THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

12000 Jefferson Avenue
Newport News, VA 23606

PS ANALYSIS NO.:
PS-SRF-18-001-A1

TITLE: LERF LCLSII Cryomodule Testing Pressure System Analysis

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BY: Matt Marchlik

CHECKED: Katherine Wilson

APPROVED: Edward Daly

APPROVED: Kevin Jordan

1. Scope

The LCLS-II cryomodules are currently being tested individually in the CMTF in the Test Lab. In order to increase the testing frequency, the LERF is being adapted to support the testing of two cryomodules simultaneously.

The helium is supplied from the existing helium supply lines that originally supplied the recently removed LERF cryomodules. U-tubes connect these lines to bayonets in the transfer lines. The transfer lines are connected to the Cryo Can that contains control valves and instrumentation. The cryo can connects to a vacuum bellows assembly on the end of the first cryomodule. The Interconnect region connects another cryomodule to the first. The system terminates at the end can assembly at the end of the second cryomodule. The transfer line, cryo can and cryomodules share insulating vacuum. These system components will be described in more detail in this analysis.

This analysis will show that all aspects of the system comply with the ES&H manual, chapter 6151 and applicable ASME code requirements.

The system P&ID is JL0043630.

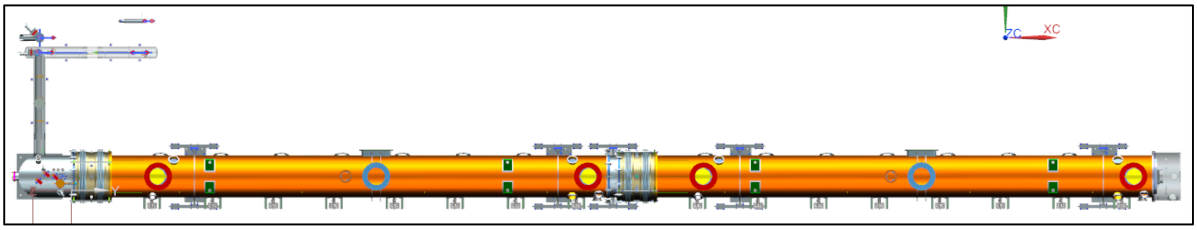


Figure 1: Overall Layout (JL0048814)

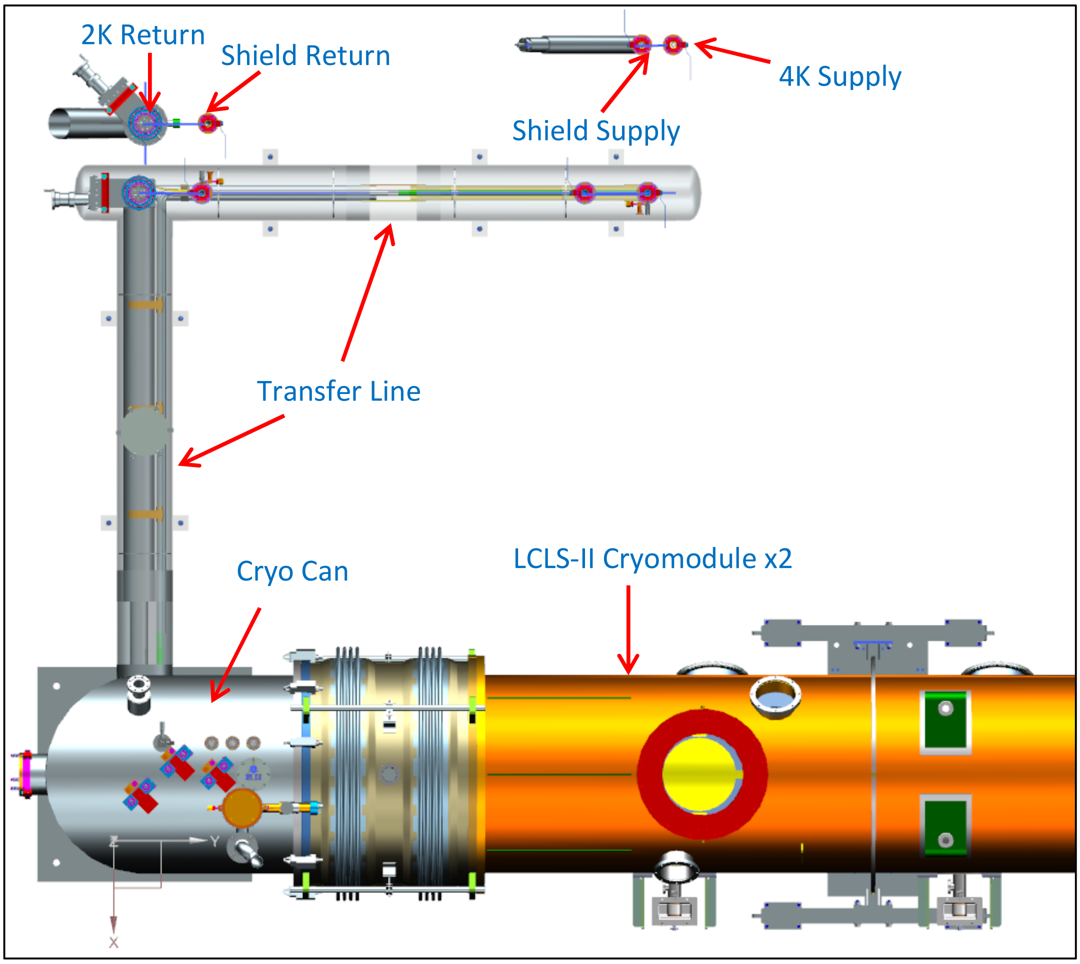


Figure 2: Transfer line Region Detail

2. System Parameters

2.1. Parameters

2.1.1. Fluid Service

2.1.1.1. Normal fluid service. [ASME B31.3, Appendix M]

2.1.2. Design Pressures

2.1.2.1. The 4 K supply circuit's design pressure is 165 psig.

2.1.2.2. The 35 K shield supply circuit's design pressure is 165 psig.

2.1.2.3. The 35 K shield return circuit's design pressure is 165 psig.

2.1.2.4. The 2 K return circuit's design pressure is 58 psig.

2.1.2.5. The 300 K supply circuit's design pressure is 150 psig.

2.1.2.6. The cool down circuit's design pressure is 58 psig upstream of CEVCM03CD and 35 psig downstream of CEVCM03CD.

3. Analysis

The calculations referenced in this analysis can be found in the appendix of this document and the pressure systems folder.

3.1. Items Omitted from this Analysis:

3.1.1. Existing LERF helium supply lines

The system is considered a legacy system that will operate within its original parameters. It is not being altered in any way.

3.1.2. Cryomodules

The cryomodules are covered in their own pressure system, “PS-SRF-16-001 LCLS-II Cryomodule.”

3.1.3. Bayonet Assemblies

The bayonet assemblies were originally designed in 1989 and have been used extensively thereafter. New assemblies are being fabricated per the existing drawings for use in this system. They have been analyzed for and used at similar or more extreme conditions in various pressure systems since the implementation of Chapter 6151 of the ES&H manual.

Design pressures have been developed for the bayonet assemblies in LCLS-II engineering note number LCLSII-4.8-EN-0820-R0. The 1-1/2” and 3-1/8” bayonets are used in this system and they have a 570 psig and 83 psig design pressure, respectively.

The highest pressure that the 1-1/2” bayonet may see in this system is 150 psig, 165 psig when taking into account that the bayonet resides within vacuum.

The highest pressure the 3-1/8” bayonet may see in this system is 43 psig, 58 psig when taking into account that the bayonet resides within vacuum.

3.1.4. U-Tubes

The u-tubes being used are the existing ones that originally supplied the LERF cryomodules. Since they are being used within their original parameters and are not being altered in any way, they are being treated as legacy items.

3.1.5. Coriolis Meters

The Emerson Coriolis meters are designed and fabricated according to ASME B31.3. They have a design pressure of 1,500 psig. The only modifications being done on these meters is to the sensing components. The pressure boundary components will remain unaltered.

3.1.6. Flex Lines

There are a 14 flex lines made from hydro formed bellows with braided jackets in the assembly made from 300 series stainless steel. All of the drawings of the flex lines in the pressure system contain the following specifications and notes that dictate ASME B31.3 compliance:

Specs

i. ASME B31.3 Service: Normal
ii. Internal design pressure: 150 psig
iii. External design pressure: 17 psia
iv. Min/max Design Temperature: 4/300 K
v. Leak test per ASME B31.3

Notes

i. Supplier shall furnish material certifications
ii. Entire assembly shall be designed, examined and tested in accordance with ASME B31.3
iii. (Cold shocking) Entire assembly shall be immersed in liquid nitrogen until stabilized, then return to room temperature and leak tested. Three cycles required.

Therefore, all bellows/flex line assemblies are considered to be compliant with the requirements of ASME B31.3.

3.2. Process Piping

3.2.1. 4 K supply line

The 4 K supply line is also sometimes referred to as the “primary supply” line. The code of record for all of the process piping components within the transfer line assembly is ASME B31.3. The design pressure of this entire supply line is 165 psig. This is driven by the 150 psig relief valve protecting this line. 1 atm is added since the piping is within vacuum.

3.2.1.1. Piping

The majority of the 4K supply line is comprised of ¾ NPS, sch10, ASTM A312 304SS piping. The maximum allowable pressure for this piping was found to be 3,017 psig. 3,017 psi >> the 150 psig design pressure of this line. This calculation covers all identical piping in this pressure system since the maximum design pressure in the system is 150 psi.

Since the ½” NPS, sch10 piping has the same wall thickness as the ¾” pipe, the ½” pipe throughout the system is covered by the ¾” calculation. This calculation may be seen in Appendix 1.

The female supply bayonet in this line is made from 1.5” OD .038” wall ASTM A269 304L SS tubing. This tube is welded to the female bayonet seal ring with a full penetration weld. The maximum allowable pressure was found to be 713 psi. 713 psi >> 165 psi design pressure. This calculation may be seen in Appendix 4.

3.2.1.2. CF Flanges

CF flanges are installed at the ends of each of the lines where they terminate into the cryomodule. They are made from 304 SS. These flanges are only required for testing and are removed for cryomodule installation at SLAC.

Inside the cryo can, the 4 K supply line branches off into the 2 K supply and the 5 K circuit immediately following control valve CEVCM0312. The 2 K supply line terminates at the cryomodule at a 4.5” CF flange after going through a Coriolis meter.

CF flanges are not designed for use in internal pressure applications and are considered unlisted components. The largest of the CF flanges was analyzed according to ASME BPVC VIII-I against the highest design pressure of the system, 165 psi.

The flange bolting force was found to be 18,403 lbf, much greater than the minimum required bolt loading for operational conditions of 2,326 lbf.

The moment induced stress in the flange was found to be 3,409 psi, which is far below the allowable stress of 20,000 psi.

The bolt tensile stress was found to be 19,735 psi, which is less than the 20,000 psi allowable.

The analysis, detailed in appendix 6, shows that the CF flanges are suitable for use in this pressure system.

3.2.1.3. Pressure Drop

A general pressure drop calculation was performed for this circuit from the supply bayonet up to the cryomodule in order to demonstrate that a mass flow rate of at least 30 g/s will be achievable for Fast Cooldown operations. The analysis is shown in a separate analysis, PS-SRF-18-001-A2.

3.2.2. 35 K Shield Supply

The 35 K shield circuit supply line is primarily comprised of ¾ NPS, sch10, ASTM A312 304SS piping. The design pressure of this entire supply line is 165 psig. This is driven by a 150 psig relief valve protecting this line. 1 atm is added since the piping is within vacuum. This circuit contains components that are identical to the 4 K supply line. No analysis is needed for this circuit.

3.2.3. 35 K Shield Return

The 35 K shield return line is primarily comprised of ¾ NPS, sch10, ASTM A312 304SS piping. The design pressure of this entire supply line is 165 psig. This is driven by a 150 psig relief valve protecting this line. 1 atm is added since the piping is within vacuum. This circuit contains components that are identical to the 4 K supply line. No analysis is needed for this circuit.

3.2.4. 2 K Return

The 2 K return line is primarily comprised of 3 NPS, sch10, ASTM A312 304SS piping. The design pressure of this entire supply line is 58 psig. This is driven by a 43 psig protecting this line. 1 atm is added since the piping is within vacuum.

3.2.4.1. Piping

The maximum allowable pressure for this piping was found to be 1,266 psi. This is well above the 58 psig design pressure. This calculation is located in Appendix 1.

3.2.4.2. GHRP Flange Assembly

The Gaseous Helium Return Piping (GHRP) flange assembly joins the 2 K return piping from the cryomodule to the 2 K return piping of the cryo can and transfer lines.

The bolt clamping force was found to be adequate per ASME/BPVC VIII-I, mandatory appendix2.

The moment induced stress in the flange was found to be an acceptable value per ASME/BPVC VIII-I, mandatory appendix2.

The flange was analyzed as an unstayed flat head per UG-34 and found to be of adequate thickness.

The flange's opening was analyzed per ASME/BPVC VIII-I, UG-39 to demonstrate that no additional reinforcement is required.

This flange assembly has been tested and used successfully in other cryomodule testing systems and has been proven to be capable of making a UHV leak tight joint.

This analysis is located in Appendix 7.

3.2.4.3. Relief Stack

The relief stack runs perpendicularly off of the 2 K return line. It contains the primary overpressure protecting relief valves for the 2 K return line.

It is primarily comprised of 2" NPS, sch10, 304 SS pipe. The max allowable pressure was found to be 1,709 psi, which is far above the 58 psi design pressure. This is calculated in Appendix 1.

3.2.4.4. Cryogenic Check Valve

A check valve is located directly upstream of the relief stack. Since this valve is being fabricated from scratch, it may not be considered a "legacy" item and is not eligible for omission from the requirements of ES&H Manual chapter 6151.

The use of this valve in this application without supplying detailed calculations is justified through ASME B31.3 paragraph 304.7.2(a).

Identical valves have been fabricated from the identical drawing which will be used to fabricate the valve for this system and they have been used extensively for years under similar operating conditions.

3.2.5. JT Valves

There are three JT valves within this system. They are designated as CEVCM0312, CEVCM0313 and CEVCM03CD on the P&ID. CEVCM0312 is the primary helium supply control valve, CEVCM0313 is the 4.5 K helium supply valve and CEVCM03CD is the cool down bypass control valve.

The JT valve assemblies were originally designed in 1989 and have been used extensively thereafter. New assemblies are being fabricated for use in this system. Since the valves are being fabricated from scratch, they cannot be considered “legacy” items and are not eligible for omission from the requirements of ES&H Manual chapter 6151.

The use of these valves in this application without supplying detailed calculations is justified through ASME B31.3 paragraph 304.7.2(a). Identical valves have been fabricated from the identical drawing which will be used to fabricate the valves for this system and they have been used extensively for years under similar operating conditions.

3.2.6. Cooldown Circuit

The cooldown circuit is primarily comprised of ¾ NPS, sch10, 304 SS pipe. It increases in size to 2 NPS, sch10, 304 SS pipe after exiting the cryo can vacuum boundary. Allowable pressures for this piping have already been calculated elsewhere in this analysis. This circuit does not contain any additional items requiring analysis.

3.2.7. Interconnect Region

3.2.7.1. GHRP Spool

The GHRP spool assembly connects the 2 K return between the two cryomodules. The spool piece is machined as one solid body. Its end flanges are identical to those already evaluated above in 3.2.4.2.

The spool piece was verified to be of adequate wall thickness for the internal design pressure as well as 1 atm external loading conditions. This is detailed in Appendix 2.

3.2.7.2. Bellows

The interconnect region joins all of the process piping, beam line vacuum and shared insulating vacuum between the two cryomodules.

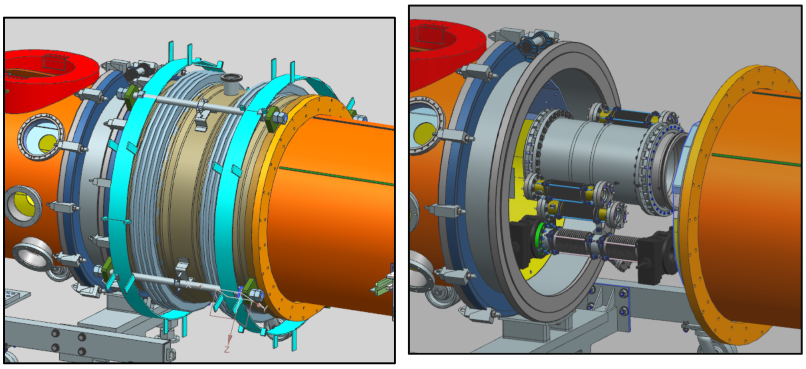


Figure 3: Interconnect Region

All of the process piping lines link through a hydro formed bellows assembly, JL0056926. The bellows are detailed in drawing F10050694. The drawing specifies that the design pressure is 20 bar, or 294 psi and that the manufacturer must comply with EMJA standards. The highest design pressure in this system is 150 psi, 165 psig since the components are within vacuum.

The bellows assemblies are the only process piping components within the interconnect region.

3.2.8. End Cap

The pressure components within the End Cap have already been analyzed and documented in PS-SRF-16-001, no further analysis is required.

3.2.9. 300 K Helium Supply Circuit

The 300 K helium supply circuit is primarily comprised of ½ NPS, sch10, 304 SS pipe. This pipe has the same wall thickness as the ¾ NPS pipe already analyzed to show adequate thickness.

The line contains a control valve, CEVCM03MIX and a flow meter, CFICM0314, which is comprised of an orifice and pressure transducer. The valve, orifice and transducer have 300 psid, 290 psig and 3,600 psig design pressures, respectively. This line terminates into the 2 K supply line within the cryo can.

3.3. Vacuum Components

The transfer line vacuum jacket, cryo can, cryomodules and end can share the same insulating vacuum.

3.3.1. Transfer Line

Since the transfer line vacuum jacket contains a credible pressure source that can exceed 15 psig and is protected from pressurization exceeding 15 psig through engineering controls, it is classified as a category 2 vacuum system.

The transfer line is primarily made from 10 NPS sch10 304SS pipe. Since the cross sectional area is below 33 in^2 and the internal volume is less than 35 ft^3, the transfer line is only required to meet the pressure relief criteria in section 7.5.1 of the PVSSS.

There are four 2 psig parallel plate relief valves that protect the vacuum volume from overpressure. There is one installed on each cryomodule, one on the cryo can and one on the end can. The sizing of the valve is outlined in PS-SRF-16-001. Since the helium inventory within the transfer line and cryo can is much less than that within an individual cryomodule for which the valve was sized for, it is considered more than adequate to protect the transfer line from overpressure.

3.3.2. Cryo Can

Since the cryo can contains a credible pressure source that can exceed 15 psig and is protected from pressurization exceeding 15 psig through engineering controls, it is classified as a category 2 vacuum system.

Since the cross sectional area is greater than 33 in^2 and the internal volume is greater than 35 ft^3, the transfer line is required to meet the all of the requirements of section 7.5 of the PVSSS.

3.3.2.1. Design

The cryo can's wall thickness was evaluated per AMSE BPVC VIII-I, UG-28. The maximum allowable external pressure of the cryo can was found to be 118 psi. This is well above the 1 atm design pressure. This calculation is detailed in Appendix 5.

3.3.2.2. Pressure Relief

Since the helium inventory within the cryo can is much less than that within an individual cryomodule for which the valve was sized for, it is considered more than adequate to protect the cryo can from overpressure.

3.3.3. Interconnect Region

3.3.3.1. Interconnect bellows

The large interconnect vacuum bellows were designed and supplied by FNAL. The bellows design is considered adequate and is assumed to be legacy. It is FNAL's design intent that the bellows not be under atmospheric axial loading since the cryomodules are constrained longitudinally to resist this load at SLAC. However, the cryomodules being tested in the LERF will not be fully constrained longitudinally. This means that the bellows are not being used per design intent. Since they are a part of a vacuum category two system, the flange tabs of the bellows needed to be analyzed to show adequate strength against compression. The welds of the tabs are shown to be inadequate in the calculation shown in Appendix 10.

To strengthen the bellows against the axial 1 atm loading, tab reinforcement blocks will be bolted to the weld tabs as shown in fig.3. The analysis of these blocks show that they alone are capable of handling the full load if the welded tabs were to fail.

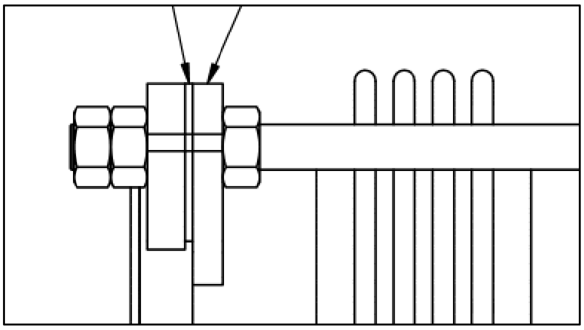


Figure 4: Bellows Tab Reinforcement

3.3.3.2. Interconnect Spool

A large aluminum flanged spool weldment, JL0049562, connects the interconnect bellows to the next cryomodule's vacuum vessel. The spool's wall thickness was verified to be of adequate thickness per ASME BPVC VIII-I, UG-28. This calculation is detailed in Appendix 2.

3.3.4. Return End Cap

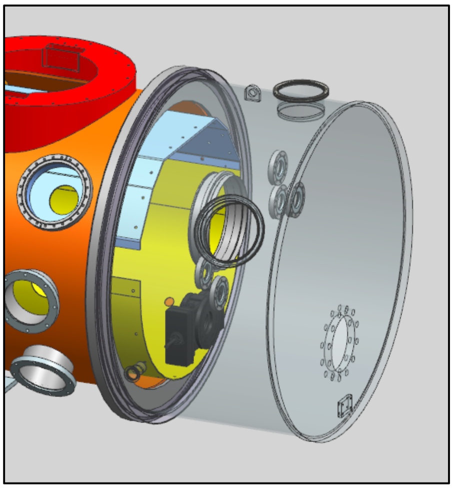


Figure 5: Return End Cap (Internal Components not shown)

The end cap vacuum boundary components have already been analyzed and documented in PS-SRF-16-001, no further analysis is required.

The parallel plate relief valve CRVCM0063 is sized to handle the helium inventory of a single cryomodule. Therefore, it's adequate for over pressure protection of the end cap.

3.3.5. Guard Vacuum

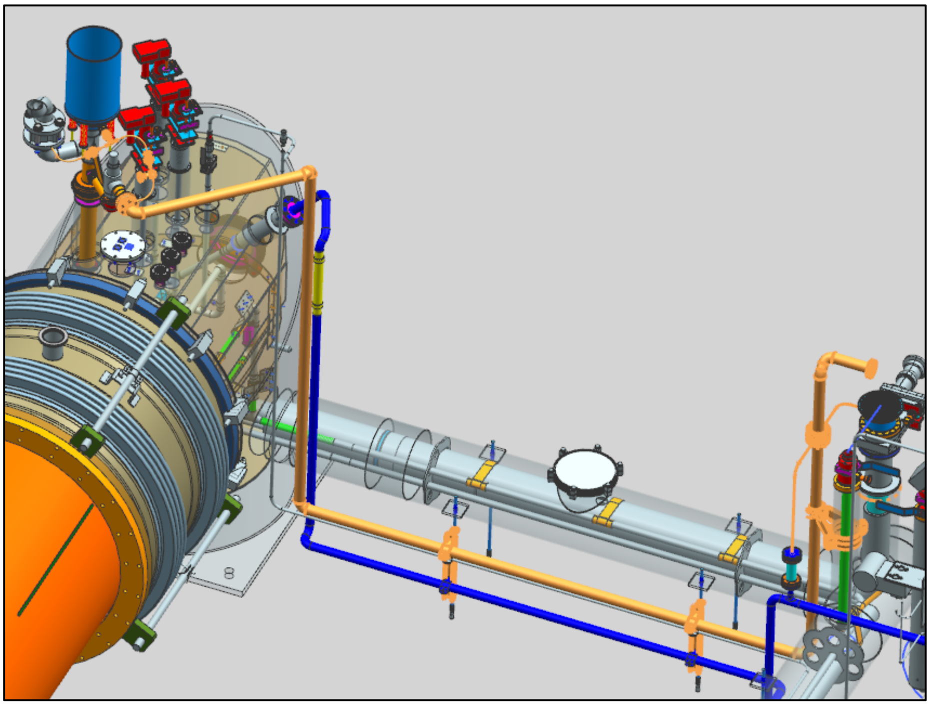


Figure 6: Guard Vacuum (Lines highlighted in orange)

The Guard vacuum system provides a protective vacuum boundary on the 2 K return bayonet, 2 K parallel plate relief, and the 2 K burst disk double o-ring joints. The system is considered a category 0, no further analysis is required.

3.4. Over Pressure Protection

3.4.1. Shield Circuit

The shield circuit contains a single relief valve, CRVCM0311, set at 150 psig. It provides overpressure protection in the case where 35 K helium becomes trapped between the supply and return bayonets when the bayonet valves are closed. The worst case scenario is that insulating vacuum is lost while these valves are closed.

The warm up rate was determined with the assumptions that the pipe sees convection with 295 K air and MLI effects are neglected. The warm up rate and corresponding mass flow were found to be very slow. This valve is more than adequate for limiting pressure to 150 psig in any plausible condition. This analysis is detailed in appendix 8.

3.4.2. 4.5 K Supply

The 4.5 K supply circuit contains a 150 psig relief valve, CRVCM0310, to relieve the volume between CMVCM0310 and CEVCM0312 in the case of trapped helium.

Since the helium mass within these lines is so much smaller than that of the entire shield circuit, this valve is considered adequate for limiting the overpressure to 150 psig in any plausible condition.

3.4.3. 2 K Return

The 2 K relief stack containing the relief valves CRVCM0361, CRVCM0362 and burst disk CRVCM0360 is identical to the one used on the CEBAF C50 cryomodules. Since the C50 and LCLSII CMs have 1500 and 600 (300x2CMs) liter inventories, respectively, this relief stack is capable of protecting the LERF 2 K return line.

3.4.4. 300 K Supply

The 300 K supply contains a 150 psig relief valve, CRVCM0364, to limit the region between CMVCM0365, CEVCM0312, CEVCM0313 and the other 2 K supply control valves within the cryomodule to relieve trapped helium upon warming. It is assumed to be sized adequately as shown above in 3.4.1.

3.4.5. Cool Down Circuit

CRVCM0361 limits the pressure between CEVCM03CD and CMVCM0366 to 30 psig by relieving trapped helium upon warming. The volume between these two valves is small. Based upon previous mass evolution calculations, there is no need to size this valve.

4. Fabrication

All of the fabrication requirements and specifications are outlined in “LERF Cryo Transfer Line Statement of Work” JL0056850SOW and “LERF Cryo Can Statement of Work” JL0049629SOW. All fabrication is being performed by outside vendors.

5. Installation

The only pressure and/or vacuum boundary field welding performed during the installation is in the joining of the two transfer line segments JL0049136 and JL0049135 to one another as shown in drawing JL0056850. This welding will comply with all ES&H manual chapter 6151 requirements.

6. Testing

All process piping and vacuum components fabricated off site will be leak tested by the responsible vendor(s) in compliance with the statements of work.

The transfer line field weld joints will be leak tested prior to the closure of the transfer line vacuum jacket. This is not a requirement of ASME B31.3 since both segments will have already been tested. However, if any leaks were present in the piping their location could not be identified after the vacuum jacket is welded.

The transfer line vacuum jacket welds will be vacuum leak tested along with the entire insulating vacuum space after installation.

6.1. Stored Energy

6.1.1. 35 K Shield Line

The Shield Supply section being pneumatically tested is from bayonet valve CMVCM0310 up to control valve CEVCM0312 at a test pressure of 165 psig*1.1=182 psig. The stored energy of testing in this section is 103 kJ.

6.1.2. 4.5 K Supply Line

The 4.5 K Supply region between supply bayonet manual valve CMVCM0316 and 4.5 K supply valve CEVCM0312 is being pneumatically tested at 165 psig*1.1=182 psig. The stored energy of this test is only 6.3 kJ.

6.1.3. 2 K Return Line

The 2 K Return region contained within supply bayonet manual valve CMVCM0360, CEVCM03CD, control valves CPVCM01CD & CPVCM02CD and JT valves CPVCM01JT1 & CPVCM02JT is being pneumatically tested at (43+14.7) psig*1.1= 64 psig. The stored energy of this test is 932 kJ.

6.1.4. Warm Helium Line

The warm helium line section within valves CEVCM03MIX, CEVCM0312, CEVCM0313, CPVCM01CD & CPVCM02CD and CPVCM01JT & CPVCM02JT is being pneumatically tested at 165 psig*1.1=182 psig. The sored energy of this test is 23 kJ.

Since the stored energy of testing the shield lines is above 100 kJ, an OSP is required per the JLAB ESH&Q manual. However, since the length to diameter ratio is so large and the piping is within the robust stainless steel transfer line and cryo can, and the energy is only slightly above 100 kJ, the risk is greatly mitigated. No OSP will be written for these leak tests.

Appendices

1. Piping Allowable Pressure Calculations
2. GHRP Interconnect Spool Allowable Pressure Calculation
3. Interconnect Vacuum Spool Allowable Pressure Calculation
4. 4.5 K Supply Female Bayonet to Pipe Weld Analysis
5. Cryo Can Allowable Pressure Analysis
6. CF Flange Analysis
7. GHRP Flange Analysis
8. Trapped Helium 150 psi Relief Valve Sizing Check
9. Leak Testing Stored Energy calculations
10. Interconnect Bellows Weld Tab Analysis

Appendix 1: Piping Allowable Pressure Calculations

3/4 NPS sch10

$t_{.75} := .083 \cdot (.9) \cdot in = 0.075\ in$ 3/4" NPS sch10 304 SS pipe wall

$D_{.75} := 1.05 \cdot in$ 3/4" NPS OD

$\frac{D_{.75}}{6} = 0.175\ in$

t < D/6

$S_{A312} := 20000 \cdot \frac{lb}{in^2}$ ASME B31.3 Table A-1 allowable stress

$E := 1.0$ Quality factor

$W := 1.0$ Weld joint factor

$Y := .4$

$P_g := 150 \cdot psi$ Gauge pressure, driven by 150 psig relief valve

$P_{design} := P_g + 14.7 \cdot psi = 164.7\ psi$ Design pressure. 1 atm added, piping is within vacuum

Per ASME B31.3, par.304.1.2

$$P_{max.75} := \frac{(S_{A312} \cdot E \cdot W \cdot 2 \cdot t_{.75})}{(D_{.75} - Y \cdot 2 \cdot t_{.75})} = 3017.45\ \frac{lb}{in^2}$$

$$P_{max.75} >> P_{design}$$

3 NPS sch10

$t_3 := .12 \cdot (.9) \cdot in = 0.108\ in$ — 3" NPS sch10 304 SS pipe wall

$D_3 := 3.5 \cdot in$ — 3" NPS OD

$\frac{D_3}{6} = 0.583\ in$

t < D/6

$S_{A312} := 20000 \cdot \frac{lb}{in^2}$ — ASME B31.3 Table A-1 allowable stress

$E := 1.0$ — Quality factor

$W := 1.0$ — Weld joint factor

$Y := .4$

$P_{g3} := 43 \cdot \frac{lb}{in^2}$ — Gauge pressure, driven by 43 psig relief valve

$P_{design} := P_{g3} + 14.7 \cdot \frac{lb}{in^2}$ — Design pressure. 1 atm added, piping is within vacuum

Per ASME B31.3, par.304.1.2

$$P_{max3} := \frac{S_{A312} \cdot E \cdot W \cdot 2 \cdot t_3}{(D_3 - Y \cdot 2 \cdot t_3)} = 1265.53\ \frac{lb}{in^2}$$

$P_{max3} >> P_{design}$

2 NPS sch10

$t_2 := .109 \cdot (.9) \cdot in = 0.098\ in$ — 2" NPS sch10 304 SS pipe wall

$D_2 := 2.375 \cdot in$ — 2" NPS OD

$\frac{D_2}{6} = 0.396\ in$

t < D/6

$S_{A312} := 20000 \cdot \frac{lb}{in^2}$ — ASME B31.3 Table A-1 allowable stress

$E := 1.0$ — Quality factor

$W := 1.0$ — Weld joint factor

$Y := .4$

$P_{g2} := 43 \cdot \frac{lb}{in^2}$ — Gauge pressure, driven by 43 psig relief valve

$P_{design} := P_{g2} + 14.7 \cdot \frac{lb}{in^2}$ — Design pressure. 1 atm added, piping is within vacuum

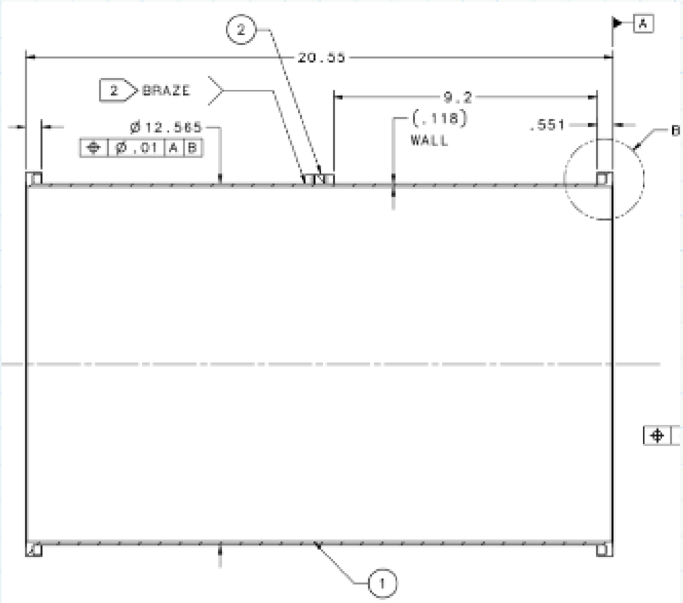
Per ASME B31.3, par.304.1.2

$$P_{max2} := \frac{S_{A312} \cdot E \cdot W \cdot 2 \cdot t_2}{(D_2 - Y \cdot 2 \cdot t_2)} = 1708.67\ \frac{lb}{in^2}$$

$P_{max2} >> P_{design}$

Appendix 2: GHRP Interconnect Spool Allowable Pressure Calculation

Interconnect GHRP Spool



The GHRP spool is made from ASTM A312 304 SS.

$t_{ghrp} := .118 \cdot (.9) \cdot in = 0.106\ in$ — wall thickness

$D_{ghrp} := 12.564 \cdot in$ — Spool OD

$\frac{D_{ghrp}}{6} = 2.094\ in$

t < D/6

$S_{A312} := 20000 \cdot \frac{lb}{in^2}$ — ASME B31.3 Table A-1 allowable stress

$E := 1.0$ — Quality factor

$W := 1.0$ — Weld joint factor

$Y := .4$

$P_{g\_ghrp} := 43 \cdot \frac{lb}{in^2}$ — Gauge pressure, driven by 43 psig relief valve

$P_{design} := P_{g\_ghrp} + 14.7 \cdot \dfrac{lb}{in^2}$ Design pressure. 1 atm added, piping is within vacuum

Per ASME B31.3, par.304.1.2

$P_{max\_ghrp} := \dfrac{S_{A312} \cdot E \cdot W \cdot 2 \cdot t_{ghrp}}{\left(D_{ghrp} - Y \cdot 2 \cdot t_{ghrp}\right)} = 340.41 \; \dfrac{lb}{in^2}$ $P_{max\_ghrp} > P_{design}$

The spool will normally operate sub atmospherically. per ASME B31.3, par.304.1.3, the minimum wall thickness and stiffening requirements shall be determiend per BPVC VIII-I, UG-28.

304 SS, A-312

$S_{tensile} := 75 \cdot ksi$ Allowable tensile strength per ASME BPVC-II-D, Table 1-A

$S_{yield} := 30 \cdot ksi$

$t_{ghrp} := .118 \cdot in$ Shell thickness

$D_{ghrp} := 12.564 \cdot in$ OD of shell

$ratio_{DT} := \dfrac{D_{ghrp}}{t_{ghrp}} = 106.5$ OD to thickness ratio

Since ratio > 10, follow procedure of UG-28 (c)-(1)

Step 1

$L := 20.55 \cdot in$ Total length between supports

$ratio_{LD} := \dfrac{L}{D_{ghrp}} = 1.6$

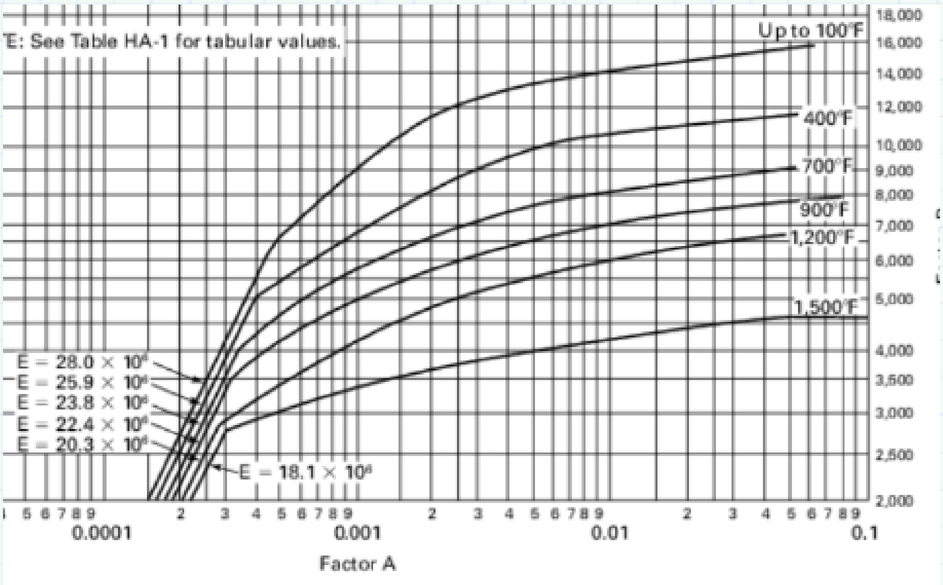
Step 2 & Step 3

Factor A from BPVC-II-D(CUSTOMARY), Figure G

$$Factor_A := .0006$$

Step 4 & 5

Factor B from BPVC-II-D, Figure HA-1



$$Factor_B := 7000 \cdot psi$$

Step 6

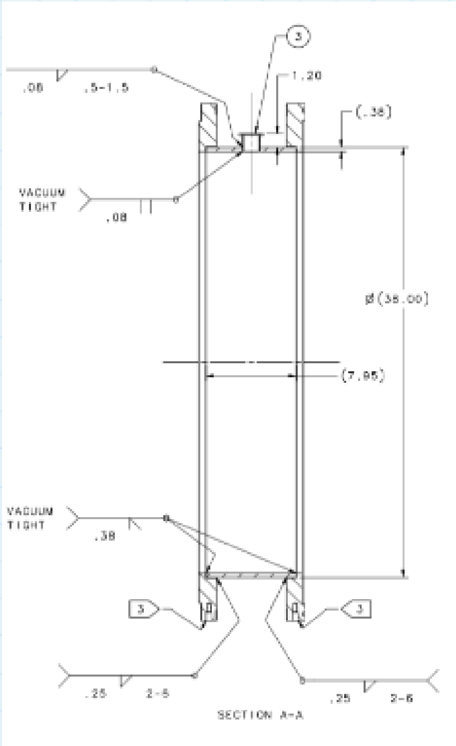
Calculate the maximum allowable external working pressure

$$P_a := \frac{(4 \cdot Factor_B)}{\left(3 \cdot \left(\frac{D_{ghrp}}{t_{ghrp}}\right)\right)} = 87.658\ psi$$

$P_a > 1$ atm

Appendix 3: Interconnect Vacuum Spool Allowable Pressure Calculation

Interconnect Vacuum Spool



The GHRP spool is made from 6061-T6 aluminum

$t_{spool} := .375 \cdot in - .02 \cdot in = 0.355\ in$ wall thickness

$D_{spool} := 38 \cdot in$ Spool OD

$P_{spool} := 15 \cdot \frac{lb}{in^2}$ 1 atm external pressure

Minimum wall thickness and stiffening requirements shall be determiend per BPVC VIII-I, UG-28.

6061-T6, ASTM B209

$S_{yield} := 24 \cdot ksi$ Allowable tensile strength per ASME BPVC-II-D, Table 1-B. Welded 6061-T6

$$ratio_{DT} := \frac{D_{spool}}{t_{spool}} = 107$$

OD to thickness ratio

Since ratio > 10, follow procedure of UG-28 (c)-(1)

Step 1

$L := 9.2 \cdot in$

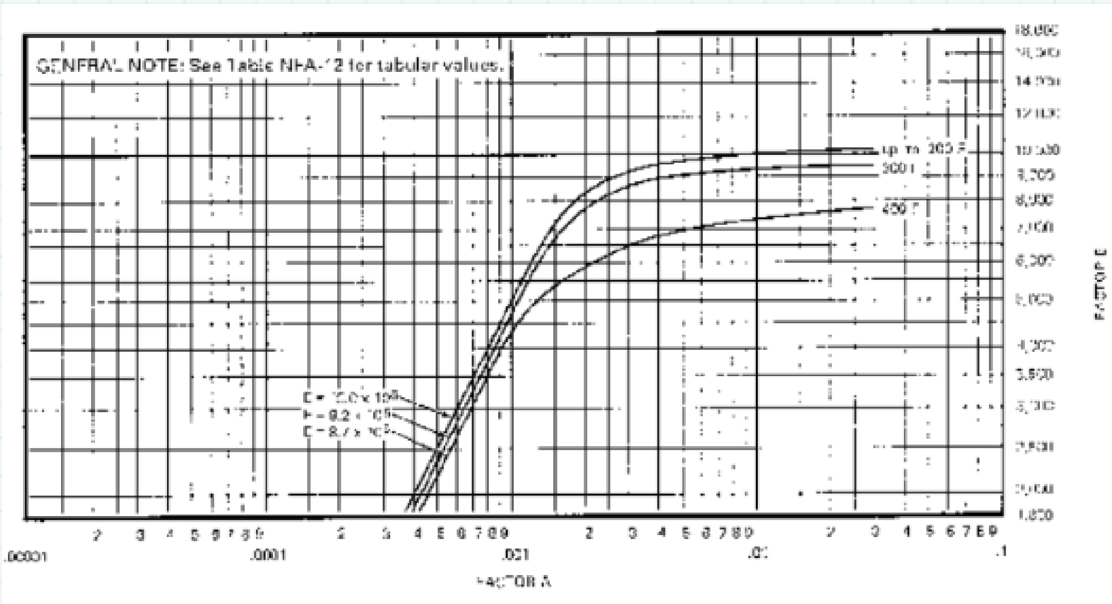
Total length between supports

$$ratio_{LD} := \frac{L}{D_{spool}} = 0.2$$

Step 2 & Step 3
Factor A from BPVC-II-D(CUSTOMARY), Figure G

$Factor_A := .008$

Step 4 & 5
Factor B from BPVC-II-D, Figure NFA-12



$Factor_B := 10000 \cdot psi$

Doc: PS-SRF-18-001-A1

Step 6
Calculate the maximum allowable external working pressure

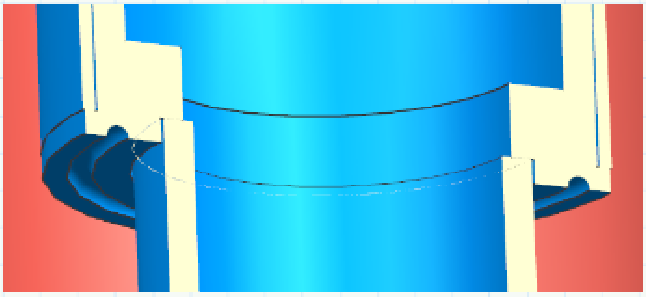
$$P_a := \frac{\left(4 \cdot Factor_B\right)}{\left(3 \cdot \left(\frac{D_{spool}}{t_{spool}}\right)\right)} = 124.56 \; \frac{lb}{in^2}$$

P_a >> 1 atm

The cylinder is also under a longitudinal compressive load from atmospheric loading. There is no longitudinal restraint on the cryomodules.

$$\sigma_2 := \frac{\left(P_{spool} \cdot D_{spool}{}^2\right)}{\left(\left(D_{spool} + 2 \cdot t_{spool}\right)^2 - D_{spool}{}^2\right)} = 397.693 \; \frac{lb}{in^2}$$

4.5K Supply female bayonet to pipe weld



Outer female tube

$t_{fbt} := .035 \cdot (.9) \cdot in = 0.032\ in$ 1.5" OD, ASTM A269 304L SS tube

$D_{fbt} := 1.5 \cdot in$ 1.5" OD tube

$\frac{D_{fbt}}{6} = 0.25\ in$

t < D/6

$S_{A269} := 16700 \cdot \frac{lb}{in^2}$ ASME B31.3 Table A-1 allowable stress 304 SS

$E := 1.0$ Quality factor

$W := 1.0$ Weld joint factor

$Y := .4$

Per ASME B31.3, par.304.1.2

$$P_{max\_bayonet1} := \frac{(S_{A269} \cdot E \cdot W \cdot 2 \cdot t_{fbt})}{(D_{fbt} - Y \cdot 2 \cdot t_{fbt})} = 713.385\ \frac{lb}{in^2}$$

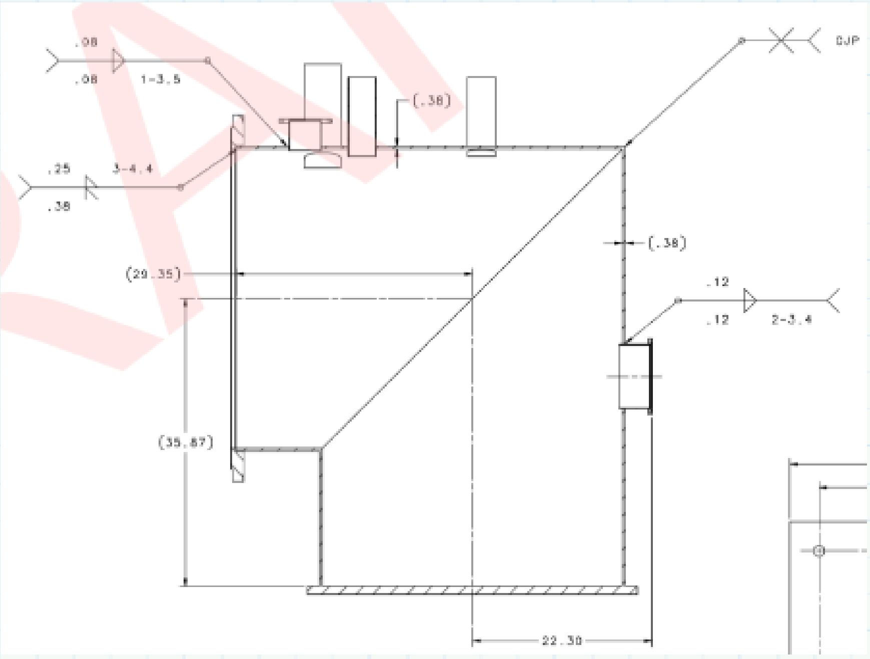
$$P_{max\_bayonet1} >> P_{design}$$

Appendix 5: Cryo-Can Allowable Pressure Analysis

LCLS-II LERF Cryomodule Testing
Cryo Can Analysis

The cryo can will be analyzed per ASME BPVC-VIII-I UG-28. It will be shown that it is of adequate thickness when treated as a shell under external pressure. The internal pressure could only go slightly above 2 psig. When evacuated it will see 1 atm(14.7 psi) of external pressure. Therefore, only external pressure case is considered.

The can is comprised of rolled 3/8' thick ASTM A240 304 SS at a 38" OD. It is welded into a 90 degree miter with only two segments.



304 SS plate, SA-240

$S_{tensile} := 75 \cdot ksi$ Allowable tensile strength per ASME BPVC-II-D, Table 1-A

$S_{yield} := 30 \cdot ksi$

$t := .375 \cdot in$ Shell thickness

$D_o := 38 \cdot in$ OD of shell

$$ratio_{DT} := \frac{D_o}{t} = 101.3$$ OD to thickness ratio

Since ratio > 10, follow procedure of UG-28 (c)-(1)

Step 1

$$L := 54.9 \cdot in$$ Total length between supports

$$ratio_{LD} := \frac{L}{D_o} = 1.4$$

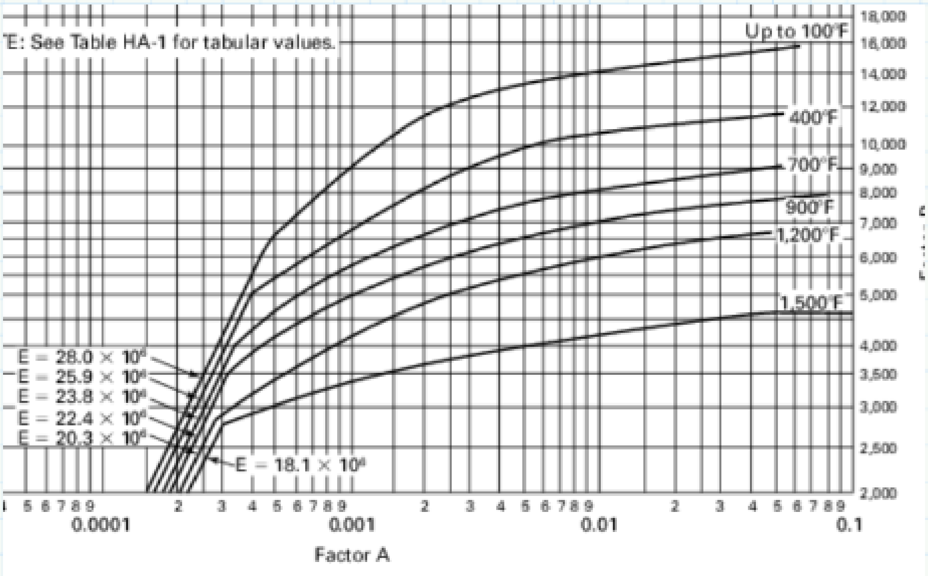
Step 2 & Step 3

Factor A from BPVC-II-D(CUSTOMARY), Figure G

$$Factor_A := .001$$

Step 4 & 5

Factor B from BPVC-II-D, Figure HA-1



$$Factor_B := 9000 \cdot psi$$

Step 6

Caculate the maximum allowable external working pressure

$$P_a := \frac{(4 \cdot Factor_B)}{\left(3 \cdot \left(\frac{D_o}{t}\right)\right)} = 118.421\ psi$$

The bottom plate treated as an Unstayed Flat head and checked against UG-34

$t_{head} := 1 \cdot in$ Actual head thickness

$d := D_o - t \cdot 2 = 37.25\ in$

$P_{design} := 15 \cdot psi$

$E := 1$ Joint efficiency, from Table UW-12 (N/A)

$C := .33$ Head attachment method factor

$$t_{min} := d \cdot \sqrt{\frac{(C \cdot P_{design})}{S_{yield} \cdot E}} = 0.478\ in$$ UG-34. eq.(c)(2)(1)

$t_{min} < t_{head}$

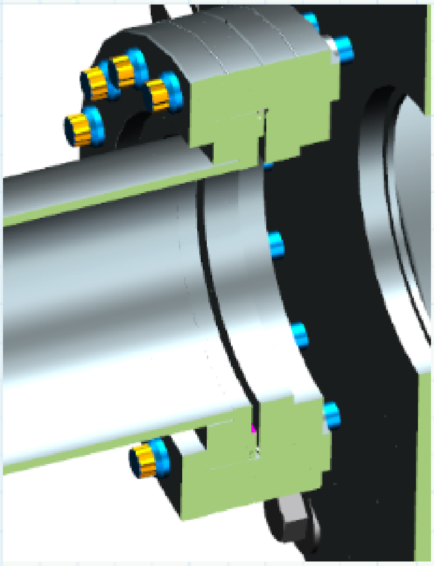
Appendix 6: CF Flange Analysis

The CF flanges are considered an unlisted component. The manufacturer does not design them for use in positive internal pressure applications, so they do not produce relevant data.

The largest flange in the pressure system will be analyzed using the highest design pressure within the system in order to cover all of the CF flanges in the system. The Cf flange joint shown below is at the end begginning of the 2 K return line after the GHRP flange assembly.

The flanges are made from 304 SS.

The flange is analyzed per ASME BPVC VIII-1, Mandatory Appendix 2.



$OD := 6 \cdot in$	Flange OD
$ID := 3.81 \cdot in$	Flange ID
$t := .735 \cdot in$	Flange thickness, thinnest section used
$BC := 5.128 \cdot in$	Bolt circle diameter

$Torque := 15 \cdot ft \cdot lb = 180\ in \cdot lb$ MDC recommended bolt torque for 5/16-24 bolts

$OD_{screw} := .313 \cdot in$ MDC recommended bolt torque for 5/16-24 bolts

The following nomenclature and equations are found in ASME BPVC VIII-I, 2-3

$G_1 := 4.5 \cdot in$

$G_2 := 4.75 \cdot in$

$G_{gasket} := \frac{(G_1 + G_2)}{2} = 4.625\ in$ Diameter at gasket load reaction. bo < 1/4in.
Ggasket = mean diameter of gasket contact face

$P_{design} := 150 \cdot \frac{lb}{in^2}$ Maximum system design pressure

$f_{screw} := .5$ Conservatively assumed torque friction coefficient

$F := \frac{Torque}{f_{screw} \cdot OD_{screw}} = 1150.16\ lb$ Clamp force per bolt

$F_{bolt\_net} := F \cdot B_{no} = 18402.56\ lb$ Total bolting clamp force

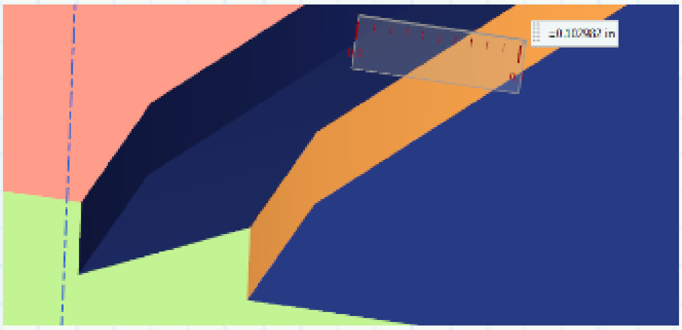
Flange anlaysis per ASME BPVC VIII-I

$ID_p := 4.5 \cdot in$ Pressure face of flange

$H := .785 \cdot G_{gasket}{}^2 \cdot P_{design} = 2518.75\ lb$ Total hydrostatic end force

$H_D := .785 \cdot ID^2 \cdot P_{design} = 1709.27\ lb$ Hydrostatic end force on area inside of flange

Assumed gasket seating width, table 2-5.2



$N := .103 \cdot in$

$b_o := \dfrac{N}{2} = 0.052\ in$

$m_{gasket} := 3.5$

Gasket material factor, table 2-5.1

$H_p := 2 \cdot b_o \cdot 3.14 \cdot G_{gasket} \cdot m_{gasket} \cdot P_{design} = 785.304\ lb$

Total joint-contact surface compression load

$W_{m1} := H_D + H_p = 2494.57\ lb$

Minimum required bolt load for operating conditions eq.2-5(1)

$F_{bolt\_net} = 18402.56\ lb$

$F_{bolt\_net} >> W_{m1}$

Flange Moment anlaysis per ASME BPVC VIII-I, Table 2-6

$h_D := \dfrac{(BC - ID)}{2} = 0.659\ in$

Radial distance from bolt circle to the circle on which H_D acts

$M_D := H_D \cdot h_D = 1126.41\ in \cdot lb$

Component moment due to H_D

$h_G := \dfrac{(BC - G_{gasket})}{2} = 0.252\ in$

Radial distance from gasket load reaction to the bolt circle

$h_T := \frac{(h_D + h_G)}{2} = 0.455\ in$ — Radial distance from bolt circle to circle on which HT acts

$H_T := H - H_D = 367.172\ kg$ — Difference between total hydrostatic end force and hydrostatic end force on area inside of flange

$M_T := H_T \cdot h_T = 368.514\ in \cdot lb$ — component of moment due to HT

$H_G := W_{m1} - H_D = 785.304\ lb$ — Gasket load

$M_G := H_G \cdot h_G = 197.504\ in \cdot lb$ — Component of moment due to HG

$M_o := M_D + M_T + M_G = 1692.43\ in \cdot lb$ — Total moment acting upon the flange

Flange Stress anlaysis per ASME BPVC VIII-I

Based on image 4(a) of fig.2-4. equation 11:

$$K := \frac{OD}{ID} = 1.575$$

$$Y := \left(\frac{1}{K-1}\right) \cdot \left(.66845 + 5.71690 \cdot \frac{(K^2\ \log(K))}{K^{2-1}}\right) = 4.252$$

$$S_T := \frac{(Y \cdot M_o)}{(t^2) \cdot ID} = 3496.28\ \frac{lb}{in^2}$$

$S_{allow} := 20000 \cdot \frac{lb}{in^2}$ — 304SS Allowable stress from ASME B31.3 Table A-1

$S_T << S_{allow}$

Bolt Strength Analysis

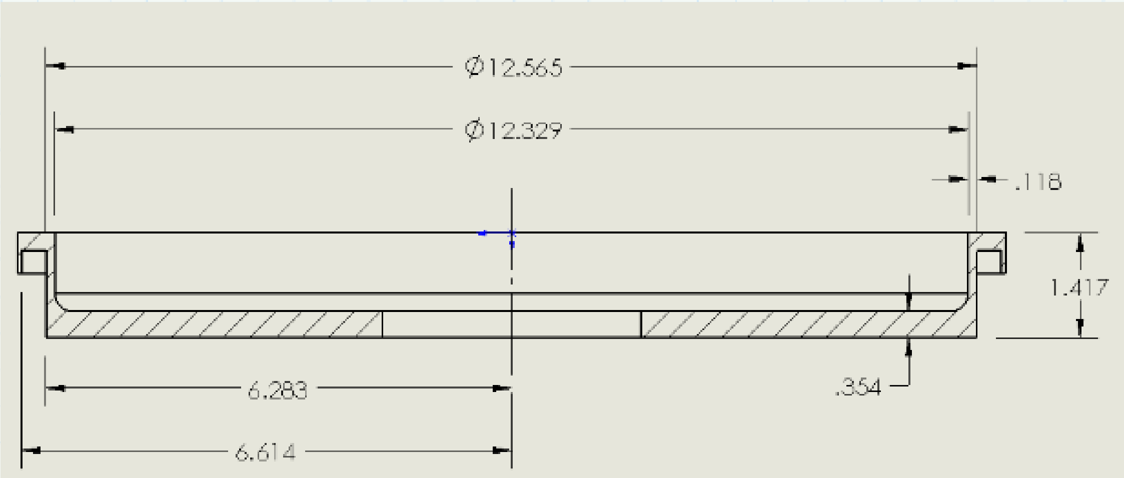
$n := 24$ Thread pitch/in

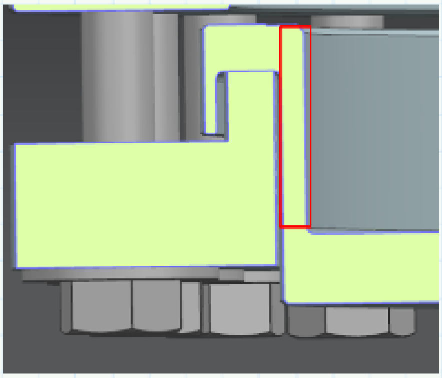
$$A_t := .7854 \cdot \left(OD_{screw} - \frac{.9743 \cdot in}{n}\right)^2 = 0.058\ in^2$$ Tensile stress area

$$\sigma_{bolt} := \frac{F}{A_t} = 19735.12\ \frac{lb}{in^2}$$

$\sigma_{bolt} < S_{allow}$

Appendix 7: GHRP Flange Analysis





This calculation determines the moment induced stress in the flange. The flange is dished shaped, giving its cross section a large moment of inertia and increased stiffness against rotation compared to a comparable one with a flat profile. Thickness is assumed to be that as shown in the red rectangle.

$OD := 13.23 \cdot in$ Flange OD

$ID := 12.33 \cdot in$ Flange ID, bore

$bore := 3.26 \cdot in$ Flange tube ID

$t := 1.04 \cdot in$ Flange thickness

$BC := 12.9 \cdot in$ Bolt circle diameter

$B_{no} := 32$ Number of bolt holes

$Torque := 12.5 \cdot ft \cdot lb = 150\ in \cdot lb$ Torque used for installaing the 5/16-24 bolts

$OD_{screw} := .375 \cdot in$

$G_{gasket} := 12.47 \cdot in$

The gasket is a 2mm diameter indium wire.

Diameter at gasket load reaction. bo < 1/4in.
Ggasket = mean diameter of gasket contact face

$P_{design} := 58 \cdot \dfrac{lb}{in^2}$ Maximum system design pressure

$f_{screw} := .5$ Conservatively assumed torque friction coefficient

$F := \dfrac{Torque}{f_{screw} \cdot OD_{screw}} = 800\ lb$ Clamp force per bolt

$F_{bolt\_net} := F \cdot B_{no} = 25600\ lb$ Total bolting clamp force

Flange anlaysis per ASME BPVC VIII-I

$H_T := \left(\dfrac{\pi}{4}\right) \cdot \left(G_{gasket}{}^2 - bore^2\right) \cdot P_{design} = 6599.43\ lb$ Total hydrostatic end force

$N := .16 \cdot in$ Assumed gasket seating width, table 2-5.2

$b_o := \dfrac{N}{2} = 0.08\ in$ Gasket seating width

$m_{gasket} := 3.5$ Gasket material factor, table 2-5.1

$H_p := 2 \cdot b_o \cdot 3.14 \cdot G_{gasket} \cdot m_{gasket} \cdot P_{design} = 1271.78\ lb$ Total joint-contact surface compression load

$W_{m1} := H_T + H_p = 7871.21\ lb$
Minimum required bolt load for operating conditions

$F_{bolt\_net} = 25600\ lb$

$F_{bolt\_net} >> W_{m1}$

Flange Moment anlaysis per ASME BPVC VIII-I

$h_G := \frac{(BC - G_{gasket})}{2} = 0.215\ in$ Radial distance from gasket load reaction to the bolt circle

$h_D := \frac{(BC - ID)}{2} = 0.285\ in$ Radial distance from the bolt circle, to the circle on which H_D acts

$h_T := \frac{(h_D + h_G)}{2} = 0.25\ in$ Radial distance from bolt circle to circle on which HT acts

$M_T := H_T \cdot h_T = 1649.86\ in \cdot lb$ component of moment due to HT

$H_D := \left(\frac{\pi}{4}\right) \cdot ID^2 \cdot P_{design} = 6925.39\ lb$ Hydrostatic end force on area inside of flange

$M_D := H_D \cdot h_D = 1973.74\ in \cdot lb$ Component of moment due to H_D

$H_G := F_{bolt\_net} - H_T = 19000.57\ lb$ Gasket Load

$M_G := H_G \cdot h_G = 4085.12\ in \cdot lb$ Component of moment due to H_G

$M_o := M_D + M_T + M_G = 7708.72\ in \cdot lb$ Total moment acting upon the flange

Moment Induced Flange Stress anlaysis per ASME BPVC VIII-I

Based on image 4(a) of fig.2-4. equation 11:

$$K := \frac{OD}{ID} = 1.073$$

$$Y := \left(\frac{1}{K-1}\right) \cdot \left(.66845 + 5.71690 \cdot \frac{\left(K^2\ \log(K)\right)}{K^{2-1}}\right) = 11.729$$

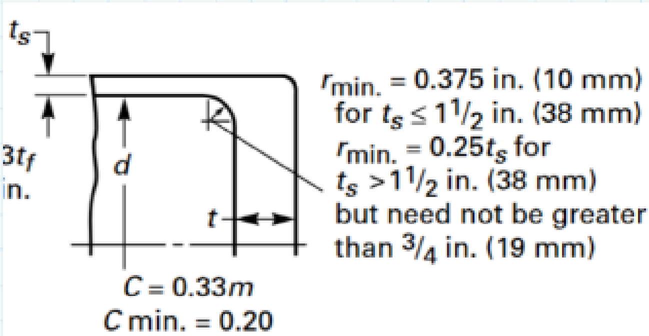
$$S_T := \frac{\left(Y \cdot M_o\right)}{\left(t^2\right) \cdot ID} = 6779.78\ \frac{lb}{in^2}$$

$$S_T < S_{allow}$$

Unstayed Flat Head per ASME BPVC VIII-VI, UG-34

This analysis evaluates the minimum thickness of an unstayed flat head under internal pressure. Since the opening in the flat head is less than 1/2 the head diameter, the opening is neglected.

The head is most representative of that shown in image b-2 of Figure UG-34.



(b-2)

$R := \frac{12.328}{2} \cdot in = 6.164\ in$ Shell inner radius

$E := 1$ Joint efficiency, assumed to be 1

$t_s := .119 \cdot in$ Nominal cylindrical shell thickness

$t_r := \frac{(P_{design} \cdot R)}{(S_{allow} \cdot E - .6 \cdot P_{design})} = 0.018\ in$ Minimum required thickness of seamless shell for pressure. UG-27, eq.2-2

$t_s >> t_r$

$m := \frac{t_r}{t_s} = 0.15$

$d_o := R \cdot 2 = 12.328\ in$ Diameter per fig. UG-34

$C := .33 \cdot m = 0.05$ Head attachment method factor

$t := .354 \cdot in$ Actual head thickness

$$t_{head\_min} := d_o \cdot \sqrt{\frac{C \cdot P_{design}}{S_{allow} \cdot E} + \frac{(1.9 \cdot W_{m1} \cdot h_G)}{S_{allow} \cdot E \cdot d_o^{\ 3}}} = 0.187\ in$$

$t > t_{head\_min}$

Reinforcement requirement for opening in Flat Head
per ASME BPVC-VIII-I, UG-39

$d := 3.26 \cdot in$ Opening diameter
$d < d_o/2$

$t_n := .12 \cdot in$ Nozzle wall thickness

$S_n := 20000 \cdot psi$ Allowable stress in nozzle

$S_v := 20000 \cdot psi$ Allowable stress in vessel

$$f_{r1} := \frac{S_n}{S_v} = 1$$

$$A_{min} := .5 \cdot d \cdot t + t \cdot t_n \cdot (1 - f_{r1}) = 0.58\ in^2$$

Minimum required reinforcement cross sectional area
UG-39, eq.(b)(1)

$$E_1 := 1$$

$$F := 1$$

Internal pressure stress correction factor

$$A_1 := d \cdot (E_1 \cdot t - F \cdot t_{head\_min}) = 0.54\ in^2$$

Area in excess thickness in the vessel wall available for reinforcement

$$t_{rn} := .005 \cdot in$$

Required thickness of seamless nozzle wall. Calculated minimum required thickness for shell under internal pressure in the piping wall thickness calculation

$$A_2 := 5 \cdot (t_n - t_{rn}) \cdot f_{r1} \cdot 2 \cdot t = 0.407\ in^2$$

Area in excess thickness of the nozzle wall available for reinforcement

Since $A_1 + A_2$ is well above A_{min}, no additional reinforcement is required.

Appendix 8: Trapped Helium 150 psi Relief Valve Sizing Check

This analysis will show that the 150 psig relief valve within the shield circuit is sized adequately. It is assumed that the line is full of 35 K helium when the bayonet valves are closed.

The relief valve is a REGO 19430, set at 150 psig.

1. Determine the total helium mass trapped within the line

$T_1 := 35 \cdot K$

$\rho_{shield} := .259 \cdot \frac{lb}{ft^3}$ He density @ 35 K, 3 atm

$\rho_{4K} := 22.12 \cdot \frac{kg}{m^3}$ He density @ 4.5 K, 3 atm

$P_1 := 3 \cdot atm = 44.09\ psi$ Supply design pressure

$P_1 = 303.975\ kPa$

$ID_{.75} := .884 \cdot in$ 3/4 sch10 pipe ID

$OD_{.75} := 1.05 \cdot in$ 3/4 sch10 pipe OD

$ID_2 := 2.157 \cdot in$ 2 NPS sch10 pipe ID

$OD_2 := 2.375 \cdot in$ 2 NPS sch10 pipe OD

$A_{.75} := \frac{\left(\pi \cdot ID_{.75}^{\ 2}\right)}{4} = 0.614\ in^2$ 3/4NPS, sch10 ID cross sectional area

$A_2 := \frac{\left(\pi \cdot ID_2^{\ 2}\right)}{4} = 3.654\ in^2$

$l_{.75} := 800 \cdot in$ Estimated 3/4 NPS length shield circuit

$l_2 := 24 \cdot m = 944.882\ in$ Estimated 2NPS length shield circuit

$l_3 := 24 \cdot m = 944.882\ in$ Estimated 3/4 NPS length 4.5 K circuit. The fluid between CEVCMXX13 and CCVCMXX11 would flow through this relief as well

$V_{shield} := A_{.75} \cdot l_{.75} + A_2 \cdot l_2 = 0.065\ m^3$ Total internal volume shield circuit

$V_{4K} := A_{.75} \cdot l_3 = 0.01\ m^3$ Total volume 4K circuit section

$m_{shield} := \rho_{shield} \cdot V_{shield} = 268.12\ gm$ Helium mass within pipe

$m_{4K} := \rho_{4K} \cdot V_{4K} = 0.21\ kg$

$m_m := 4 \cdot \frac{gm}{mol}$ Helium molar mass

$n_{shield} := \frac{m_{shield}}{m_m} = 67\ mol$ Moles of helium within pipe

$n_{4K} := \frac{m_{4K}}{m_m} = 52.6\ mol$ Moles of helium within 4 K pipe

$P_{set} := 164 \cdot psi = \left(1.131 \cdot 10^3\right)\ kPa$

$T_{150p} := \frac{\left(P_{set} \cdot V_{shield}\right)}{\left(n_{shield} \cdot R\right)} = 131.1\ K$

This is the estimated average temperature at which the relief valve set point is reached in shield circuit

$T_{4K} := \frac{\left(P_{set} \cdot V_{4K}\right)}{\left(n_{4K} \cdot R\right)} = 24.593\ K$

An ANSYS transient thermal analysis was performed to determine the warm up rate of the pipe within the transfer line assuming that there is a loss of insulating vacuum. It was assumed that the fluid and pipe began at 120 K. The effects of MLI were neglected and 295 K stagnant air convection was applied to the outer surface of the pipe.

The density was kept constant, and the pressure was calculated using Hepak in Excel based on the density and temperature.

t(s)	P(kPa)	P(psia)	Density(kg/m^3)	T(K)	mass Flow(kg/s)	mass Flow(g/s)	Net He mass(kg)	He Mass Remaining (%)
5	1049.15	152.167	4.149	120.190	#REF!	#REF!	0.268	100%
10	1050.99	152.433	4.149	120.4	0.00	0.00	0.268	100%
15	1052.91	152.711	4.149	120.620	0.00	0.00	0.268	100%
20	1054.74	152.977	4.149	120.830	0.00	0.00	0.268	100%
25	1056.66	153.256	4.149	121.050	0.00	0.00	0.268	100%
30	1058.58	153.534	4.149	121.270	0.00	0.00	0.268	100%
35	1060.41	153.800	4.149	121.480	0.00	0.00	0.268	100%

Once the set point of 164 psia was reached it was kept constant, the density was calculated based on the temperature and pressure.

The change in density required to maintain the constant pressure was used to determine the required mass flow rate.

The temperature rise was found to be very slow and the required mass flow rate was found to be very low as well. Therefore, this valve is more than adequate for limiting the pressure to 150 psig.

220	1127.19	163.485	4.149	129.130	0.00	0.00	0.268	100%
225	1128.94	163.738	4.149	129.330	0.00	0.00	0.268	100%
230	1130.59	163.979	4.149	129.520	0.00	0.00	0.268	100%
235	1130.59	163.98	4.143	129.720	0.00	0.0017	0.268	100%
240	1130.59	163.98	4.136	129.920	0.00	0.0017	0.267	100%
245	1130.59	163.98	4.130	130.110	0.00	0.0016	0.267	100%
250	1130.59	163.98	4.124	130.310	0.00	0.0016	0.267	99%
255	1130.59	163.98	4.118	130.500	0.00	0.0015	0.266	99%
260	1130.59	163.98	4.112	130.700	0.00	0.0015	0.266	99%
265	1130.59	163.98	4.106	130.890	0.00	0.0014	0.265	99%

Appendix 9: Leak Testing Stored Energy Calculations

Stored energy calculation from ES&H manual 6151, 6.1.4.1

Shield Circuit

$$P_{atm} := 14.7 \cdot psi$$

$$P_{test} := (150 + 14.7) \cdot 1.1\ psi = 181.17\ psi$$

$$V := 2.282 \cdot ft^3 = 3943.3\ in^3$$

$$k := 1.4$$

$$E := \frac{(P_{test} \cdot V)}{(k-1)} \cdot \left(1 - \left(\frac{P_{atm}}{P_{test}}\right)^{\left(\frac{(k-1)}{k}\right)}\right) = (103.333 \cdot 10^3)\ J$$

Stored energy calculation from ES&H manual 6151, 6.1.4.1

4.5 K Supply Circuit

$$P_{test} := (150 + 14.7) \cdot 1.1 \cdot psi = 181.17\ psi$$

$$ID := 1.05 \cdot in$$

$$L := 277 \cdot in$$

$$V := \frac{(\pi \cdot ID^2)}{4} \cdot L = 239.85\ in^3$$

$$E := \frac{(P_{test} \cdot V)}{(k-1)} \cdot \left(1 - \left(\frac{P_{atm}}{P_{test}}\right)^{\left(\frac{(k-1)}{k}\right)}\right) = (6.285 \cdot 10^3)\ J$$

2 K Return Circuit

$$P_{test} := (43 + 14.7) \cdot 1.1 \cdot psi = 63.47\ psi$$

$$ID_1 := 2.64 \cdot in$$

$$L_1 := 277 \cdot in$$

$$V_1 := \frac{(\pi \cdot ID_1^{\ 2})}{4} \cdot L_1 = 1516.27\ in^3$$

Cryo can section volume

$$ID_2 := 12.3 \cdot in$$

$$L_2 := 960 \cdot in$$

$$V_2 := \frac{(\pi \cdot ID_2^{\ 2})}{4} \cdot L_2 = 114069.97\ in^3$$

GHRP section volume

$$V_3 := 600 \cdot L = (3.661 \cdot 10^4)\ in^3$$

Helium bath and header section volume

$$V := V_1 + V_2 + V_3 = (1.522 \cdot 10^5)\ in^3$$

$$E := \frac{(P_{test} \cdot V)}{(k-1)} \cdot \left(1 - \left(\frac{P_{atm}}{P_{test}}\right)^{\left(\frac{(k-1)}{k}\right)}\right) = (932.059 \cdot 10^3)\ J$$

Stored energy calculation from ES&H manual 6151, 6.1.4.1

300 K Supply Circuit

$$P_{test} := (150 + 14.7) \cdot 1.1 \cdot psi = 181.17\ psi$$

$$ID := .884 \cdot in$$

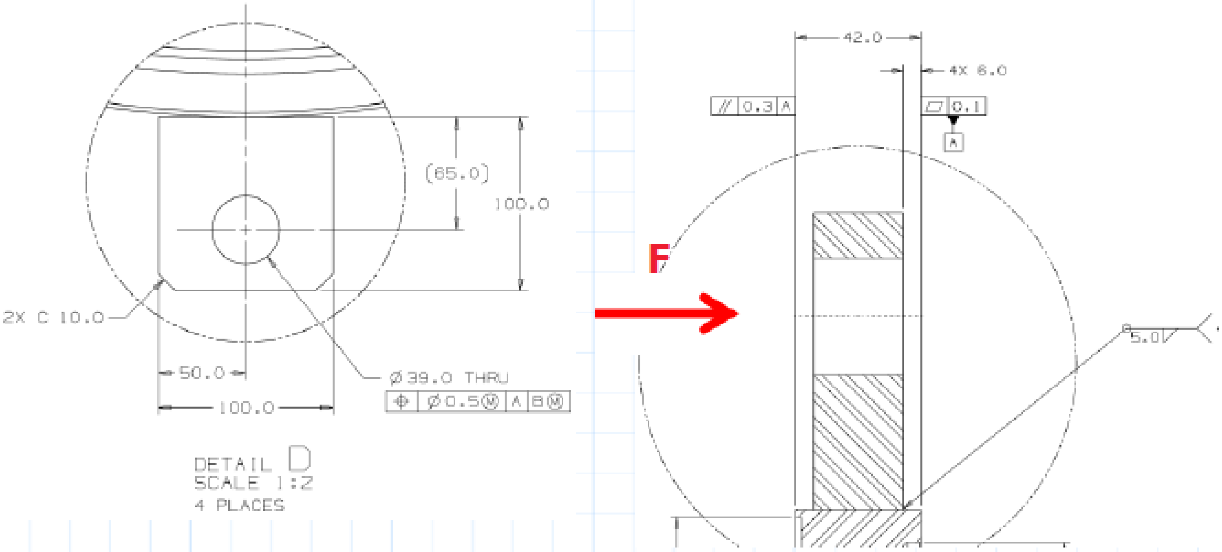
$$L := 1455 \cdot in$$

$$V := \frac{(\pi \cdot ID^2)}{4} \cdot L = 893.01\ in^3$$

$$E := \frac{(P_{test} \cdot V)}{(k-1)} \cdot \left(1 - \left(\frac{P_{atm}}{P_{test}}\right)^{\left(\frac{(k-1)}{k}\right)}\right) = (23.401 \cdot 10^3)\ J$$

Appendix 10: Interconnect Bellows Weld Tab Analysis

Interconnect Bellows Tab Weld Analysis



Analysis per Shigley's Mechanical Engineering Design, 8th edition

$$ID_{bellows} := 42.7 \cdot in$$

$$atm := 14.7 \cdot psi$$

$$A := \pi \cdot \frac{ID_{bellows}^{\ 2}}{4} = 1432.01\ in^2$$ Bellows internal area

$$F_{atm} := atm \cdot A = 21050.5\ lbf$$ Atmospheric load

$$F := \frac{F_{atm}}{4} = 5262.6\ lbf$$ Force on each tab

$h := 5 \cdot mm$

$b := 100 \cdot mm$

$d := 30 \cdot mm$

$A_{weld} := 1.414 \cdot h \cdot (b + d) = 1.425 \; in^2$ Weld Area

$I_u := \frac{d^2}{6} \cdot (3 \cdot b + d) = 3.021 \; in^3$ Unit Second Moment of Area

$I := .707 \cdot h \cdot I_u = 0.42 \; in^4$ Second Moment of Area

$\tau' := \frac{F}{A_{weld}} = 3694.09 \; psi$ Primary Shear Stress

$\tau'' := \frac{\left(F \cdot 2.56 \cdot in \cdot \frac{d}{2}\right)}{I} = 18925.2 \; psi$ Secondary Shear Stress

$\tau := \sqrt{\left(\tau'^2 + \tau''^2\right)} = 19282.37 \; psi$ Shear Stress Magnitude

The stress limits of the welds and base material are taken from AWS D1.6, Structural Welding Code-Stainless Steel, 2017

Material is 316L SS

$\tau_{allow\_filler} := .3 \cdot 70000 \cdot psi = 21000 \; psi$ Allowable filler metal stress

$\tau < \tau_{allow\_filler}$

$\tau_{allow\_base} := .4 \cdot 25000 \cdot psi = 10000 \; psi$ Allowable base metal stress

$\tau > \tau_{allow\_base}$

Stainless steel support blocks have been added to the interconnect bellows flanges. In the unlikely scenario where a weld tab's welds were to fail, the load would be transferred from the support block to the all thread rod. The tabs are made from 304 SS.

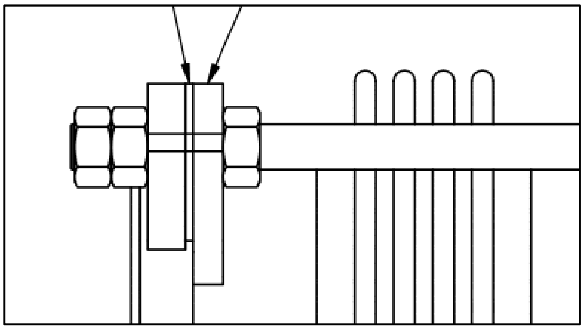


Figure 7: Reinforcement Tabs

The tabs were verified to be robust enough in ANSYS Workbench. 5,300 lb was applied to each tab in ANSYS workbench. Compression only supports were applied to both sides to represent the large nuts that clamp the support block to the bellows tabs. A cylindrical support was used on the inside through hole of the support block.

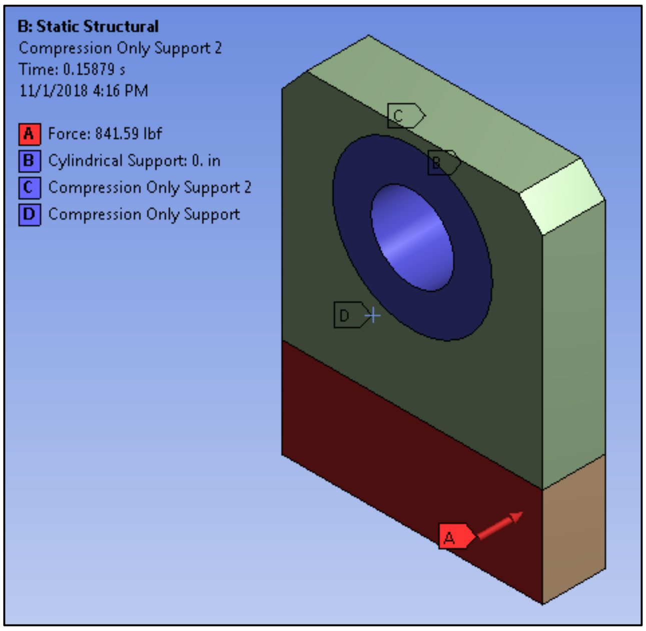


Figure 8: Boundary Conditions

The maximum deformation was found to be only .006 in.

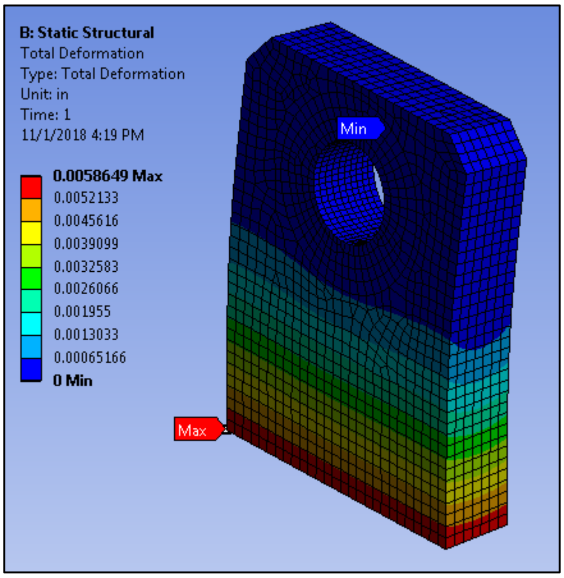


Figure 9: Total Deformation

The maximum equivalent stress was found to be 28.4 ksi. The maximum stress is located at the edge of the through hole in a very small number of elements. The maximum stress found through the bulk of the material is only 18.5 ksi. Since the yield strength of 304 SS is 42 ksi, the block's design is strong enough to handle any plausible load condition.

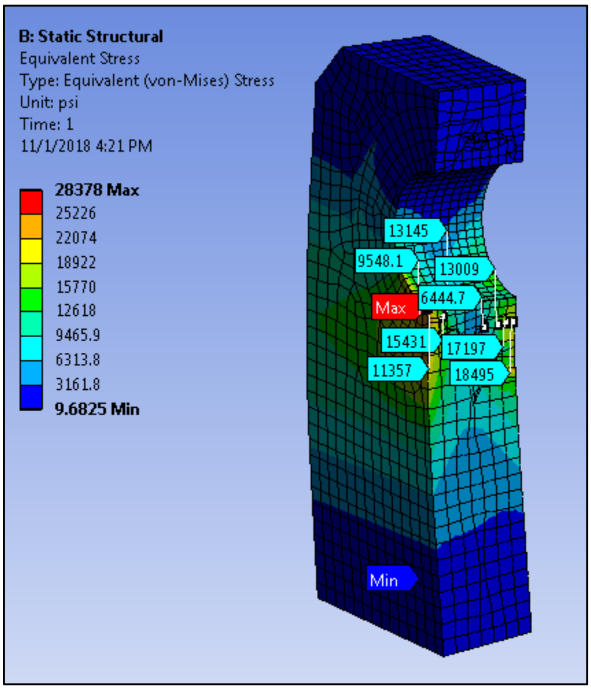


Figure 10: Equivalent Stress