare. Either may be used during the initial filling of the cryostat.

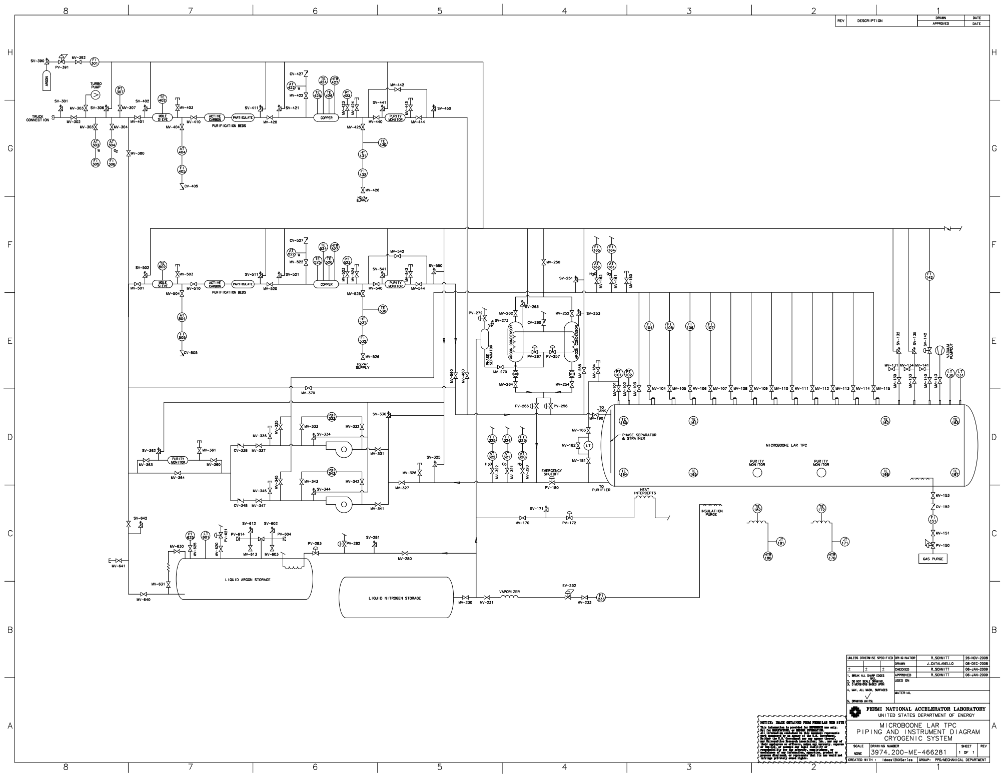

Figure 4.2.3 – Piping and instrumentation diagram for the cryogenics system.

4.2.2.2.3 Liquid Argon Circulation

The liquid argon is circulated through the system using custom built pumps to avoid contaminating the liquid. The pumps can cycle 6000 L of liquid argon each hour, corresponding to a complete cryostat volume every 1 days. The capacity of the pump has been selected to optimize the rate of circulation through the purification system against the initial cost of the equipment. The pump must be located below the cryostat to provide adequate suction head. An identical backup pump will be installed as a spare. A purity monitor is located immediately after the pumps to give an initial estimate of the electron drift lifetime before the argon is purified.

4.2.2.2.4 Liquid Argon Condensation

Several penetrations are provided in the cryostat to allow gaseous argon to move from the vessel to a condensation unit. This unit is cooled by liquid nitrogen. The condensed liquid argon then flows to the circulation pumps described above and is sent through the purification system. Dual condensers will be installed, each with the capacity for steady state operation. Both condensers would operate during the filling process.

4.2.2.2.5 Liquid Argon Monitoring

The liquid argon in the cryostat will be monitored for the electron drift lifetime and for its temperature. There will be 4 purity monitors positioned in various locations inside the cryostat in order to monitor the drift lifetimes, and oxygen and water monitors will sample both liquid and the gas above the liquid. There will be several temperature monitors located at various depths in the argon to measure the temperature of the argon as well as any gradients that may develop.

The cryogenic control system will be designed to operate automatically, reliably and securely using commercially available hardware and software. The cryogenic instrumentation and control system will include controllers, displays, web servers, interfaces to the data acquisition, and backup power supplies.

4.2.2.2.6 Liquid Argon Storage

A liquid argon storage vessel will be located at the MicroBooNE site in order to provide a location for storing liquid argon in the event that the cryostat must be emptied. This vessel gives added flexibility in the receiving and filling process to deal with problems in either process. The cost of the vessel is approximately equivalent to the cost of one load of liquid argon required to fill the cryostat.

4.2.3 Alternatives Considered

A double walled design was considered for the cryostat. This design would allow a vacuum between the two walls which would provide additional insulation for the vessel. The design was rejected because it would decrease the fiducial volume of transportable vessel while adding cost. The current design still allows for the possibility of purifying the vessel by placing it under vacuum.

We have not seriously considered other than a cylindrical cryostat even though we are building a nearly square cross section TPC. The area of each segment, the regions between a circle and the inscribed square, is about 10% the area of the circle. One segment is used by the photo-multipliers and purity monitors, and one is taken up with the ullage. In principle, we could have constructed the cathode to follow the curvature of the cryostat but we have decided the simplicity of a flat cathode outweighs the benefit in added active mass.

There are two options for attaching the removable dish head to the vessel. One option has the dish head flanged and bolted. The flange would be sealed with a helicoflex seal; however the low operating pressure means that an indium or GoreTex seal could be used instead, reducing the number and size of the flange bolts. The other option is to weld the dish head to the main body of the cryostat. This avoids problems that may be encountered in making a good seal over the 12 ft diameter end-flange. In this case, the cryostat will be delivered with both caps welded on, and one end must be removed for installation of the detector assemblies at FNAL and then re-welded. The new welds made to reattach the end cap after installation must be ASME certified.

The cryostat vessel support design choice will be based on cost, heat load, and ability to withstand thermal contraction of the vessel.

An alternate insulation scheme has also been explored. This scheme would use layers of 1 inch thick fiberglass batting. The same insulation capability as the PU can be achieved with this scheme however it would require more labor to implement.

The design of the cryogenics and purification system has benefited from experience gained with the Bo and Luke test stands operated at Fermilab. As such no alternatives have been explicitly considered. We are however investigating the feasibility and cost of a commercial system.

4.2.4 Optimization

The size of the cryostat was optimized to be as large as possible such that it could be manufactured by an outside vendor but yet still transported over the road to the Fermilab site.

Various sizes of the pumps have been examined. The final choice will be based on the cost of the pump offset against the necessary circulation rate in order to purify one volume of the cryostat in one day.

The specification on the liquid argon supply will balance the cost of a tighter specification on contaminants against the extra capacity required of the purification system. This optimization will depend on prices nearer the time of ordering.

4.2.5 Quality Control & Quality Assurance

The specification for the treatment of the inside surface of the vessel, to provide the necessary cleanliness for containing the high-purity LAr, is currently under development. The tests of the LAPD will provide a basis for cleanliness specification. The vessel will be manufactured to the ASME code and certified. Site visits will be made to bidder's plants and samples of the steel will be required to qualify the winning bidder.

The quality of the liquid argon will be checked against the specification on delivery and after purification before being pumped into the system.

Extensive system and component checks will be made to ensure the integrity of the piping and valves in the entire cryogenic and purification system.

All materials that will be placed inside the cryostat will be tested in the Materials Test System at Fermilab to ensure that they do not contaminate the liquid argon.

Since we are interested in temperature gradients within the liquid, special care will be taken to cross-calibrate the temperature probes using the final cabling and readout.

Detailed plans and procedures will be written for commissioning, testing, and normal and abnormal operation of the system.

There will be communication between the group working on this WBS element with the other elements to ensure the various systems can be assembled seamlessly.

4.2.6 Risks

The cryostat and purification system designs are quite conventional. It is, however, important to avoid any contaminant on the surface of the cryostat that affects the ability to achieve long electron drift lifetimes. This will be addressed by taking a sample of cryostat wall material that has undergone the standard processing and testing it in the materials test stand at Fermilab.

It is possible to construct the experiment without an additional liquid argon storage tank. The risk of not having this tank is that an entire volume of purified liquid argon could be lost if there is a problem with the active detector elements and the cryostat must be emptied.

4.2.7 ES&H

A preliminary hazard analysis for the components of this WBS item will be performed and it will include a list of relevant Fermilab safety requirements and how they will be addressed.

The use of liquid argon makes the MicroBooNE site a potential oxygen deficiency hazard (ODH) area. The area will be analyzed and classified according to Fermilab ODH standards. Based on the results of that analysis appropriate ventilation, oxygen sensors, alarms, signs and training will be implemented. Besides the indoor spaces normally covered under the Fermilab standards, potential outdoor problems will also be studied. It will also include a discussion of secondary containment, despite the absence of national standards requiring secondary containment for liquid argon storage.

The liquid nitrogen and argon are also extremely cold and can cause frostbite if they come in contact with skin. Individuals making connections between the delivery trucks and the system must wear protective equipment including gloves, aprons and face shields. Individuals working with the plumbing system must do so as well. There will be training provided and people will have to be qualified for tasks involving either ODH or cryogenic hazards as provided in the FESHM.

Fermilab environmental safety and health standards will be followed in the design and implementation of the cryogenic system.

References

[1] One example of such a company is General Plastics Manufacturing Co LAST-A-FOAM at www.generalplastics.com

[2] http://lartpc-docdb.fnal.gov/cgi-bin/ShowDocument?docid=410

[3] G. Carugno at al., ``Electron lifetime detector for liquid Argon” NIM A292 (1990), 580. and D. Finley et al., ``Work at FNAL to achieve long electron drift lifetime in liquid argon.” FERMILAB-TM-2385-E, Oct 2006. 9pp