FESHM 5031.7 Technical Note

Guidelines for the Design, Fabrication, Installation and Testing of Metallic Membrane Cryostats

Revision History

Author	Description of Change	Revision Date
Michael Geynisman	• Modifications for the pressure test requirements to allow both, pneumatic and hydrostatic testing • Modifications per Lab-wide review comments, including: - Grammatical improvements - Addressing potential spill due to piping penetrations below the liquid level - Listing all loads to the support structure - Clarifying attachment of the top plate to structural support	November 2015
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1.0 INTRODUCTION

Metallic membrane tank technology has been used in liquefied natural gas (LNG) stationary and transportation storage across the globe for the last half-century. It is now being used for neutrino physics using liquid argon (LAr) as the contained cryogenic fluid. It may also contain liquid nitrogen for testing or storage purposes.

Metallic membrane cryostat technology utilizes containment at pressures below 15 psig and therefore falls outside the scope of the ASME Boiler and Pressure Vessel Code, Section VIII.

"*Guidelines for the Design, Fabrication, Installation and Testing of Metallic Membrane Cryostats" (this guideline)* has been developed by the Cryogenic Safety Subcommittee, and references the current understanding of the best international practice in the design, fabrication, installation, examination, and testing of metallic membrane cryostats. This guideline discusses the applicability and use of the specific codes, standards, and recommended practices for the membrane industry. It also recognizes that while the suppliers of the metallic membrane cryostats are duly regulated by their respective international standards, Fermilab shall assure the level of safety per ASME Boiler and Pressure Vessel Code, Section VIII as required by Code of Federal Regulations, 10 CFR 851 Worker Safety and Health Program.

2.0 DESCRIPTION

A metallic membrane cryostat is an integrated assembly, wherein a polyurethane foam-insulated stainless steel membrane formed of prefabricated panels containing the cryogen isintegrated within a structural support with a top plate attached to the structural support and providing all cryogenic feed-throughs and pipe penetrations. The stainless steel membrane only contains the liquid and gas and maintains the leak tightness. The load exerted by the liquid head and the gas pressure is transferred from the stainless steel membrane vessel to the structural support through the insulation. The metallic membrane cryostat constitutes a complete low pressure vessel, which provides for leak tightness and pressure containment.

Figure 2.1 shows a basic construction of the metallic membrane cryostat. It shows how the foam-insulated stainless steel membrane formed of prefabricated panels is joined to a structural support with a top plate welded to the structural support and providing all cryogenic feed-throughs and pipe penetrations. Figure 2.2 shows a section of a metallic membrane cryostat with the different layers:

- Metallic membrane
- Fireproof board
- Insulation (two layers with secondary barrier in-between)
- Vapor barrier
- Support structure (concrete in this figure, but could be also a steel support structure)

The welded pre-fabricated panels of the stainless steel metallic membrane constitute the primary containment of the metallic membrane cryostat. The top plate(s) completes the metallic membrane cryostat and typically provides all the penetrations through the vessel.

The fireproof board protects the insulation from heat generated during welding of the membrane panels. It is part of the insulation.

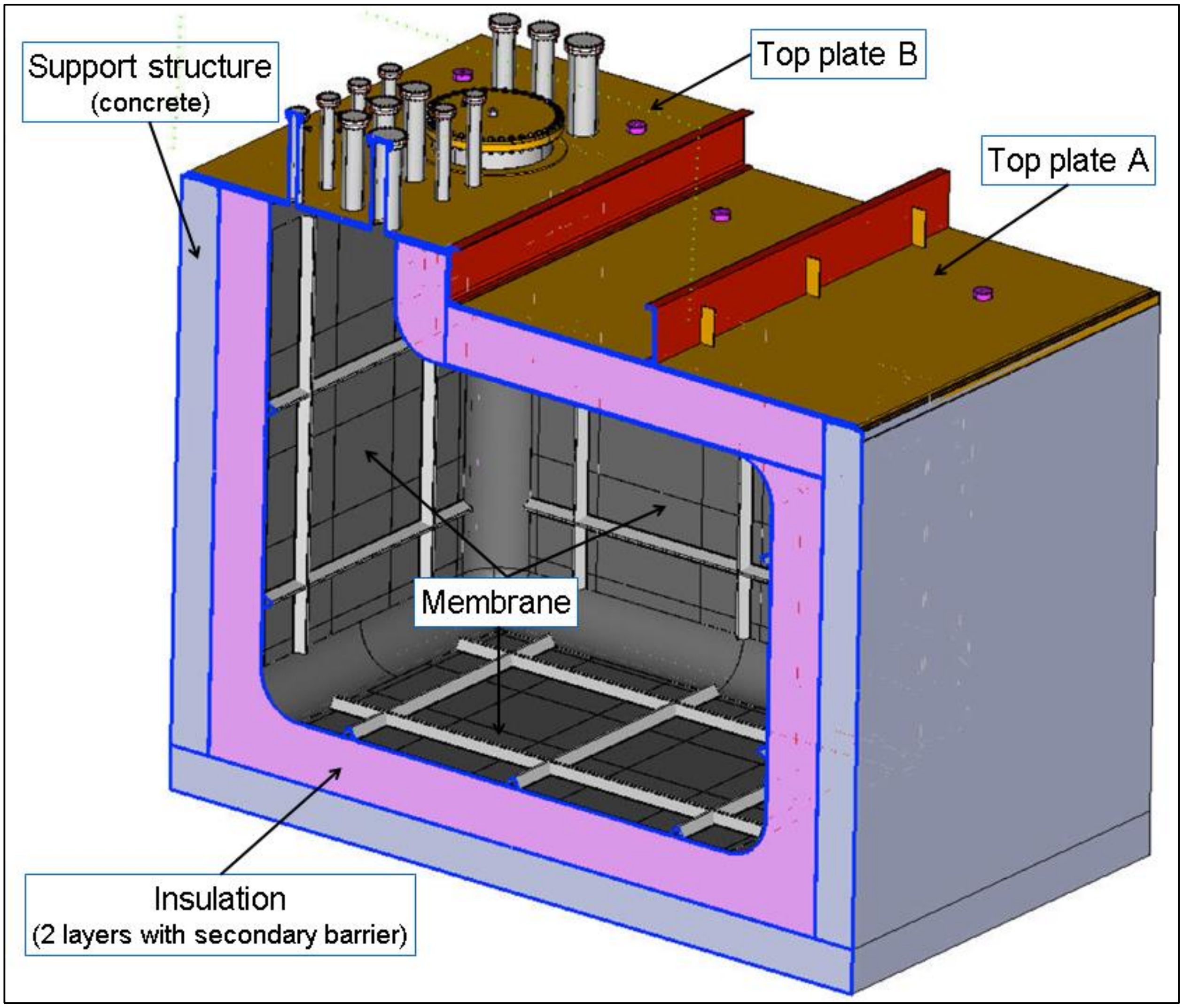

Figure 2.1 – basic construction of a metallic membrane cryostat

Two layers of the polyurethane insulation provide a thermal barrier between the membrane at the liquid cryogen temperature and the support structure at ambient temperature.

The secondary barrier is a physical protection that contains the liquid cryogen in case of a failure of the membrane. This secondary containment can be part of the insulation, or the steel support structure. Figure 2.2 shows alternative options when the secondary barrier is part of the insulation or part of the support structure.

The vapor barrier is attached to the support structure and keeps external moisture out of the insulation (particularly in the case of a concrete support structure).

The support structure made of steel or concrete, or combination of both, provides support for all internal and external loads exerted on the cryostat, including pressure, thermal, weight, and seismic loads.

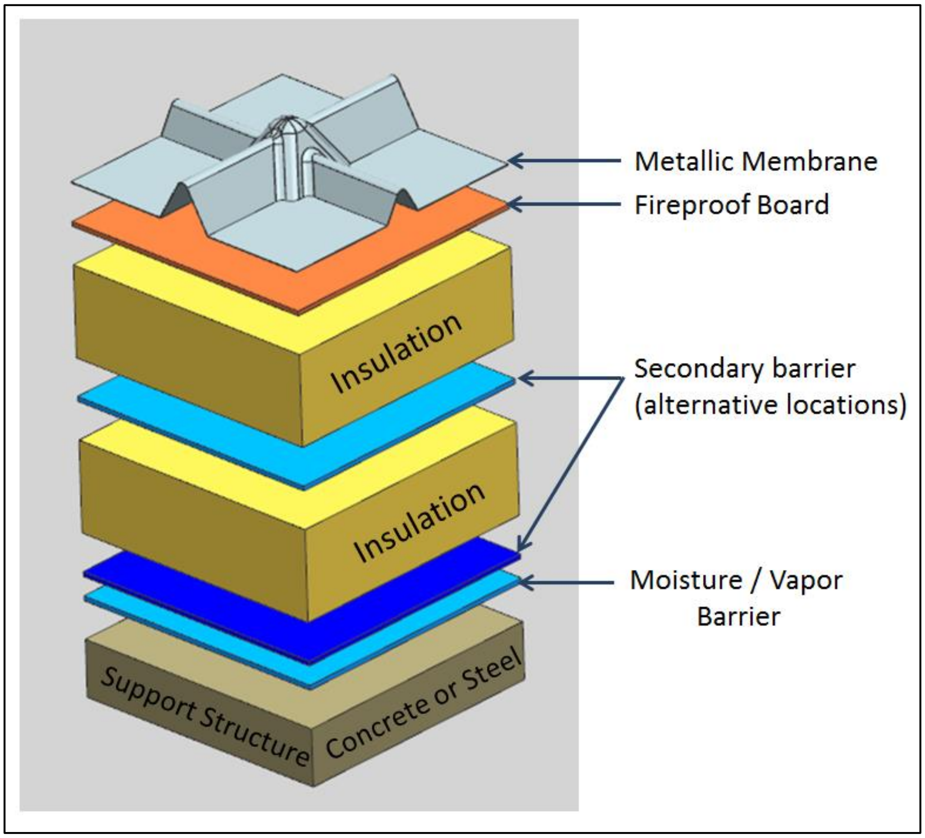

Figure 2.2 – Typical metallic membrane cryostat technology

3.0 CODES, STANDARDS AND RECOMMENDED PRACTICES

There are two known suppliers of metallic membrane cryostat technology: Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) out of Japan, and GazTransport & Technigaz (GTT) out of France. Therefore, the following standards and recommended practices are used in the design, fabrication, installation, and testing of metallic membrane cryostats:

- Japanese Gas Association Recommended Practice 107-02 (JGA RP-107-02) "*Recommended Practice for LNG Inground Storage*"
- British Standard BS EN 14620 "*Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0 Celsius and -165 Celsius*"

IHI primarily uses the JGA RP-107-02 recommended practice, but may also use the BS EN 14620 standard if required by the Authority Having Jurisdiction. GTT only uses the BS EN 14620.

While both, JGA RP-107-02 and BS EN 14620, are developed specifically for containing LNG, they describe the practices that can be used for containing argon. The European Technical Committee CEN/TC 265 made a recommendation in 2014 to revise EN 14620 to include nitrogen, oxygen and argon into its scope in section 6. The main differences between nitrogen/argon and LNG are analyzed in this section and show the applicability of the JGA RP-107-02 and EN 14620 to argon and nitrogen tanks as well. Table 3.1 presents the main differences between nitrogen/argon and LNG.

	LNG	**Nitrogen**	**Argon**
Boiling temperature (at atmospheric pressure)	108K	77K	87K
Liquid Density at 0.101 MPa	410-500 kg/m^3	806 kg/m^3	1,395 kg/m^3
Ratio of Liquid to Vapor Density at 0.101MPa	233	242	175
Specific Heat Ratio	1.31	1.40	1.67
Latent Heat of Vaporization	$5.1x10^5$ J/kg	$1.991x10^5$ J/kg	$1.63x10^5$ J/kg
Compatibility with materials	Limited	Very high	Very high

Table 3.1 – Differences between LNG, Nitrogen, Argon.

The materials listed in ASME Boiler and Pressure Vessel Code and suitable for LNG service are also suitable for service at liquid nitrogen and argon temperatures.

Nitrogen and argon are heavier than LNG. Provisions shall be made to ensure that the design is suitable for a denser medium. For example, the insulation at the bottom of a vessel designed for nitrogen/argon shall be adequate to withstand the higher hydrostatic load when compared to a vessel designed for LNG.

It is therefore possible to use JGA RP-107-02 and EN 14620 for the design, fabrication, installation and testing of vessels containing liquid nitrogen and liquid argon with provisions to compensate for the density of argon.

ASME BPVC, Section VIII applies to the design and construction of the top plate(s).

ASME Code for Process Piping B31.3 applies to the process piping penetrating the top plate(s) of the cryostat.

If structural support, which bears the pressure loads of the cryostat, is made of reinforced concrete, then American Concrete Institute Standard ACI 318 (latest edition) "Building Code Requirements for Structural Concrete" applies to the design and construction of the concrete support structure. If the structural support, which bears the pressure loads of the cryostat, is made of structural steel, then American Institute for Steel Construction Standard ANSI/AISC 360 (latest edition) "Specification for Structural Steel Buildings" applies to the design and construction of the steel support structure. Additionally, the design of any structural support shall incorporate a level of safety commensurate with ASME Boiler and Pressure Vessel Code, Section VIII as required by Code of Federal Regulations, 10 CFR 851 Worker Safety and Health Program.

"*Guidelines for the Design, Fabrication, Installation and Testing of Metallic Membrane Cryostats"* does not cover all possible aspects of metallic membrane cryostats. It is reasonable, possible, and at times necessary, to diverge from the methods presented here. For these cases, alternatives procedures and measures shall be developed and shown to assure a level of safety level of safety commensurate with ASME Boiler and Pressure Vessel Code, Section VIII as required by Code of Federal Regulations, 10 CFR 851 Worker Safety and Health Program. These alternative methods are subject to written approval by the Large Quantity Liquid Argon Panel prior to onset of a metallic membrane cryostat fabrication.

4.0 GENERAL REQUIREMENTS FOR DESIGN AND MATERIALS

The design and construction of the metallic membrane cryostat shall be established by accepted engineering practice, according to the relevant codes, standards and recommended practices listed in section 3.0. Subsequently, the selection of the design parameters, materials, practices and calculation methods for each part of the cryostat shall be subject to the codes, standards and recommended practices listed in section 3.0, as well the codes cross-referenced in them. For example, BS EN 14620-2 lists normative references that shall be applied to selection of materials used by GTT for design and manufacturing of the metallic membrane cryostats.

It should be understood that when a metallic membrane cryostat is designed and manufactured by GTT, the European standards will apply to its entirety, including material; while when a metallic membrane cryostat is designed and manufactured by IHI, either the European or the Japanese standards will apply to its entirety, including material.

As stated in section 3.0, the design and materials chosen for design shall assure a level of safety level of safety level of safety commensurate with ASME Boiler and Pressure Vessel Code, Section VIII as required by Code of Federal Regulations, 10 CFR 851 Worker Safety and Health Program.

Design data required to be included into Engineering Note is specified in section 6.0 of FESHM 5031.7.

5.0 SPECIAL REQUIREMENTS FOR STAINLESS STEEL MEMBRANE

The metallic membrane is not a structural component of the system and has a containment function only. It is a double network of orthogonal corrugations allowing its free contraction and expansion, in two directions, under thermal variations. Design of the metallic membrane shall be done per referenced standards and recommended practices based on the design pressures and temperatures. The metallic membrane can be designed according to the plastic deformation method. Additionally, design shall address cyclic deformations based on the number of specified thermal cycles.

The metallic membrane panels are purchased components and are to be assembled on site. As they are integral components of the metallic membrane cryostat, the assembly shall strictly follow the installation procedures designed by the manufacturer, including special procedures for welding and post-assembly testing.

The top plate(s) of the cryostat shall be designed per ASME Boiler Pressure Vessel Code, Section VIII, including design of the penetrations and nozzles.

6.0 SPECIAL REQUIREMENTS FOR INSULATION

The hydrostatic load and the gas pressure from the metallic membrane are transferred to the support structure through layers of polyurethane foam that insulate the vessel to reduce the conductive heat to the required value. The insulation shall be designed according to the maximum load transferred to the support structure. The thickness of the passive insulation is determined by the required heat leak.

If a secondary barrier is embedded inside the layers of insulation, it shall be designed to contain the liquid cryogen in case of a failure of the membrane.

A fireproof board, i.e. made of fire retardant plywood or calcium silicate, is attached to the inner most layer of insulation and protects it from the heat generated during the welding of the membrane panels.

The insulation transmits the load to the support structure. The main functions of the insulation are:

- To maintain the boil off below the specific limits.
- To protect the non-low temperature materials/parts of the tank (e.g. the support structure) by maintaining them at the required temperature.
- To limit the cooling of the foundation/soil underneath the tank to prevent damage from frost heave.
- To prevent/minimize condensation and icing on the outer surfaces of the tank.

The design of the insulation shall conform to BS EN 14620 Part 4 and/or JGA RP-107-02 Section 9. Properties of different insulating materials are listed in BS EN 14620 Table A.3 and JGA RP-107-02 Section 9.2.

The insulation purge system is typically installed to facilitate ammonia leak check during installation and to remove impurities during operations.

The design of the metallic membrane cryostat shall specify insulation flow path volumes, purge flow rates, purity of the purge argon gas, recommended delivery pressure, and requirements for external overpressure protection for the metallic membrane.

The outermost containment layer of the insulation space, e.g. steel liner, shall be leak checked and verified leak tight.

As per BS EN 14620, Part 1 Sections 7.2.1.8, the insulation space shall be monitored for controlling the differential pressure between insulation vapor space and primary containment space so that no damage can occur to the membrane. If the insulation space overpressure protection relies on active pressure reliefs (versus orifices), such pressure reliefs should be described in the Engineering Note per FESHM 5031.7.

7.0 SPECIAL REQUIREMENTS FOR SUPPORT STRUCTURE

Figure 7.1 shows an example of two types of support structures: steel (left) and concrete (right). Both are valid design choices.

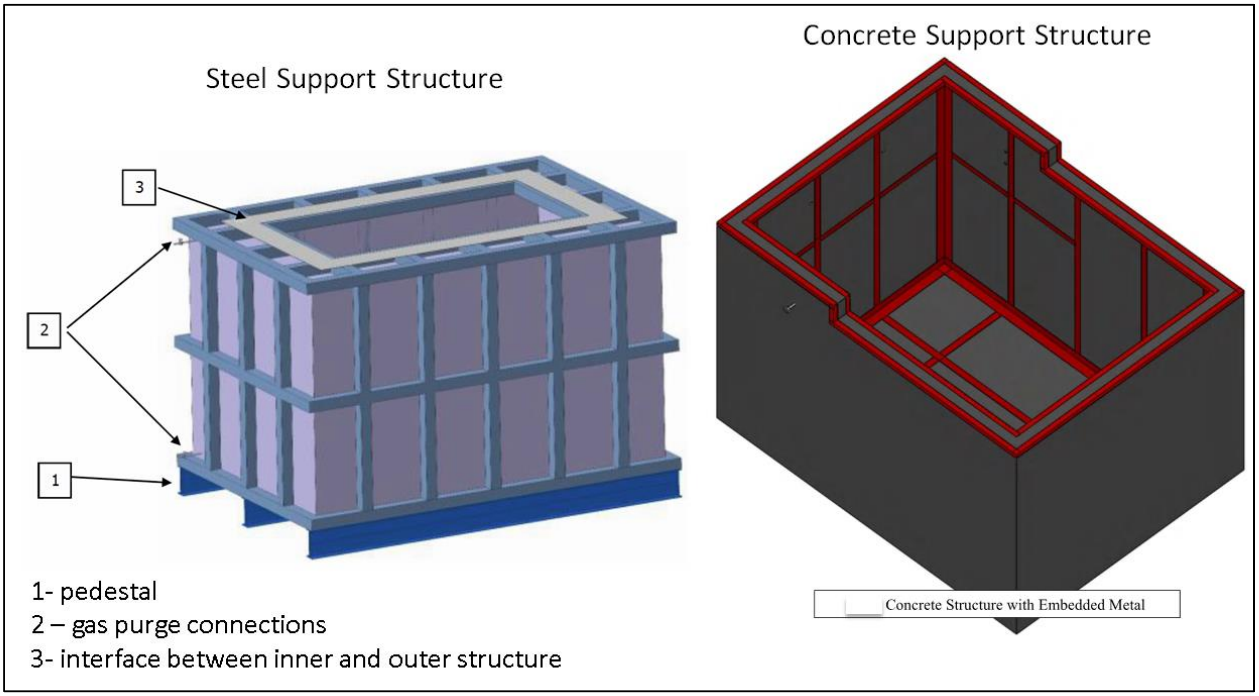

Figure 7.1 – Examples of steel support structure (left) and concrete support structure (right).

The support structure (steel plates and beams, concrete, or any other type) shall withstand the load of the liquid head and gas pressure and any other load applied to it. For example: the weight of the top plate, the equipment mounted inside the cryostat or on the top plate, the seismic load, and any wind load.

If the secondary barrier is part of the support structure, the secondary containment and the support structure shall be designed to contain the liquid cryogen in case of a failure of the membrane. The design shall address the issues of the high boil-off rates due to non-insulated secondary containment and low temperature of the support structure.

The design of any structural support shall be based on U.S. codes and specifications. Additionally, the design of any structural support shall incorporate a level of safety commensurate with the ASME Boiler and Pressure Vessel Code, Section VIII, as required by the Code of Federal Regulations, 10 CFR 851, "Worker Safety and Health Program."

If the structural support which bears the pressure loads of the cryostat is made of reinforced concrete, then the American Concrete Institute Standard ACI 318 (latest edition) “Building Code Requirements for Structural Concrete” shall apply to the design and construction of the support structure. Compliance with 10 CFR 851 shall be demonstrated by showing that the ratio of ultimate capacity to utilized capacity at every point in the structure is commensurate with the requirements of the ASME Boiler and Pressure Vessel Code, Section VIII, Div. 2. A U.S. licensed Professional Structural Engineer shall independently verify the design per ACI 318.

If the structural support which bears the pressure loads of the cryostat is made of structural steel, then the American Institute of Steel Construction Standard ANSI/AISC 360 (latest edition) “Specification for Structural Steel Buildings” shall apply to the design and construction of the support structure. Compliance with 10 CFR 851 shall be demonstrated by showing that the sum of primary membrane plus bending stress at every point in the structure (excluding bolts and welds) is commensurate with the requirements of the ASME Boiler and Pressure Vessel Code, Section VIII, Div. 2. Additional material and structural tests may be done to verify basis for the calculations with FEA and establish the maximum allowable stresses. The compliance to 10 CFR 851 shall be reviewed and certified by a Professional Engineer who is licensed under the jurisdictions of the country and state where the membrane cryostat is installed and employed by a company non-affiliated with Fermilab or CERN. Large Quantity Liquid Argon Cryogenic Panel shall review credentials and results of such independent certifications.

Due to lack of precedents of using rectangular steel support structures for cryogenic fluid containment, due to integral nature of the membrane cryostat where membrane is responsible for leak tightness, while steel construction is responsible for bearing pressure and hydrostatic loads, and due to allowing use of ASME Section VIII Div.2 for stress verification for the membrane cryostat steel structure, stricter requirements for design, procurement and construction of the cryostats supported with steel structures are needed, most notably for independent verification and quality control and assurance.

Therefore, the design per ANSI/AISC 360 shall be independently verified and certified by a U.S. licensed Professional Engineer employed by U.S. company (non-Fermilab or CERN) and submitted for review by the Large Quantity Liquid Argon Cryogenic Panel. Additionally, the procurement and construction of the structural support shall follow the full extent of quality control (QC) and quality assurance (QA) per ANSI/AISC 360, chapter N without modifications. The fabrication and erection of the cryostat shall be inspected, reviewed and certified by a Professional Engineer who is licensed under the jurisdictions of the country and state where the membrane cryostat is installed and employed by a company non-affiliated with Fermilab or CERN. Large Quantity Liquid Argon Cryogenic Panel shall review credentials and results of such independent certifications.

Where applicable, steel frames and a steel-reinforced concrete support structures for metallic membrane cryostats may be designed following guidance of BS EN 14620 and/or JGA RP-107-02 based on material maximum allowable stress criteria given above.

Provisions shall be made to not exceed the listed temperature limits of the materials, as well as recommended temperature differentials for the structural elements. Natural convection and/or active heating (by means of heating tapes or any other heating system) are allowable methods. Details are presented in BS EN 14620 Part 1 Sections 7.1.9, 7.1.10, 7.1.11 and JGA RP-107-02 Section 3.2.

In case of in-ground storage tanks with concrete support structure, an alternative approach is to intentionally freeze the soil (in a controlled way) to improve the performances of the vessel. Detailed calculations of the temperature profile of the soil shall be provided following JGA RP-107-02 Section 3.2, 4, and 5. Finite Element Analysis may also be used to calculate the temperature profile within the concrete.

Between the support structure and the outer insulation layer a vapor barrier shall be placed that guarantees a maximum permeability of water vapor towards the insulation of 0.5 g/m2 per 24 hr. as per BS EN 14620 Part 4 Section 5.3.

Where an in-ground cryostat is supported directly by a concrete liner and the ground behind it is sufficient for additional stable support (such as hard rock), the concrete liner shall be designed to transmit the outward forces from the cryostat to the rock without damaging any intermediate layers such drainage systems that may be required for geotechnical reasons. Any inward forces on the concrete liner shall be accommodated through analysis of load combinations to meet the level of safety commensurate with ASME Boiler and Pressure Vessel Code, Section VIII.

8.0 ADDITIONAL REQUIREMENTS

Manufacturer or supplier of the metallic membrane cryostat shall be required to provide documentation for approval by Fermilab to be sufficient to complete an Engineering Note per FESHM 5031.7 and form FESHM 5031.7TA. At a minimum, the following shall be required from the manufacturer of the metallic membrane cryostat:

- Solid model of a typical corrugated sheet
- Design stress calculations for membrane and support structure
- Load bearing calculations for the insulation
- Heat load calculations
- Drawings to support design calculations
- Material specifications and certifications to support design calculations
- Detailed assembly procedures
- Design for the insulation purge, including flow rate calculations and overpressure protection
- Detailed leak checking and testing procedures

Calculations of relief valve sizing should follow appropriate standards such as American Petroleum Institute Standard API 2000 “Venting Atmospheric and Low-Pressure Storage Tanks”.