Fermilab

Particle Physics Division
Mechanical Department Engineering Note

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Project: Muon g-2

Title: g-2 Helium Piping Engineering Note

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Reviewer(s): Mark Adamowski

Key Words: Piping note, 31.3, ASME, 5031

Abstract Summary:

This document describes the LHe tubes in the g-2 cryogenic system which were designed and fabricated at Brookhaven National Laboratory in the early 90's. The LHe tubes supply Liquid Helium to the aluminum superconductor containing mandrel. The piping system is made of several sizes of pipe/tube, and uses 304SS, Aluminum T6063-T52, and Alloy 122 Copper. The system contains several sections of piping rated to different design pressures from 48 psid up to 325 psid, and is protected from overpressure by relief valves set to as low as 30 psi, up to 150 psi. This piping note analyzes the tubing and shows the system complies with FESHM 5031.1 and ASME 31.3 code for process piping for operational pressure/temperature design, as well as all relief scenarios, calculated for each section of piping.

FESHM 5031.1 PIPING ENGINEERING NOTE FORM

Prepared by: **Erik Voirin** Preparation Date: **03-12-2015**

Piping System Title: **Muon g-2 Helium Piping**

Lab Location: **MC1 Building** Location code: **209**

Purpose of system**: Supply and Return Two-phase Helium to Superconducting Rings.**

Piping System ID Number: **none assigned**

Appropriate governing piping code: **ASME B31.3**

Fluid Service Category (if B31.3): **Normal Fluid Service**

Fluid Contents: **Two-phase Helium**

Design Pressure: **48 / 65 / 80 / 115 / 165 / 250 / 325 psid** **@ 4.4K,**

Piping Materials: **Aluminum 6063-T52 / 304SS / Alloy 122 Copper**

Drawing Numbers (PID's, weldments, etc.): **g-2 Doc 1830 - APPENDIX C**

Designer/Manufacturer: **Brookhaven National Laboratory / Fermilab**

Test Pressure: **53 / 72 / 88 / 127 / 182 / 275 / 360 psid** Test Fluid: **Nitrogen** Test Date: **TBD**

Statements of Compliance

Piping system conforms to FESHM 5031.1, installation ***is not*** exceptional: **Yes**

Piping system conforms to FESHM 5031.1, installation ***is*** exceptional and has been designed, fabricated, inspected, and tested using sound engineering principles: **N/A**

Reviewed by: ____ (Print Name)

Signature: ____Date: _____________

D/S Head's Signature: ___________________________________Date: _____________

The following signatures are required for exceptional piping systems:

ES&H Director's Signature: _______________________________Date: _____________

Director's Signature or Designee: ___________________________Date: _____________

Pipe Characteristics

Size: **Sch10S Pipe: (½"), (¾"), (1"),** Volume: **~ 20 Liters**

SS tube: (0.25"OD), (0.5"OD), (0.75"OD), (0.1"OD) x 0.035" wall minimum

Copper Pipe: (0.25/0.5" OD x 0.035 wall), (½", 5/8", 3/4", 1" Type M),

Aluminum tube: (0.5"OD x 0.0625 wall)

Relief Valve Information:

Type: **Spring Loaded** Manufacturer: **Generant / Circle Seal / Flow Safe / RSXO**

Set Pressure: not applicable Relief Capacity: **30 / 50 / 65 / 100 / 150 psig**

Relief Design Code: **ASME**

Is the system designed to meet the identified governing code? **Yes**

Fabrication Quality Verification:

Process and Instrumentation diagram appended? **Yes, APPENDIX C**

Process and Instrumentation component list appended? **Yes, APPENDIX C**

Is an operating procedure necessary for safe operation? **No**

If 'yes', procedure must be appended.

Exceptional Piping System

Is the piping system or any part of it in the above category? **No**

If "Yes", follow the requirements for an extended engineering note for Exceptional Piping Systems.

Quality Assurance

List vendor(s) for assemblies welded/brazed off site: **Brookhaven Nat'l Lab**

List welder(s) for assemblies welded/brazed in-house: **Leonard Harbacek**

Append welder qualification Records for in-house welded/brazed assemblies. **APPENDIX G**

Append all quality verification records required by the identified code (e.g. examiner's certification, inspector's certification, test records, etc.)

Table of Contents

Piping Note Body:

1. Description and Identification

The scope of this piping note is all of the general Helium piping for the Muon g-2 cryogenic helium transfer lines not covered in other piping or pressure vessel notes [References 1 and 2]. The piping system was previously used at Brookhaven Nation Laboratory on their Muon g-2 project in the early 1990's. Several additions such as the cool down piping, transfer lines, additional instruments have been added to the piping.

There are several sections of piping with different pressure ratings as described in form 5031.1. The following page shows the P&ID of the piping covered in this document, as well as related piping covered in previous notes. Double clicking on the figure will open it, and the specific pipe sections covered in this document are color coded and labeled according to their specific design pressure.

The reason the entire piping system isn't rated for the same pressure is there are low range pressure transmitters meant to be accurate at several psi, which do not have a high proof pressure. These Pressure Transmitters are from BNL, along with most of the relief valve pressure settings. Several relief valve settings were lowered from 300 psi to 150 psi, but none were raised. All piping from BNL was pressure tested at fabrication time according to those original relief settings, though a full pressure test of all piping will still be performed at Fermilab.

2) Piping and Instrument diagram

The piping and instrument diagram is in g-2 DocDB: Doc 1830, and also shown in APPENDIX C. This contains all helium piping with inflector and nitrogen system hidden for clarity. The Valve and instrument list for the entire cryogenic system is attached as well.

3) Design codes and evaluation criteria

These LHe transfer lines meet the requirements of section 5031.1 of the Fermilab ES&H Manual, which states that this piping system falls under the category of Normal Fluid Service. This means it shall adhere to the requirements of the ASME Process Piping Code B31.3. Section 5032 contains additional requirements for cryogenic system components.

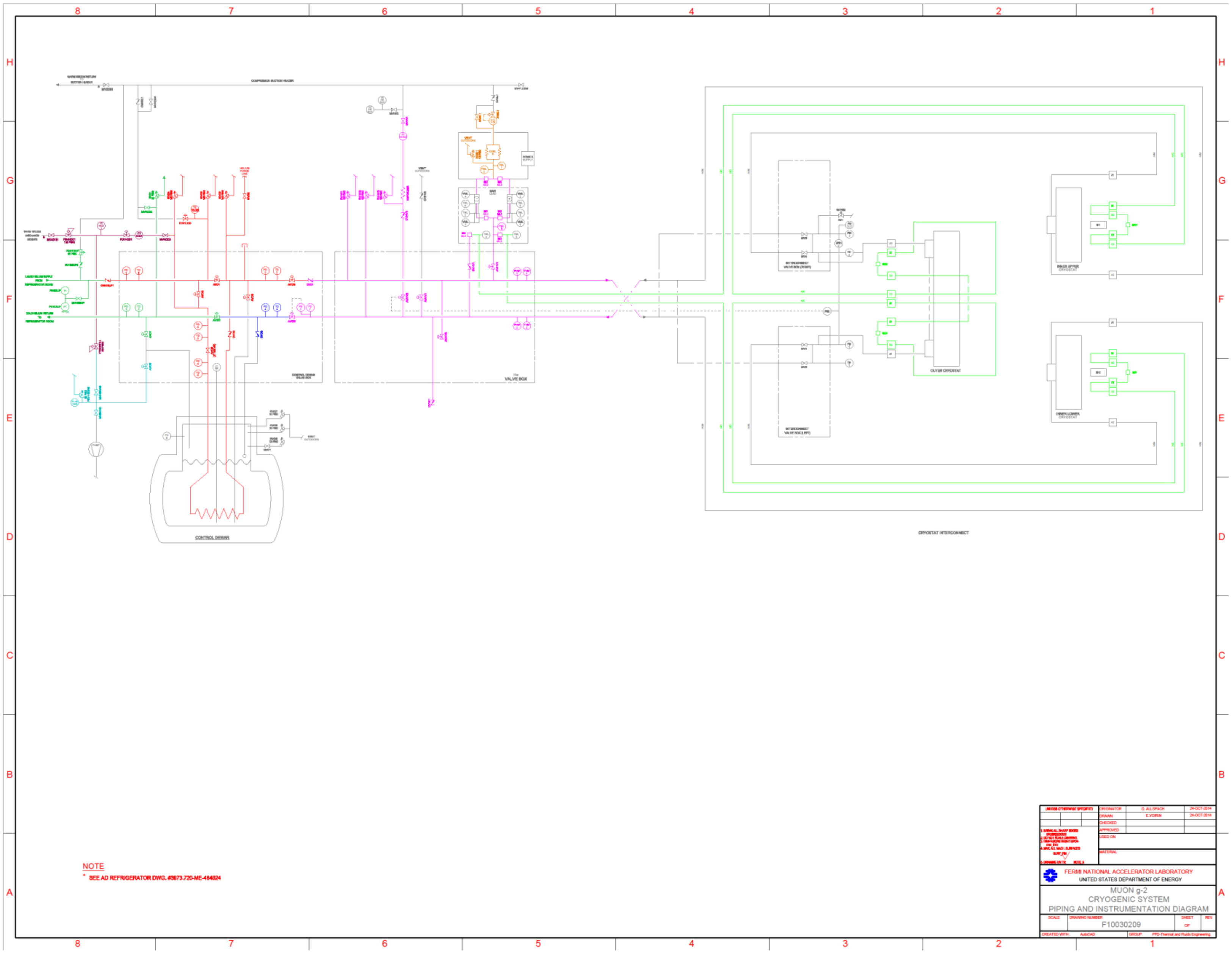


Figure 1: P&ID of Helium Piping (double click figure without "protected mode" enabled to open PDF)

4) Materials

Some sections of the tubing, such as the conductor cooling lines are fabricated from 6063-T52 Aluminum. The allowable stress for this temper is not listed, though it can be seen by the values in the ASME Table that they use 1/3 the Minimum specified strength, so 1/3 of the 27 ksi listed for this material would be 9 ksi allowed by the code for this material/temper. The piping will be operated at 4.4K (-451.75 F). This is above the minimum temperature listed for this material (-452K)

Other sections of the tubing for the helium lines, such as instrument tubes and concentric copper tubes used as the main leads are fabricated from Alloy 122 Copper Pipe. The allowable stress for this material is de-rated to 6 ksi due to potential softening at brazed joints, which is recommended by the Copper Tube Handbook [9]. The piping will be operated at 4.4K (-451.75 F). This is above the minimum temperature listed for this material (-452K).

The rest of the helium piping is fabricated from 304 and 316 SS. The lowest allowable stress (i.e., that of 304L stainless steel, 16.7 ksi) from Table A-1 of B31.3 will be used in this analysis. The piping used for LHe is subject to 4.4 K (-452 ^{o}F). This is below the minimum temperature listed for 304/304L stainless steel. According to 323.2.2 of the Code, impact testing is required for this material. Fermilab has extensive service experience using 304/304L stainless steel piping down to 4.4 K. In addition, the ASME BPV Code Section UHA-51(g) exempts impact testing of materials listed in UHA-23 for vessels when the coincident ratio of design stress in tension to allowable tensile stress is less than 0.35, which is an additional safety factor of 1/0.35 = 2.86. B31.3 Table 323.2.2 Note 6 also provides an exception to impact testing for temperatures below the minimum listed temperature "…when the maximum obtainable Charpy specimen has a width along the notch of less than 2.5 mm (0.098 in)."

5) Pipe Design / Internal pressure design

The pressure rating of all system pipes/tubes is evaluated using the procedures in 304.1.2(a) of ASME B31.3. Calculations show all pipes are rated for higher pressure than the maximum design pressure of the system (325 psi). It would in fact be difficult to find a commercial pipe/tube which isn't rated for at least 325 psi, even standard 1" PVC plastic pipe is rated for 450 psi. Including the additional safety factor of 2.86, the SS parts must be rated for at least 928 psi, which they all are, the lowest rating being the 1" tube at 1203 psi.

ASME Equation for required wall thickness >> Converted to pressure rating

$$t_m = \frac{P_1 \cdot D_1}{2 \cdot (S_1 \cdot E_1 \cdot W_1 + P_1 \cdot Y_1)} \ \text{solve}, P_1 \ \rightarrow \frac{2 \cdot E_1 \cdot S_1 \cdot W_1 \cdot t_m}{D_1 - 2 \cdot Y_1 \cdot t_m}$$

D = outside diameter of pipe as listed in tables of standards or specifications or as measured

$E_1 := 1$ — E = quality factor from Table A-1A or A-1B

$Pressure_{rating}$ — P = internal design gage pressure

S = stress value for material from Table A-1

t_m = minimum required thickness, including mechanical, corrosion, and erosion allowances

$W_1 := 1$ — W = weld joint strength reduction factor in accordance with para. 302.3.5(e)

$Y_1 := 0.4$ — Y = coefficient from Table 304.1.1, valid for $t < D/6$ and for materials shown. The value of Y may be interpolated for intermediate temperatures. For $t \geq D/6$,

$$P_{ratingASME}(S_1, D_o, t_m) := \frac{2 \cdot E_1 \cdot S_1 \cdot W_1 \cdot t_m}{D_o - 2 \cdot Y_1 \cdot t_m}$$

All piping/tubing sizes are rated for higher than the maximum 325 psid:

$Pipe_{data} :=$

"Pipe/Tube Description"	"Allowable Stress"	"OD"	"t.wall"	"Pressure Rating"
"1/2" Schedule 10"	16.7	0.84	0.083	3584
"3/4" Schedule 10"	16.7	1.05	0.083	2818
"1" Schedule 10"	16.7	1.315	0.109	2965
"SS Tube"	16.7	0.25	0.035	5266
"SS Tube"	16.7	0.5	0.035	2477
"SS Tube"	16.7	0.75	0.035	1619
"SS Tube"	16.7	1	0.035	1203
"Copper Pipe"	6	0.25	0.035	1892
"Copper Pipe"	6	0.5	0.035	890
"Copper Pipe"	6	0.625	0.028	558
"Copper Pipe"	6	0.875	0.032	452
"Copper Pipe"	6	1.125	0.035	383
"Aluminim Tube"	9	0.5	0.0625	2500

```
PressureRating :=  for i ∈ 1..13
                     Rating_i ← PratingASME(Pipedata_i,1·ksi, Pipedata_i,2·in, Pipedata_i,3·in)
                   return Rating
```

Additional Pressure Components:

All other system components, valves, and instruments are listed in Appendix C in the Valve and instrument list and Purchase Orders. The valve and instrument list also lists the design pressure for each component based on which section of pipe the device is located. All system components are rated for pressured above the sections design pressure.

6) Pressure Containment / Relief Valves

The piping is protected from overpressure by a system of relief valves located along the piping at pressure settings either equal to, or below the design pressure of the piping. There are several sections of the piping which have relief valves set much lower than their design pressure, which is because of the high pressures which may develop in the Helium Mandrel tube in the event of a total loss of vacuum combined with a magnet quench without the installed quench protection dump resistor. That scenario is rigorously analyzed in Mandrel Piping Engineering Note, g-2 document 1981 [1]. In the event of abnormal pressure rise resulting from a quench, an automated valve (AVD5) will close to isolate the high pressure and prevent it from being transferred through the helium return piping and to the downstream sections of piping. The closing of this “fail closed” valve is controlled by a pressure transmitter (PD7) and the PLC logic, for redundancy, it can also be closed by the in-line pressure switch (PS7). A check valve on the Helium Supply line (CVD1) serves the same purpose for the upstream piping. Another step taken during a quench is automated valve (AVHV2) will open to vent Helium back into the suction line. This is controlled by PLC logic and occurs in the event of abnormally high pressure (30 psi) read by PIH1 and the redundant pressure switch PS2. The above automated venting is not taken into account in helium relief calculations, it is there only to hopefully save some helium from being lost and be venting into the atmosphere.

There are no system sources of pressure that can supply cold Helium at a rate high enough to exceed relief capacity and increase the pressure above any pipe sections design pressure. Supply flow from the cold helium source, MYCOM compressors, is estimated at less than 120 gm/sec, which is far below any relief valve capacity even without the upstream relief valves. The warm helium can be supplied at 325 psi, and relief valves are adequately sized to vent flow from this source.

Fire is not considered credible due to the lack of combustible material in the vicinity of the piping, which is encased inside vacuum jackets and/or surrounded by heat shields. Even if it were included, the heat load would surely be less than the worst case scenario analyzed, catastrophic loss of vacuum with air, which would condense and freeze on the helium piping.

APPENDIX A describes all 9 pipe sections and their relief scenarios.

7.) Welding Information

Nearly all welding was done during manufacture in the early 90's by BNL. Several helium tubes in the interconnect region had to be cut to prepare for transport. These tubes will be re-welded here at Fermilab by Leonard Harbacek, qualifications attached, but all these welds will be socket type welds, meaning no radiography or in-process weld inspection is required by ASME B31.3.

8.) Vacuum Jacket Relief

The Vacuum jackets for this piping do not require a formal engineering note, so we describe their volume and relief requirements in this note.

Area of relief valve required per CGA S-1.3 is 0.00024in^2 per pound of water capacity.

$\rho_{water} := 1000 \frac{kg}{m^3}$ $\qquad CGA_{VacRelief} := 0.00024 \frac{in^2}{lb}$

Vacuum Volume and Relief Requirements for Vacuum Space A

Included Sections: (See Appendix B - Transfer Line Drawings, and Dewar Box Piping)

1.) From Connection to AD Transfer Line to Dewar Box
2.) Dewar Box
3.) From Dewar Box to Lead Can Connection

Volume of Part 1:

$D_{transLine1} := 6in \qquad L_{transLine1} := 16ft \qquad Volume_{TransLine1} := \frac{\pi}{4} \cdot D_{transLine1}^{\ 2} \cdot L_{transLine1} = 3.142\, ft^3$

Volume of Part 2:

$Volume_{DewarBox} := 26in \cdot 26in \cdot 22.5in = 8.802\, ft^3$

Volume of Part 3:

$D_{transLine3} := 6in \qquad L_{transLine3} := 18ft \qquad Volume_{TransLine3} := \frac{\pi}{4} \cdot D_{transLine3}^{\ 2} \cdot L_{transLine3} = 3.534\, ft^3$

Total Volume and Relief Requirements:

$Volume_{VacA} := Volume_{TransLine1} + Volume_{DewarBox} + Volume_{TransLine3} = 15.478\, ft^3$

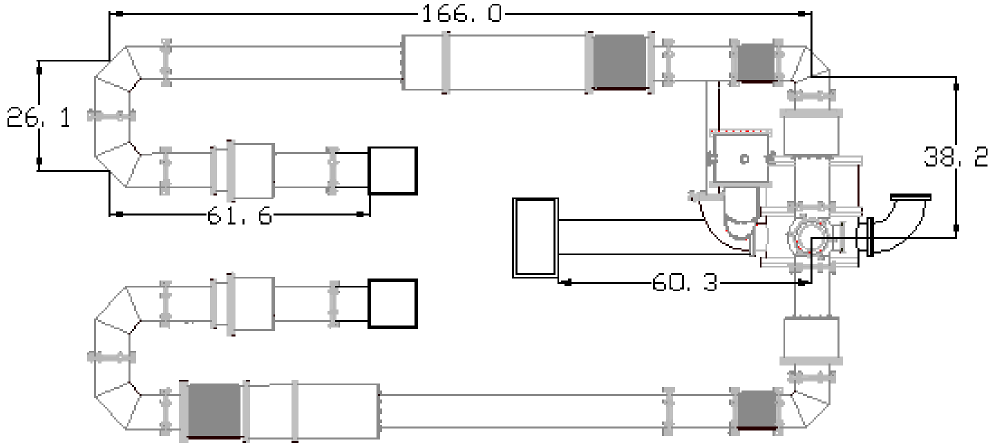
$VacRelief_{areaRequired\_SectA} := Volume_{VacA} \cdot \rho_{water} \cdot CGA_{VacRelief} = 0.232 \cdot in^2 \quad < \quad Area_{CVI} := 0.25in^2$

This required relief area is satisfied by the 1" CVI pumpout valve on the piping which has a relief area of 0.25 in² according to CVI Calculations / Testing by Russ Rucinski 2/12/1999, See ATTACHMENT #1)

Relief Requirements for Vacuum Space B

Included Sections:

All Interconnect Piping, Helium Valve Box, Nitrogen Valve Box, Lead Can, Hairpin and all instrument and valve cans in the dongle region



This vacuum space is connected to the Cryostat Vacuum Space. This vacuum space was analysed in g-2 document #1699: "E989 Note 14: Muon g-2 Cryostat - Vacuum Vessel Engineering Note" [8]. That analysis involved rigourous calculations of a scenario of a pipe rupture, which dumps all the liquid helium in the lines into the vacuum space and calculates the transient leak rate, pressure rise, and relief rate during the scenario. Since that analyses included this vacuum space, it suffices to show this space it protected against overpressurization as well.

9) References

1. g-2 document # 1981 – v5, October 8, 2014. E989 note 21: g-2 mandrel LHe piping engineering note <http://gm2-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1981>

2. g-2 document # 1886 – v4 , Sept 10, 2014. g-2 LHe Dewar Pressure Vessel Engineering Note <http://gm2-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=1886>

3. Flow Equations for sizing Control Valves. Standard ISA-S75.01-1985

4. W.Lehman & G Zahn, *Safety Aspects for LHe cryostats,* Proc. ICEC7, IPC Science and Technology (1978) 569 – 579

5. g-2 document # 1586 – v1, June 21, 2014. E821 documents on Cryogenics < http://gm2-docdb.fnal.gov:8080/cgi-bin/RetrieveFile?docid=1586&filename=309%20Jia.pdf&version=1>

6. g-2 document # 1830 – v1 , June 21, 2014. Piping and Instrumentation Diagram for Muon g-2 Cryogenic and Vacuum Systems
<http://gm2-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=1830>

7. g-2 document # 1892 – v1, June 21, 2014. “Some cryo info”
<http://gm2-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=1892>

8. g-2 document # 1699 – v0, Mar 12, 2014. “Note 14: Muon g-2 Cryostat - Vacuum Vessel Engineering Note < http://gm2-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=1699>

9. Copper Development Assoc. Inc. THE COPPER TUBE HANDBOOK Web. 8 Aug. 2014.
<http://www.copper.org/publications/pub_list/pdf/copper_tube_handbook.pdf>