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Development of membrane cryostats for large liquid argon neutrino detectors

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Abstract. A new collaboration is being formed to develop a multi-kiloton Long-Baseline neutrino experiment that will be located at the Surf Underground Research Facility (SURF) in Lead, SD. In the present design, the detector will be located inside cryostats filled with 68,400 ton of ultrapure liquid argon (less than 100 parts per trillion of oxygen equivalent contamination). To qualify the membrane technology for future very large-scale and underground implementations, a strong prototyping effort is ongoing: several smaller detectors of growing size with associated cryostats and cryogenic systems will be designed and built at Fermilab and CERN. They will take physics data and test different detector elements, filtration systems, design options and installation procedures. In addition, a 35 ton prototype is already operational at Fermilab and will take data with single-phase detector in early 2016. After the prototyping phase, the multi-kton detector will be constructed. After commissioning, it will detect and study neutrinos from a new beam from Fermilab. These cryostats will be engineered, constructed, commissioned, and qualified by an international engineering team. This contribution presents the on-going effort on the development of the cryostats and details the requirements and the current status of the design.

1. Introduction

A new project has been formed, composed by the Deep Underground Neutrino Experiment (DUNE) and the Long-Baseline Neutrino Facility (LBNF). DUNE, the scientific collaboration, is in charge of developing, producing and installing the detectors; LBNF is in charge of developing, producing and installing the facilities. The DUNE-LBNF project envisions using membrane tank technology for a large liquid argon detector with the start of the construction in the 2020 time frame and operations in 2024 for neutrino physics. The current detector configuration has a total fiducial mass of 40,000 tons

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of liquid argon to be located at the 4850L of the Sanford Underground Research Facility (SURF), in Lead, SD, USA, about 1.5 km underground. The experiments are being developed in a phased approach, which is to total four identical cryostats of about 12,100 m^3 of total liquid argon each. The initial phase is to include two cryostats, with the corresponding required cryogenic system. The remaining cryostats will come at a later time. Each cryostat will be instrumented with Time Projection Chambers (TPCs) and filled with liquid argon. The cryostats and all other infrastructures are to be developed by LBNF.
In order for the TPCs to operate properly and drift electrons with a lifetime greater than 3.0 milliseconds (ms), the detector requires extreme purity of the liquid argon inside the tank, better than 100 parts per trillion (ppt) of oxygen equivalent contamination. There is an empirical correlation between electron lifetime and parts of oxygen [1].
To qualify the membrane cryostat technology for these very large underground applications a strong prototyping effort is being developed with cryostats of growing size being developed in the next 2-3 years at CERN and Fermilab by an international engineering team that will follow their engineering, construction, commissioning and qualification, in collaboration with a membrane cryostat manufacturer. All cryostats will be instrumented with detectors that will take physics data and validate the performance of the detectors themselves, cryostats and associated cryogenic systems, liquid argon filtration schemes, design choices, and installation procedures. Two detector configurations, single phase and dual phase, will be tested in the process. The prototyping involves the following cryostats:

- WA105 1x1x3: containing almost 19 m^3 of liquid argon and about to be constructed at CERN. It will house a dual phase detector.
- Short-Baseline Near Detector (SBND), containing about 189 m^3 of liquid argon. It will serve as near detector for the Short-Baseline program at Fermilab. It will house a single phase detector.
- ICARUS cryostat: containing about 545 m^3 of liquid argon. It will house the refurbished ICARUS T600 detector and will serve as a far detector for the Short-Baseline program at Fermilab. (This tank is not a membrane cryostat and is not described in this contribution. It is made of extruded aluminum profiles with passive insulation and a steel support structure).
- ProtoDUNE: containing about 485 m^3 of liquid argon. It will be located on the H4 beam line extension in the CERN EHN1 area and will house a single phase detector.
- WA105 6x6x6: containing about 485 m^3 of liquid argon (different configuration than the previous one). It will be located on the H2 beam line extension in the CERN EHN1 area and will house a dual phase detector.

2. Membrane cryostat technology
Common aspects of all cryostats described in this contribution are the use of the membrane cryostat technology supported by a steel outer structure.
The membrane cryostat technology is widely used for Liquefied Natural Gas (LNG) transportation and storage, with over 100 vessels that now could be as large as 250,000 m^3 of volume [2]. Two companies own the technology and share the market: Gaztransport & Technigaz (GTT) from France and Ishikawajima-Harima Heavy Industries Co. (IHI) from Japan.
The densities of liquid argon and LNG are quite different: the latter is about one third the specific gravity. LNG ship tankers and storage tanks are more than four times taller than the future LBNF cryostat making the two applications very similar. The hydrostatic pressure at the bottom of the tank is almost identical.
A membrane cryostat is made of several parts (figure 1): the corrugated membrane that contains the liquid and gaseous argon (1), a fireproof board (2), plywood in this case, which protects the insulation against the heat generated during the welding of the membrane, the passive insulation that reduces the heat leak (3, 5), and the support structure (8), steel in this case, but can also be concrete, which is the

structural part to which the pressure is transferred. A secondary barrier system (4) embedded in the insulation protects it from potential spills of liquid argon, and a vapor barrier over the support structure (8) protects the insulation from the moisture.
Membrane and insulation do not hold the load of the liquid and gaseous argon, but only transfer it to the support structure. Membrane cryostats are not rated for internal vacuum. They will also be too large to be pumped down in a reasonable amount of time.
The Liquid Argon Purity Demonstrator (LAPD) at Fermilab proved that a slow gaseous argon purge can remove impurities down to parts per million from a large cylindrical vessel without evacuation [3]. With a liquid argon filtration system composed by a molecular sieve and copper filters, it then reached over 14.0 ms electron lifetime [4], far exceeding the level of purity for the liquid argon required by the these detectors (3.0 ms). With the same liquid argon filtration system, and a requirement of 1.4 ms lifetime, the 35 ton prototype (figure 2) exceeded 3.0 ms electron lifetime, which was the limit of the instrumentation, in a cubic membrane cryostat using the same piston purge technique [5]. The 35 ton prototype is a 29 cubic meter membrane cryostat designed, built and successfully operated at Fermilab. It is the first of this kind to be used with liquid argon and for scientific purpose. During phase 1 it demonstrated the feasibility of the membrane cryostat technology for liquid argon, exceeding the purity requirements [5]. It is now being outfitted with TPCs for a phase 2, which will be operational in early 2016. Two previous papers outline the full description of design and construction, in collaboration with IHI [1, 5]. This cryostat has a concrete support structure, differently than all the others presented in this contribution.

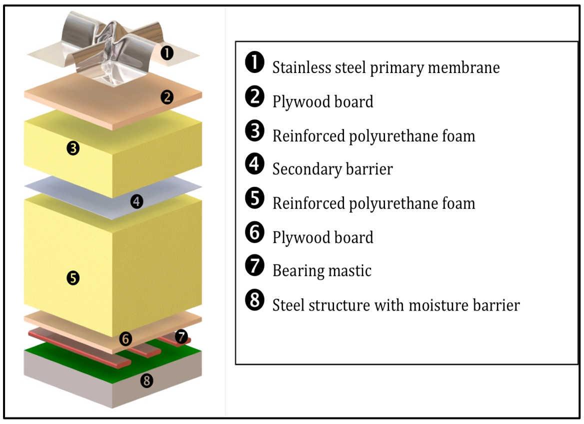

Figure 1. Membrane cryostat layout.

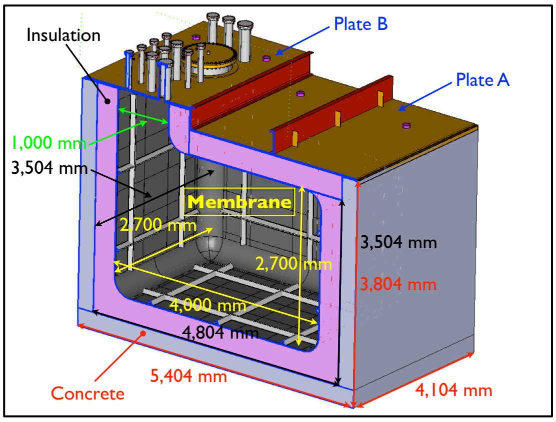

Figure 2. 3D drawing of the 35 ton cryostat

3. Design strategy

We started with a modular steel support structure for the LBNF cryostats and adapted it to the smaller cryostats, with the exception of the WA105 1x1x3 that was already designed. The design, that uses standard commercial items with guaranteed quality, employs web interlinks made with small beams (with a pitch of 0.8 m for LBNF and 0.6 m for all the others) to uniformly distribute the load, and large beams to bear the load of the liquid and gaseous argon (of the order of 20,000,000 kg on the floor of the LBNF cryostat). It also allows air to flow underneath the cryostat to maintain the temperature of the bottom part of the structure within the allowable limits.
The roof (subject to over 3,000,000 kg in the LBNF cryostat) is an integral part of the support structure and is developed in a similar way. Large openings for installation of the detectors are available as modular units (blocks of web interlinks with or without the large support beams). Penetrations are located in the available space between the smaller beams.
When the preliminary design of the support structure for a particular cryostat is available, and all requirements are defined, a feasibility study will be awarded to a membrane cryostat manufacturer, which then feeds back eventual modifications to the design, if needed. At this point, the final

engineering of the support structure and the engineering of the membrane cryostat by the manufacturer start. The preliminary design of the support structures of all the cryostats is almost completed. A feasibility study for each membrane cryostat will be awarded in the next months.
None of these cryostats will be rated for vacuum. We will use the proven slow gaseous argon purge to remove all the impurities prior to the cool down and filling.

4. WA105 1x1x3

This membrane cryostat was designed by CERN and ETH Zurich in collaboration with GTT. It is being installed this summer at CERN by Gabadi, an authorized GTT installer. It will contain a dual phase TPC anchored underneath the roof, which is welded to the top part of the outer support structure, and will not be on a beam line. Table 1 presents a summary of the design parameters.

Table 1. Design parameters for the WA105 1x1x3 cryostat.

Design Parameter	Value
Cryostat volume	23 m^3
Liquid argon total mass / volume	25,600 kg / 18.4 m^3
Inner dimensions of the cryostat	4.8 m (L) x 2.4 m (W) x 2.0 m (H) – flat plate to flat plate
Depth of liquid argon	1.6 m
Insulation	1.0 m of polyurethane foam PU Aged HFC245 (1.2 m under the top plate)
Primary membrane	1.2 mm SS 304L corrugated stainless steel (sides, floor)
Secondary barrier	Triplex (<0.1 mm): a thin sheet of aluminium between glass cloth and resin
Vapor barrier	6 mm thick SS 304L
Support structure	Steel structure with I-beams 240 mm
Liquid argon temperature	87 K +/- 1 K
Operating pressure / design pressure	+/- 50 mbarg / 160 mbarg
Leak tightness	1E-06 mbar*l/sec
Heat leak	< 5 W/m^2

Figure 3 shows a picture of the cryostat from the outside, with the outer steel support structure and the vapor barrier. Figure 4 shows the current 3D model of the cryostat with the roof installed.

Figure 3. Photo of the WA105 1x1x3 outer support structure.

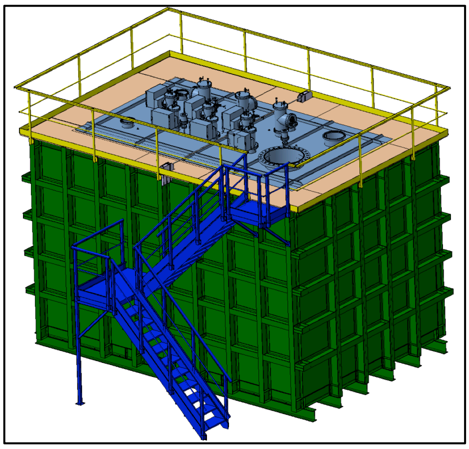

Figure 4. 3D model of the WA105 1x1x3 cryostat.

The outside dimensions are approximately: 7.3 m (L) x 4.9 m (W) x 4.9 m (H). The structure sits on longitudinal I-beams 0.24 m high (included in the height). The roof contains all the penetrations, for the detector (e.g. high voltage and signal), for the instrumentation and for the cryogenic system. From the outside to the inside, the roof composition is: a stainless steel plate, to which the penetrations are attached, a layer of insulation, and an invar plate, which replaces the corrugated membrane. Crossing pipes through the insulation connect the penetrations to the inner volume.

5. SBND

This membrane cryostat will house single phase TPCs anchored underneath the removable part of the roof, which is welded to the top part of the outer support structure. Table 2 presents a summary of the current design parameters.

Table 2. Current design parameters for the SBND cryostat.

Design Parameter	Value
Cryostat volume	200 m^3
Liquid argon total mass / volume	263,000 kg / 189 m^3
Inner dimensions of the cryostat	7.1 m (L) x 5.2 m (W) x 5.4 m (H) – flat plate to flat plate
Depth of liquid argon	5.2 m
Insulation	0.6 m of polyurethane foam PU Aged HFC245
Primary membrane	1.2 mm SS 304L corrugated stainless steel (sides, floor)
Secondary barrier	Triplex (<0.1 mm): a thin sheet of aluminium between glass cloth and resin
Vapor barrier	6 mm thick SS 304L
Support structure	Steel structure with I-beams 240 mm (may need additional reinforcement)
Liquid argon temperature	88 K +/- 1 K
Operating pressure / design pressure	70 mbarg / 350 mbarg
Leak tightness	1E-06 mbar*l/sec
Heat leak	< 15 W/m^2 (sides), < 20 W/m^2 (roof)

Figure 5 shows a section of the current 3D model of the cryostat. The top layer of crossing I-beams is not shown in figure 5. Figure 6 shows the top and the TPCs anchored underneath.

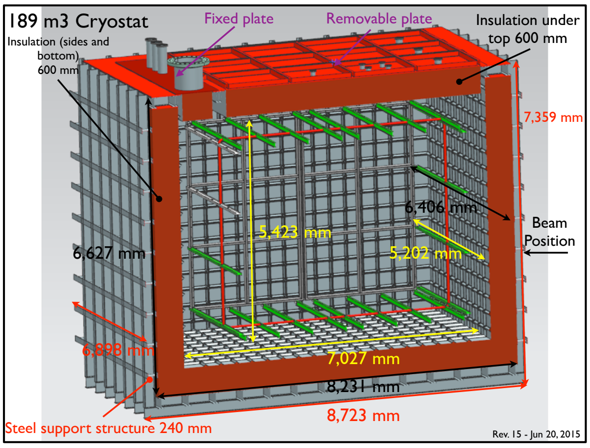

Figure 5. Preliminary 3D model of the SBND cryostat.

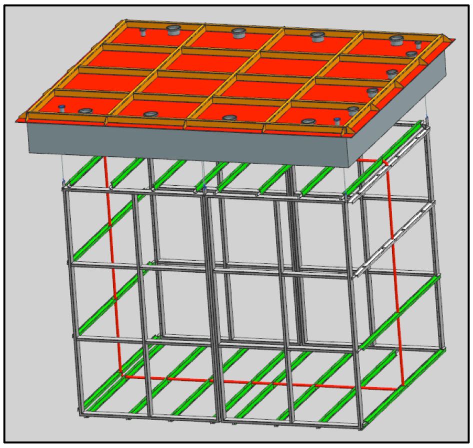

Figure 6. Top with the TPCs anchored underneath.

The outside dimensions are approximately: 8.7 m (L) x 7.0 m (W) x 7.4 m (H). The structure sits on longitudinal I-beams 0.24 m high (included in the height). The roof is made in two parts, a fixed one containing all the cryogenic and instrumentation penetrations, and a removable one containing the detector penetrations (e.g. high voltage, signal and calibrations). The TPC is installed underneath the removable plate prior to its installation on the cryostat. If the TPC needs to be removed, the process is reversed: the removable plate is disconnected from the cryostat and lifted up, while the fixed plate and its penetrations remain in position. For the top plates we envision a layout similar to the roof of the

WA105 1x1x3 with an external stainless steel plate, crossing pipes through the insulation for the penetrations and an invar plate on the inside.

6. ProtoDUNE

This membrane cryostat will contain full size DUNE single phase TPCs, which may be anchored either to the roof or to an outside structure to mechanically decouple them from potential sources of vibrations in the roof. Table 3 presents a summary of the current design parameters.

Table 3. Current design parameters for the ProtoDUNE cryostat.

Design Parameter	Value
Cryostat volume	562 m^3
Liquid argon total mass / volume	676,000 kg / 485 m^3
Inner dimensions of the cryostat	8.9 m (L) x 7.8 m (W) x 8.1 m (H) – flat plate to flat plate
Depth of liquid argon	7.3 m
Insulation	0.9 m of polyurethane foam PU Aged HFC245
Primary membrane	1.2 mm SS 304L corrugated stainless steel (sides, floor)
Secondary barrier	Triplex (<0.1 mm): a thin sheet of aluminium between glass cloth and resin
Vapor barrier	6 mm thick SS 304L
Support structure	Steel structure w web interlink I-beams 240 mm + I-beams 600 mm
Liquid argon temperature	88 K +/- 1 K
Operating gas pressure / design pressure	70 mbarg / 350 mbarg
Leak tightness	1E-06 mbar*l/sec
Heat leak	< 10 W/m^2 (sides), < 15 W/m^2 (roof)

Figure 7 shows a preliminary drawing of the outer support structure with the location of some of the penetrations on the top. The outside dimensions are approximately: 11.9 m (L) x 10.8 m (W) x 11.1 m (H). The structure sits on longitudinal I-beams 0.6 m high (included in the height). This cryostat will have three beam windows (about 0.2 m in diameter each) in the front, to allow for a discrete sweep of the beam. They will cross each layer of the membrane cryostat and be sealed at each one.

7. WA105 6x6x6

This membrane cryostat will contain a dual phase TPC, which will be constructed under the roof from inside the tank. Materials will be inserted through a Temporary Construction Opening (TCO) of about 3 m x 3 m located on the left side of the cryostat as shown in figure 8. It will be sealed at the end of the process. It is a standard construction technique used in the construction of LNG ship tankers. Table 4 presents a summary of the current design parameters.

Table 4. Current design parameters for the WA105 6x6x6 cryostat.

Design Parameter	Value
Cryostat volume	558 m^3
Liquid argon total mass / volume	676,000 kg / 485 m^3
Inner dimensions of the cryostat	8.3 m (L) x 8.3 m (W) x 8.1 m (H) – flat plate to flat plate
Depth of liquid argon	7.0 m
Insulation	1.2 m of polyurethane foam PU Aged HFC245
Primary membrane	1.2 mm SS 304L corrugated stainless steel (sides, floor)
Secondary barrier	Triplex (<0.1 mm): a thin sheet of aluminium between glass cloth and resin
Vapor barrier	6 mm thick SS 304L
Support structure	Steel structure w web interlink I-beams 240 mm + I-beams 600 mm
Liquid argon temperature	87 K +/- 1 K
Operating gas pressure / design pressure	+/- 50 mbarg / 160 mbarg
Leak tightness	1E-06 mbar*l/sec
Heat leak	< 5 W/m^2

Figure 8 shows a preliminary drawing of the outer support structure. The outside dimensions are approximately: 11.9 m (L) x 11.9 m (W) x 11.7 m (H). The structure sits on longitudinal I-beams 0.6 m high (included in the height). This cryostat will have a beam window (not shown) in the front chamfered corner. It will cross each layer of the membrane and be sealed at each one.

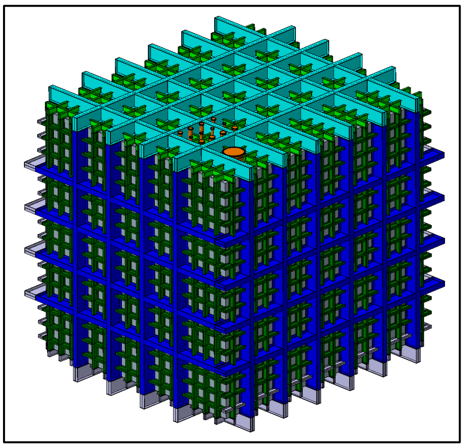

Figure 7. ProtoDUNE preliminary outer support structure.

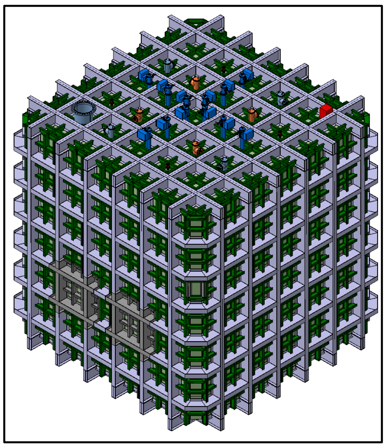

Figure 8. WA105 6x6x6 preliminary outer support structure.

8. LBNF Cryostats

There are four identical membrane cryostats. The first one will contain a single phase TPC. The following ones may contain single or dual phase, a modified version of each one of them, or a different detector. Table 5 presents a summary of the current design parameters for one cryostat.

Table 5. Current design parameters for one LBNF cryostat.

Design Parameter	Value
Cryostat volume	13,100 m^3
Liquid argon total mass / volume	17,100,000 kg / 12,100 m^3
Inner dimensions of the cryostat	62.0 m (L) x 15.1 m (W) x 14.0 m (H) – flat plate to flat plate
Depth of liquid argon	13.2 m
Insulation	0.9 m of polyurethane foam PU Aged HFC245
Primary membrane	1.2 mm SS 304L corrugated stainless steel (sides, floor)
Secondary barrier	Triplex (<0.1 mm): a thin sheet of aluminium between glass cloth and resin
Vapor barrier	10 mm thick SS 304L
Support structure	Steel structure w web interlink I-beams 0.3-0.4 m + I-beams 1.1 m
Liquid argon temperature	88 K +/- 1 K
Operating gas pressure / design pressure	130 mbarg / 350 mbarg
Leak tightness	1E-06 mbar*l/sec
Heat leak	< 10 W/m^2 (sides), < 15 W/m^2 (roof)

Figure 9 shows a preliminary drawing of the outer support structure. Figure 10 shows a detail of how the membrane panels might be installed inside. The outside dimensions are approximately: 66.0 m (L) x 19.1 m (W) x 18.0 m (H). The 1.1 m high I-beams that at the bottom have three 0.8 m holes to allow air to flow underneath the cryostat. The I-beams on the sides have the same 0.8 m holes to allow people to walk around the structure for inspection. The biggest challenge for this installation is the transportation of the beams for the support structure underground. Some beams are 14.7 m long and weigh 9,500 kg. Modifications are needed to the lifting equipment currently available at SURF and to the unloading area underground, but preliminary studies indicate that it would be possible. The structure satisfies the design codes currently mandated by Fermilab ES&H. Discussions are ongoing to verify the applicability of other design codes that might reduce the weight of the required beams.

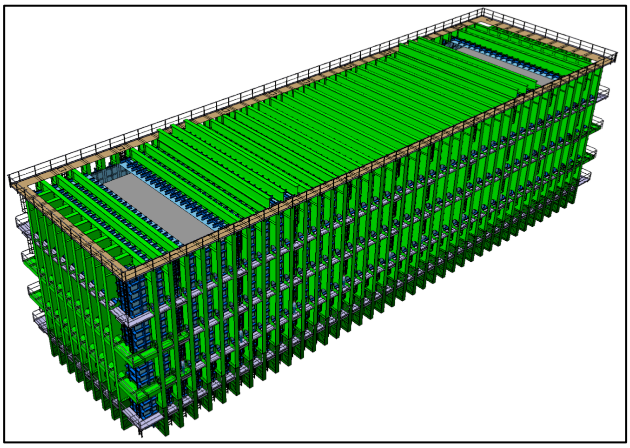

Figure 9. One of the LBNF cryostats with the openings for the installation of the detectors.

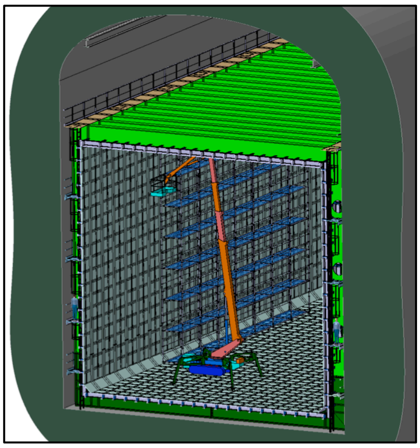

Figure 10. Section view of one of the LBNF cryostats during the installation of the membrane.

9. Summary

The DUNE-LBNF project requires the construction of four very large membrane cryostats at the SURF laboratory in Lead, SD, USA, about 1.5 km underground. Each cryostat contains 12,100 m^3 of liquid argon, equivalent to 17,100,000 kg. To qualify design choices and installation procedures for these very large underground applications and familiarize with the technology, we are developing smaller prototypes ranging from 19 to 485 m^3 of liquid argon, which will be constructed at CERN and Fermilab in the next 2-3 years by an international engineering team. These designs will test the membrane cryostat technology, the outer support structure and all the interfaces, in particular the one with the TPCs. All cryostats will be instrumented with detectors that will take physics data and validate the performance of the detectors themselves, cryostats and associated cryogenic systems, to ensure that the required purity of 100 ppt oxygen equivalent, corresponding to 3.0 ms electron lifetime, is achieved. The 35 ton prototype at Fermilab was already operated cryogenically without a detector and is now being equipped with single phase TPCs for a second run in early 2016. The WA105 1x1x3 is being constructed this summer at CERN and will be operational with a dual phase TPC at the end of 2016. The preliminary design of the support structures of all other cryostats is almost completed. A feasibility study for each membrane cryostat will be awarded in the next months.

10. Acknowledgements

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