FERMILAB
Technical Division

SMTF at MDB

Pressure Vessel Engineering Note For the DESY SCRF Cavity Type II (C22)

Author: Mayling Wong	Date: 11 April 2007
Reviewed by:	Date:
Approved by:	Date:

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Fermilab ES&H Manual
PRESSURE VESSEL ENGINEERING NOTE
PER CHAPTER 5031

Prepared by: Mayling Wong
Preparation date: 11 April 2007

3 Description and Identification
Fill in the label information below:

This vessel conforms to Fermilab ES&H Manual Chapter 5031

Vessel Title SCRF DESY Cavity at SMTA

Vessel Number IND-101

Vessel Drawing No. DESY-MKS3 1 04 4668 / A.000

Maximum Allowable Working Pressures (MAWP):
Internal Pressure 1.8 bar
External Pressure 0.1 bar

Working Temperature Range -457 ^{O}F - 100 ^{O}F

Contents Superfluid helium

Designer/Manufacturer DESY

Test Pressure (if tested at Fermi) Acceptance Date:________ ←**Document per Chapter 5034 of the Fermilab ES&H Manual**

_______PSIG, Hydraulic______ Pneumatic __________
Accepted as conforming to standard by
____

of Division/Section_______________ Date:________ ←**Actual signature required**

NOTE: Any subsequent changes in contents, pressures, temperatures, valving, etc., which affect the safety of this vessel shall require another review.

Reviewed by:_____________________________________ Date:_____________________

Director's signature (or designee) if the vessel is for manned areas but doesn't conform to the requirements of the chapter.

____ Date: _____________________

____ Date: _____________________
ES&H Director Concurrence

Amendment No.: ____________ Reviewed by: ____________ Date: ____________

Lab Property Number(s):______________________
Lab Location Code: _(Meson Detector Building)____(obtain from safety officer)
Purpose of Vessel(s): _LHe containment for nine-cell 1.3 GHz superconducting Radio frequency (SCRF) cavity______
Vessel Capacity/Size: _23 liters_ Diameter: _230 mm____Length:_1042 mm_____
Normal Operating Pressure (OP) _0.25 PSID____
MAWP-OP = _26.45_PSI

List the numbers of all pertinent drawings and the location of the originals.

Drawing #	Location of Original
1 04 4668 / A.000	DESY-MKS3

3 Design Verification

Is this vessel designed and built to meet the Code or "In-House Built" requirements?
Yes_____ No__X___.

If "No" state the standard that was used _ASME where applicable_. Demonstrate that design calculations of that standard have been made and that other requirements of that standard have been satisfied. Skip to part 3 "system venting verification."

Does the vessel(s) have a U stamp? Yes_____ No__X___. If "Yes", complete section 2A; if "No", complete section 2B.

3 Staple photo of U stamp plate below.
Copy "U" label details to the side

Copy data here:

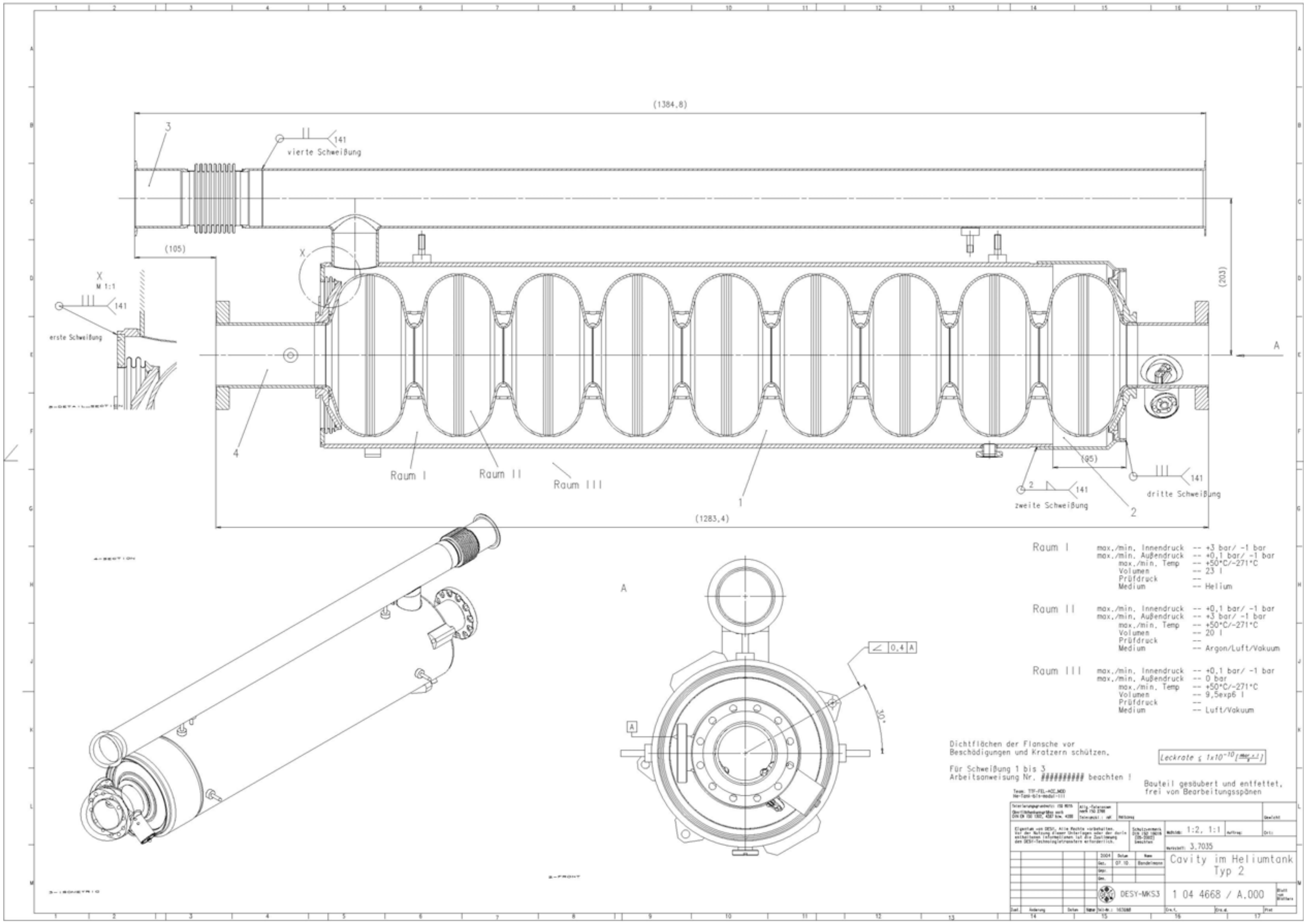


Figure 1 – DESY-MKS3 SCRF Cavity (drawing number 1 0404668 / A.000)

Provide ASME design calculations in an appendix. On the sketch below, circle all applicable sections of the ASME code per Section VIII, Division I. (Only for non-coded vessels)

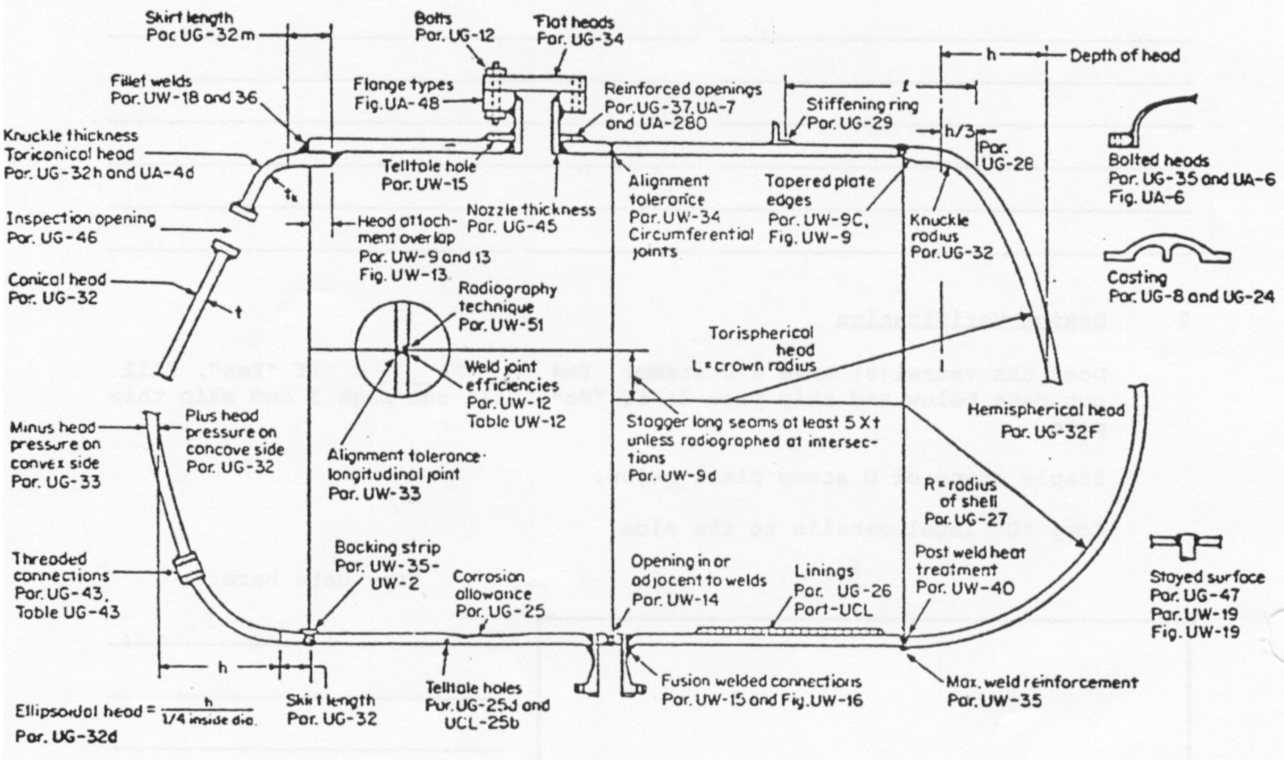


Figure 2 – ASME Code: Applicable Sections

2B.

Summary of ASME Code

Item	Reference ASME Code Section	CALCULATION RESULT (Required thickness or stress level vs. actual thickness calculated stress level)
For the helium vessel shell:		
Thickness (int. pressure)	UG-27	0.011-inch vs 0.197-inch
Maximum external pressure	UG-28	208-psi vs 1.5-psi

Refer to Appendix B for detailed calculations.

3. System Venting Verification Provide the vent system schematic.

Does the venting system follow the Code UG-125 through UG-137?
Yes__X__ No__-__

Does the venting system also follow the Compressed Gas Association Standards S-1.1 and S-1.3?
Yes __X___ No_____

Appendix C details the calculations of the relief device.

List of reliefs and settings:

Manufacturer	Model #	Set Pressure	Flow Rate	Size
BS&B	LPS	12 psig	2188 SCFM air	3-inch
MDC	BDA-M	ATM		0.75-inch

Figure 3 shows the piping and instrumentation diagram (drawing number 4906.320-ME-440302) for the horizontal cryostat system venting.

3 Operating Procedure

Is an operating procedure necessary for the safe operation of this vessel?
Yes_____ No__X___ (If "Yes", it must be appended)

3 Welding Information

Has the vessel been fabricated in a non-code shop? Yes__X__ No_____
If "Yes", append a copy of the welding shop statement of welder qualification (Procedure Qualification Record, PQR) which references the Welding Procedure Specification (WPS) used to weld this vessel.

3 Existing, Used and Unmanned Area Vessels

Is this vessel or any part thereof in the above categories?
Yes_____ No__X__

If "Yes", follow the requirements for an Extended Engineering Note for Existing, Used and Unmanned Area Vessels.

3 Exceptional Vessels

Is this vessel or any part thereof in the above category?
Yes__X__ No_____

If "Yes", follow the requirements for an Extended Engineering Note for Exceptional Vessels.

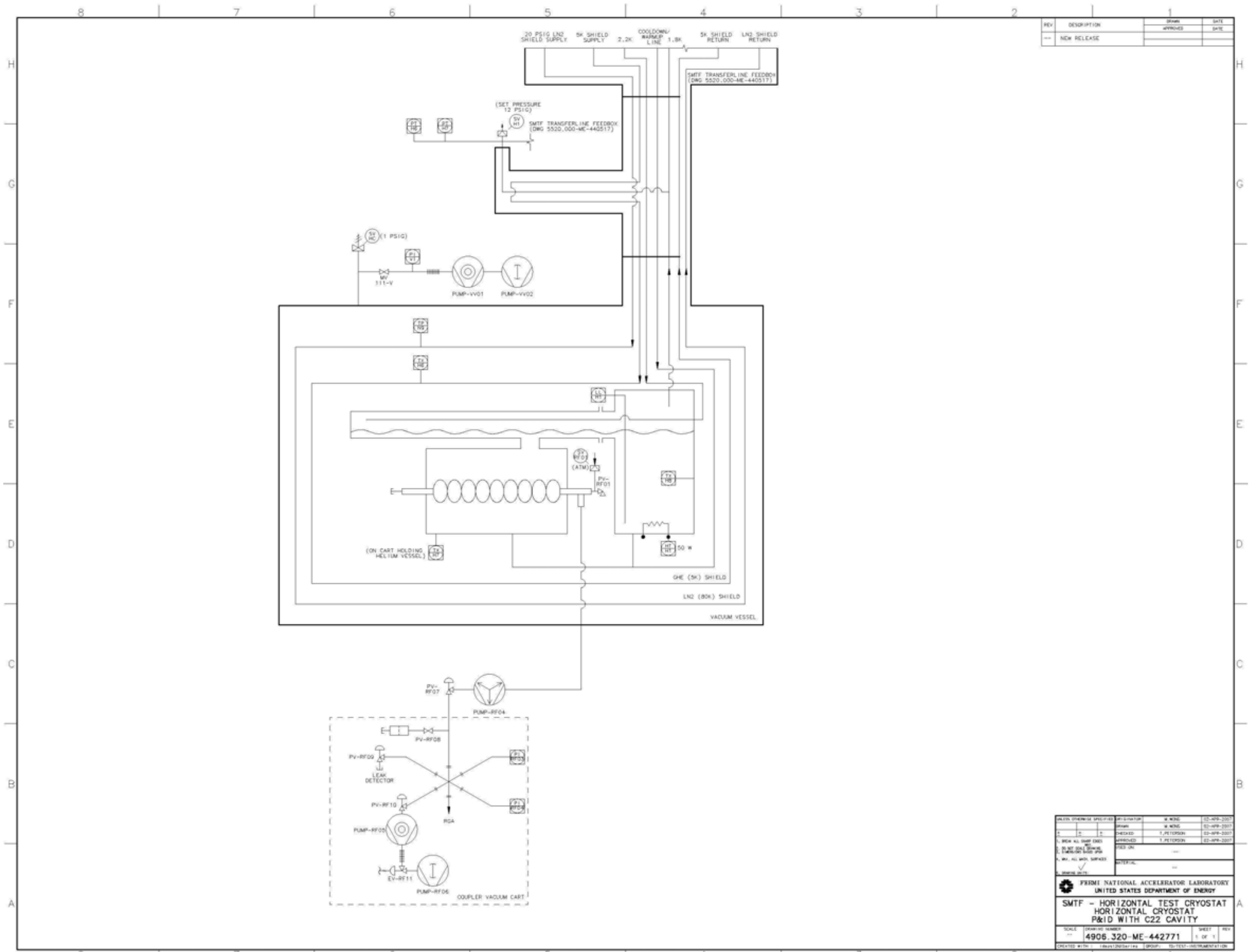


Figure 3 – P&ID (4906.320-ME-442771) of SMTA Horizontal Test Cryostat with C22 Cavity

References

1. Fermilab ES&H Manual, “Pressure Vessels,” Chapter 5033, September 2006.
2. ASME, Boiler & Pressure Vessel Code, Section VIII, Div 1, 2003.
3. CGA S-1.3-1995: Compressed Gas Association Pressure Relief Device Standards – Part 3 – Stationary Containers for Compressed Gases.
4. M. McGee, “DESY Superconducting Radio Frequency Capture Cavity II ‘RSB 569’,” FNAL Pressure Vessel Engineering Note, 2005.
5. Rao and Kneisel, “Mechanical Properties of High RRR Niobium at Cryogenic Temperatures,” Advances in Cryogenic Engineering, Vol. 40, 1994, pg. 1383-1390.
6. ASM, Metals Handbook, 9th Edition.
7. W. Lehmann, et al, “Safety Aspects for LHe Cryostats and LHe Transport Containers,” Proceedings of the 7th International Cryogenic Engineering Conference, London, 1978.
8. TTF Design Report, Section 5.5.1.
9. G. Cavallari, et al, “Pressure Protection Against Vacuum Failures on the Cryostats for LEP SC Cavities”, European Organization for Nuclear Research, 27 Sep, 1989. CERN internal note AT-CR/90-09 presented at 4th Workshop on RF Superconductivity, Tsukuba, Japan (1998).

Appendix A – Design Note

Introduction

The DESY-MKS3 1.3GHz superconducting radio frequency cavity (Cavity C22) and its helium cryostat vessel (combined called a "dressed cavity") will be used in the SMTF Horizontal Test Cryostat to commission its radio frequency system at 2K. Figure 1 shows the drawing of the dressed cavity (DESY-MKS3 drawing number 1 0404668 / A.000). As with dressed cavities of similar design, the vessel allows the nine-cell cavity to be bathed in 2K liquid helium during testing. The helium is at a vacuum pressure of 20-torr. The inner space of the nine-cell cavity will have a vacuum pulled on it. However, for purposes of commissioning, the nine-cell cavity will not be actively pumped.

The dressed cavity was originally fabricated at the Deutsches Elektron-Synchrotron (DESY) Laboratory in Hamburg, Germany. The cryostat vessel is not an ASME Boiler and Pressure Vessel Code stamped vessel. Due to the similarity in vessel design and purpose, this note follows the format of the "Design Note DESY Superconducting Radio Frequency Capture Cavity II (Fermilab vessel RSB 569) by M. McGee [4]. It also refers to the DESY/Siemens Superconducting RF Cavity S12 (RSB 513), which has been operating at the A0 building since 1998.

Note that the calculations assume an external pressure of 2-bar. However, the MAWP for the external pressure is set at 1.8-bar. The reason for this has to do with the Pressure Test that is required for an Exceptional Vessel, which this vessel will be. Any Exceptional Vessel requires a Pressure Test according to the FESHM Chapter 5034. The test's pneumatic pressure value will be 2-bar, which is 1.1 times the MAWP. The calculations in the note show that the vessel will withstand an external pressure that exceeds the rated MAWP of 1.8-bar.

Vessel Stress Analysis

Three components of the helium cryostat vessel were analyzed by considering allowable stresses or allowable thicknesses. Detailed calculations are shown in Appendix B of this note. The C22 dressed cavity falls under the FESHM 5031 definition of an In-House Built Vessel. The chapter states that the maximum allowable stress of S of the materials that make up the vessel must be reduced by 80%. So, for each component, the maximum calculated stress is compared to the 0.8 times the materials maximum allowed stress.

The maximum stress in the nine-cell cavity, made of pure annealed niobium (RRR>250) was considered. A wall thickness of 2.5-mm was analyzed under an external pressure of 3-bar external. Since the nine-cell cavity design in C22 is similar to the cavity design for Capture Cavity II and for the DESY/Siemens cavity S12 [4], the results from these engineering notes are referenced here. A maximum stress of 22.0-Mpa was calculated.

For niobium of RRR>250, the yield stress at room temperature is 50-Mpa [5]. This value is considered niobium's maximum allowed stress S (refer to the discussion of Non-standard Materials of Construction under the Exceptional Vessel Discussion). So, for niobium, the reduced maximum allowed stress at room temperature will be 40-Mpa, giving a safety factor of 1.8. For niobium at 4.2K, the stress-strain data shows a higher yield stress.

A bellows connects the nine-cell cavity to the helium vessel. The bellows of 0.2-mm thickness allows for longitudinal movement of the cavity during its tuning process. The bellows is made of Titanium 3.0725, which has a similar composition to unalloyed Titanium Grade 1 (UNS R50250) [4]. A finite element analysis (FEA) modeled the bellows in two scenarios. For the first scenario, the bellows is pressurized externally at 2-bar, modeling the possibility of the bellows (and the helium vessel) being pressurized while the horizontal test cryostat has insulating vacuum. For the second scenario, it is assumed that both sides of the bellows are at vacuum and the cavity is being tuned. The load condition is pulling the bellows axially ±500-μm. For both scenarios, the maximum calculated stress in the bellows is calculated to have a safety factor of over 1.5 for the yield stress of 25-ksi [6].

The Code's Division II analysis is applied to determine the allowable stress for the bellows. For Titanium Grade 1 (UNS R50250), S_m = 11.7-ksi. The value k = 1. The allowable stress shall be less than 1.0(k)(S_m). Reduced by 80% because the vessel is defined as an In-House Built Vessel, the allowable stress is 9.4-ksi.

The third component of the vessel stress analysis is the shell of the helium vessel. Since titanium is a material allowed by the ASME BPVC, the shell wall thickness was analyzed following the Code. The shell thickness of 0.197-inch (5-mm) is far above the minimum required thickness of 0.011-inch. Table 1 summarizes each case, its method of load, and the results.

Table 1 – Stress Calculations for the C22 Dressed Cavity

Component	Material	Load Condition	Calculated	Allowed	Yield Stress
Nine-cell cavity	Niobium	3-bar external pressure	Max. stress: 22.0 Mpa	Max stress: 40.0 Mpa	50 Mpa
Bellows	Titanium Grade 1	2-bar external pressure	Max. stress: 13.7 ksi	Max stress: 9.4-ksi	25 ksi
		Pulled axially ±500-μm	Max stress: 14.9 ksi	Max stress: 9.4-ksi	25 ksi
Shell	Titanium Grade 2	0.1-bar internal pressure	Min. thickness: 0.011 inch	Actual thickness: 0.197 inch	---

Relief System Calculations

Venting of helium from the dressed cavity takes place through a rupture disk that is part of the horizontal test cryostat. The BS&B (Model LPS) 3-inch disk has a set pressure of 12-psig. The system schematic is shown in Figure 3 (drawing 4906.320-ME-442771). Appendices C and D list detailed calculations for sizing the rupture disk. The disk is sized for primary and fire relief, following the CGA standard [3], as allowed by FESHM 5031. Also considered is venting due to loss of vacuum or an air leak into the nine-cell cavity. Table 2 summarizes the sizing calculations for the rupture disk.

The nine-cell cavity will arrive at the horizontal test cryostat with a vacuum pressure. The cavity will not be actively pumped. A 0.5-inch diameter burst disk (MDC) has been added to the cavity vacuum space. If the cavity space were pressurized at 1-bar, the disk will rupture. Since there is no added helium coming from a cavity, this scenario is not hazardous in nature.

Table 2 – Summary of Relief Sizing Calculations

Requirement	Required capacity (SCFM air)	Device	Size/capacity of device	Set point of device (psig)
Primary relief (CGA 5.2.2)	191 at 12 psig	Rupture Disk	3-inch diameter / 2188 SCFM air at 12 psig	12
Fire relief (CGA 5.3.3)	1440	Rupture Disk	3-inch diameter / 2188 SCFM air at 12 psig	12
Air condensation (secondary relief)	1643 at 12 psig	Rupture Disk (2.3” diameter min.)	3-inch diameter / 2188 SCFM air at 12 psig	12

Exceptional Vessel Discussion

There are two separate violations to the FESHM 5031 standard that are applicable to the C22 vessel: Non-Standard Materials of Construction and Maximum Stress Violation.

1) Non-Standard Materials of Construction: Standard material for a pressure vessel that is defined by FESHM 5031 is material that listed in the ASME BPVC, Section II (“The Code”). The nine-cell cavity material is niobium, which is not found in the table of allowable stresses in the Code. However, Section II, Part D of the Code allows testing and prior documentation to determine the allowable for a material. Rao and Kneisel [5] showed through their testing that the yield stress for welded and heat treated niobium at room temperature is 50-Mpa. So, the maximum allowable stress (the equivalent of “S” in the Code) for niobium for this engineering note is defined as 50-Mpa.

   For the helium vessel shell, Titanium Grade 2 (UNS R50400) is a material found in the ASME BPVC. The bellows is made of a material similar to Titanium Grade 1 (UNS R50250), which is also found in the ASME BPVC.

2) Maximum Stress Violation: The analysis of the bellows shows that the maximum calculated stress is 13.7-ksi when under 2-bar external pressure. FESHM 5031 states that the ASME Code allowable stresses shall be applied to the stress calculations. For the bellows made of material that is similar to Titanium Grade 1, the Code’s allowable stress, following the Division I analysis, is 10.0-ksi. The reduced maximum allowable stress for an In-House Built Vessel is 8.0-ksi. Since the FEA model considered all stress concentrations, the Code’s Division II analysis was applied. The allowable stress is defined as less than $1.0(k)(S_m) = 11.7$-ksi. Reduced by 80%, the allowable becomes 9.4-ksi. It is noted that the bellows design for the C22 cavity is thinner than previous cavities of similar design.

The safe operating history of the C22 cavity at DESY adds evidence that the vessel will not pose a personnel safety hazard. Also, the safe operating of dressed cavities that are similar in design (RSB 513 at the A0 building since 1998, RSB 569 at MDB since 2006) under RF power gives further evidence of safe operation.

Appendix B – Stress Analysis for Vessel Components

This section details the stress analysis for each of the three components of the vessel: the nine-cell cavity, the bellows, and the vessel shell.

Cavity Analysis

The nine-cell cavity is constructed of niobium. The cell wall thickness is specified at 2.8-mm before the cavity is processed. The cavity is similar in design as the DESY superconducting radio frequency Capture Cavity II "RSB 569" and the DESY/Siemens Superconducting RF Cavity S12 "RSB 513." [4] The RSB 513 cavity, with a wall thickness of not less than 2.5-mm, was analyzed at an external pressure of 3-bar at room temperature. The maximum stress that was calculated was 22-Mpa at the ends of the cavity 12.2-Mpa within the cells. The yield stress for pure annealed niobium (RRR>250) at room temperature is 50 Mpa [5]. For the SMTF Horizontal Test Cryostat, the maximum allowable working pressure is 2-bar at room temperature. So the C22 cavity can be externally pressurized safely. (Note: The engineering analysis for the RSB 513 nine-cell cavity is added to this note in Appendix E.)

Bellows Analysis

The bellows in the helium tank (Detail X in DESY-MKS3 drawing 1 04 4668 / A.000) allows axial movement to tune the RF cavity. The bellows is made of 0.2-mm titanium 3.7025, as seen in DESY-MHF drawing 3 98 8427/B.100 in Figure 4.

A finite element analysis verifies that the bellows is adequately designed for two scenarios. In the first scenario, the bellows is designed for a maximum pressure differential of 2 bar external at room temperature. For the analysis, both ends of the bellows are completely restrained. Figures 5 and 6 show the results of the analysis. The bellows has a maximum stress of 13,700 psi. The maximum displacement is 0.002-inch.

In the second scenario, during operation, there is equal pressure acting on both sides of the bellows. However, in order to tune the RF cavity, one end of the bellows is moving axially. The bellows was analyzed to show that the cavity end can be pulled ±500-μm (±0.020-inch) and have a maximum stress of 14,900 psi, as shown in Figure 7.

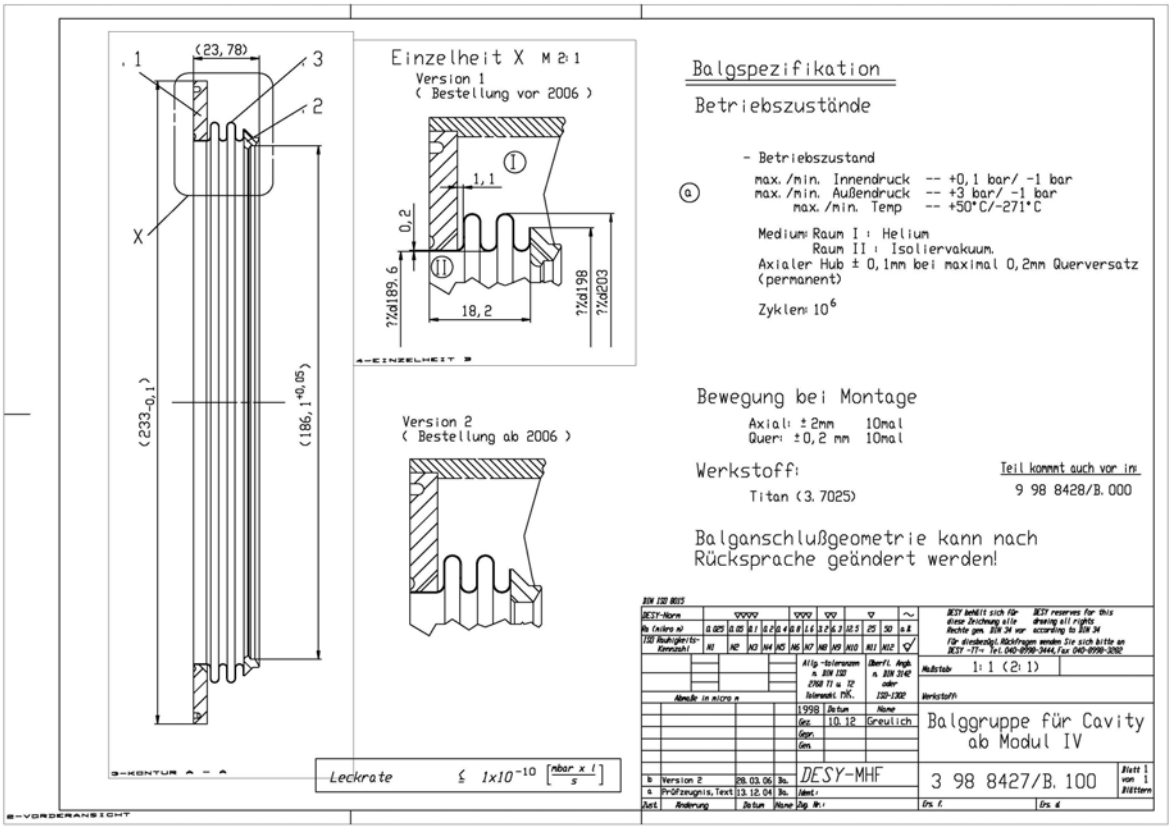


Figure 4 – Bellows for Helium Tank (DESY-MHF drawing 3 98 8427/B.100)

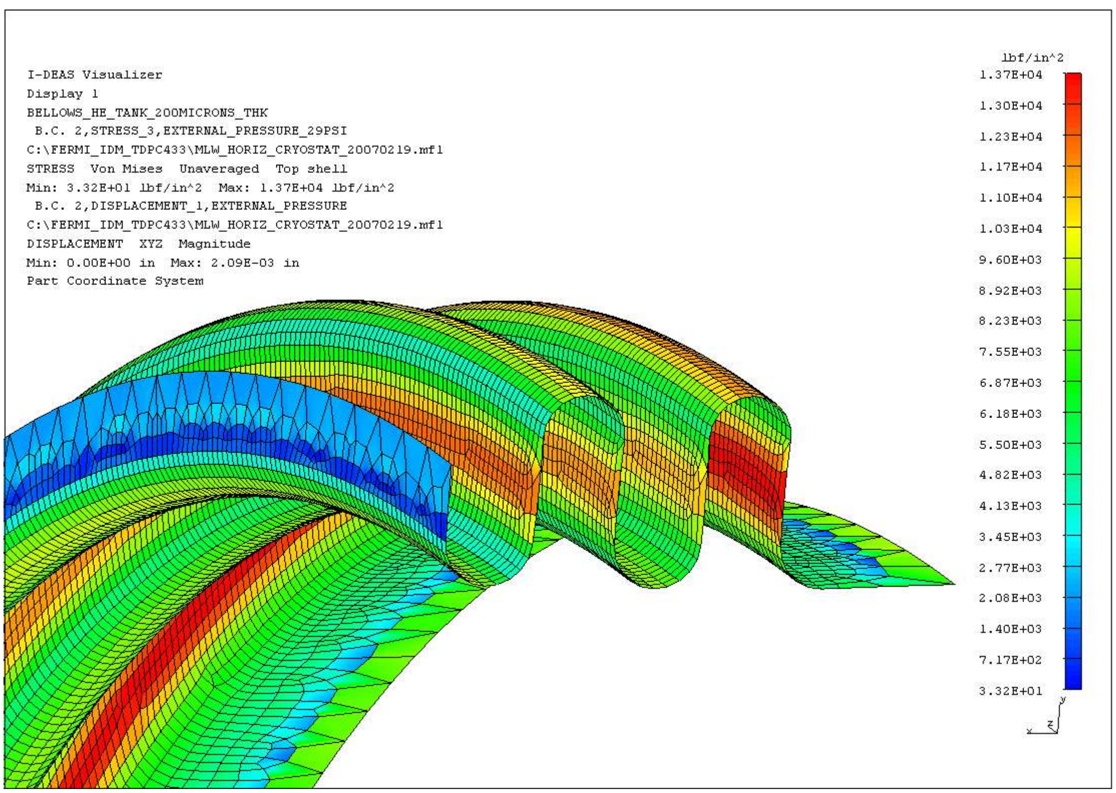


Figure 5 –Stress Results of the Titanium Bellows of the Helium Tank

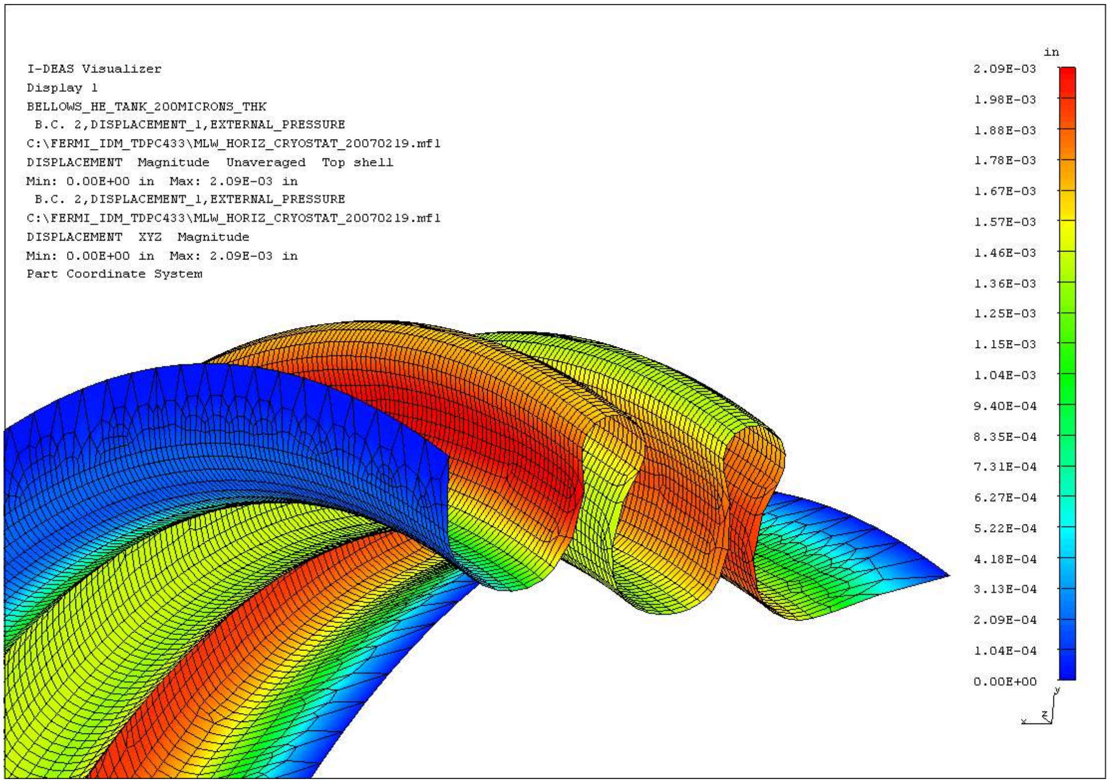


Figure 6 – Displacement Results of the Titanium Bellows of the Helium Tank

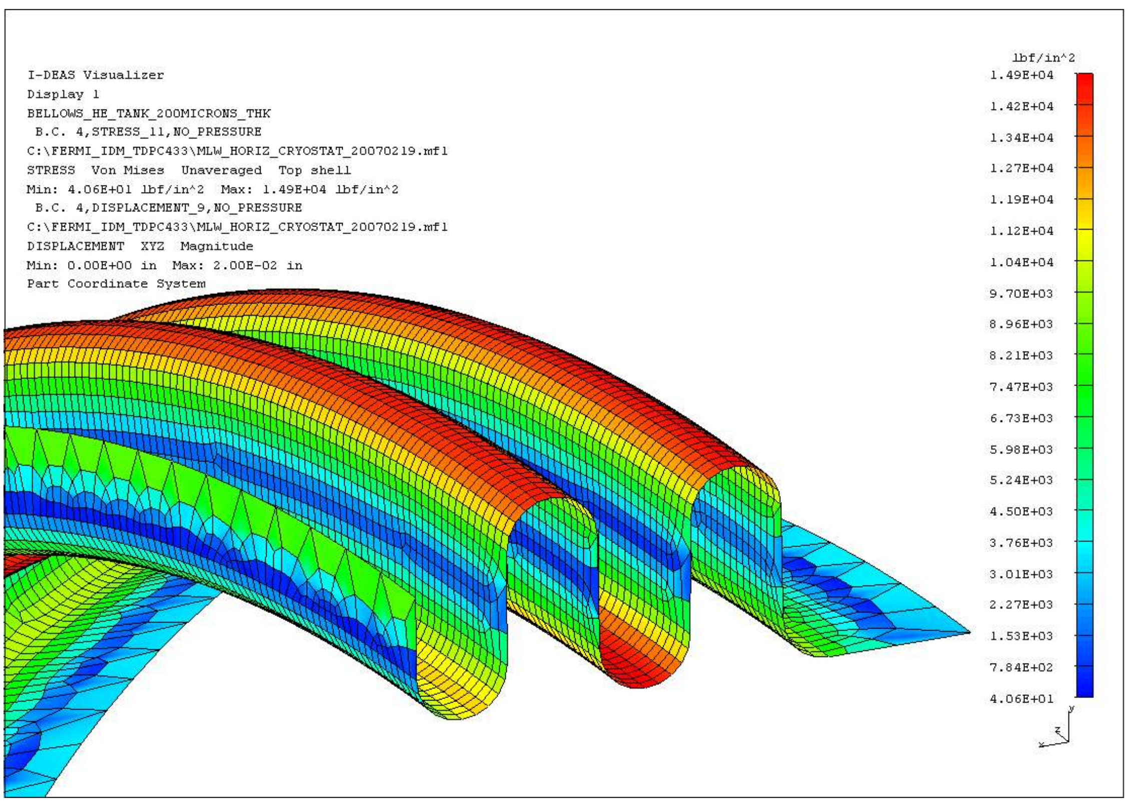


Figure 7 – Stress Results of Bellows Analysis When Cavity End is Pulled ±500μm

Vessel Shell Analysis

The shell of the helium tank is made of titanium grade 2, according to its drawing (DESY-MKS3 2 04 4668/C.001, as shown in Figure X). Its thickness is analyzed following the ASME Code, Section VIII, Division 1, Part UG-27, "Thickness of Shells Under Internal Pressure" [2]:

$Di := 230$ mm (inner diameter of shell)

$$Ri := \frac{Di}{25.4 \cdot 2}$$

$Ri = 4.528$ inch (inner radius of vessel)

$S := 16.7 \cdot 10^{3}$ psi (maximum allowable stress, according the Section II, Part D for Titanium Grade 2 [UNS No. R50400] plate/sheet not exceeding 100 deg F)

$E\_weld := 0.70$ (weld efficiency, UW-12, assuming double butt weld, no radiographic examination)

$$t\_long := \frac{P\_internal \cdot Ri}{S \cdot E\_weld - 0.6 \cdot P\_internal}$$

$t\_long = 0.011$ inch (minimum thickness for a longitudinal joint)

$$t\_circum := \frac{P\_internal \cdot Ri}{2 \cdot S \cdot E\_weld + 0.4 \cdot P\_internal}$$

$t\_circum = 5.71 \cdot 10^{-3}$ inch (minimum thickness for a circumferential joint)

$$t\_internal := \begin{cases} t\_long & \text{if } t\_long > t\_circum \\ t\_circum & \text{if } t\_long < t\_circum \end{cases}$$

$t\_internal = 0.011$ inch (minimum allowable thickness of helium vessel for internal pressure)

The actual thickness of the shell is 5-mm (0.197-inch), so it meets the minimum required thickness.

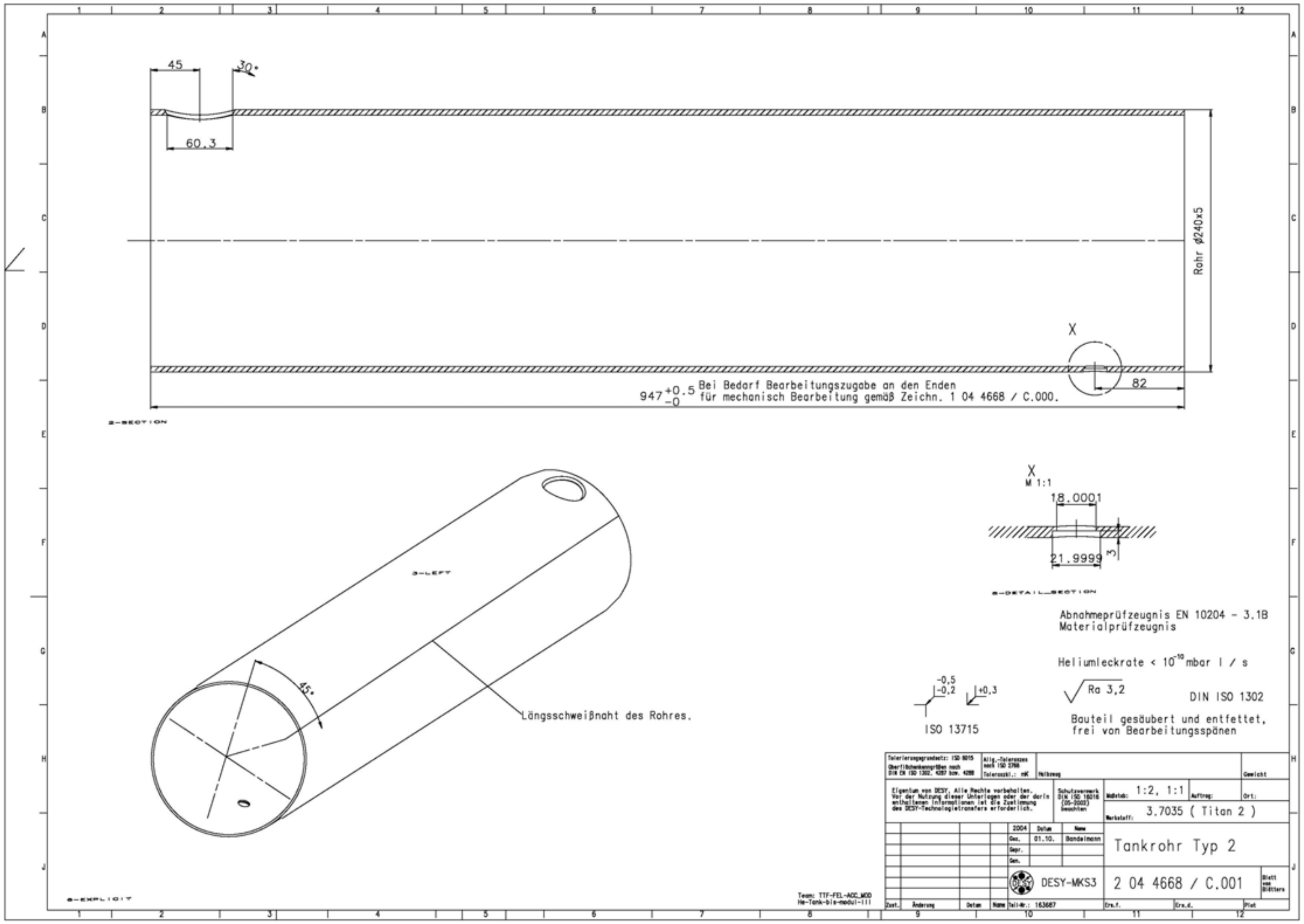


Figure X – Shell of Helium Tank (DESY-MKS3 drawing number 2 04 4668/C.001)

The thickness of the shell is then analyzed for external pressure (UG-28):

$Do := 240$ mm (outer diameter of vessel)

$$Do := \frac{Do}{25.4}$$

$t\_ext := 0.19685$ inch (thickness of helium vessel = 5-mm)

$L\_ring := \frac{947}{25.4}$ inch (distance between stiffening rings - assumption as a starting point)

$L\_ring = 37.283$ inch

$\frac{L\_ring}{Do} = 3.946$ (ratio needed to determine factor A)

$\frac{Do}{t\_ext} = 48$ (ratio needed to determine factor A)

$A := 0.0009$ (determined from Figure G in Section III, Part D)

Use Figure NFT-2 for Titanium, Grade 2 to determine Factor B

$B := 7500$

$$Pa := \frac{4 \cdot B}{3 \cdot \left(\frac{Do}{t\_ext}\right)}$$

$Pa = 208.333$ psi (maximum allowable external working pressure)

The specified maximum external pressure is 1.5 psi, which is well within the maximum allowable.

Appendix C – Relief System Calculations

For the helium system, a primary and secondary system of relief devices are required by paragraph 4.1.1 of CGA S-1.3-1995 [3]. Paragraph 1.7 of this code states: "CGA believes that reclosing pressure relief devices on a container shall be able to handle all operational emergency conditions except fire…. The operational emergency conditions referred to here shall include but not be limited to loss of vacuum, runaway fill…." Nevertheless, for loss of insulating vacuum to air, the venting rate from a liquid helium vessel is so large that a rupture disk is the only practical solution, and that is the approach taken here. The rupture disk will be the primary, secondary, and fire relief for the horizontal cryostat. It is sized for fire or loss of vacuum to air and is sufficient as a primary relief.

With the primary relief sized per paragraph 5.2 and retested every 5 years, a secondary relief may be set to a maximum of 150% of the MAWP (paragraph 4.1.2.3(2)). For the DESY SCRF Type II Cavity in the SMTA Horizontal Test Cryostat, the MAWP is 29.0 psia (2 bar). Therefore, the primary relief device must be set at 29.0 psia or less, and the secondary relief device set at 1.5 x 29.0 = 43.5 psia or less. The cryostat has a 3.0-inch rupture disk with a set pressure of 12 psig (SV-H1 in Figure 3). It acts as the primary, secondary, and fire relief device. There is a separate relief valve with a set pressure of 5 psig. However, its 0.5-inch diameter limits its use as mainly to relieve operational pressure transients.

C.1 – Primary relief sizing

The primary relief size for conditions other than fire is estimated per paragraph 5.2.2 [3]:

$$Qa := \frac{(590 - T)}{4 \cdot (1660 - T)} \cdot F \cdot Gi \cdot U \cdot A$$

The parameters in this equation and the result are evaluated in Appendix C. The primary relief size must be at least 191 SCFM air.

C.2 – Fire relief sizing

The fire relief size is estimated per paragraph 5.3.3 [3]:

$$Qa\_fire := F \cdot Gi \cdot U \cdot A^{0.82}$$

The parameters in this equation and the result are shown in Appendix C. The fire relief size must be at least 1440 SCMF air.

C.3 – Relief for loss of insulating vacuum or air leak into RF cavity

There are two scenarios that can cause a sudden increase in pressure of helium in the dressed 1.3 GHz RF cavity helium vessel. One scenario is when the insulating vacuum of the cryostat leaks to air. The heat boil-off was calculated based on the total surface area of the cold mass, which included the helium vessel, the liquid level dewar, and the associated piping leading to the tee where the piping branches towards the burst disk. The total surface area is estimated to be 2636 in^2. References for air condensation on an uninsulated helium vessel are Lehmann and Zahn [7] and the TTF Design Report [8]. Both references use a heat influx of about 2.0 W/cm^2 for a superinsulated vacuum vessel with an uninsulated helium vessel. This heat influx results in a required flow rate of helium though a safety relief valve, such as a burst disk, of 2483 g/sec.

The second scenario is when the vacuum of the RF cavity itself leaks to air. The surface area of the RF cavity, 1354 in^2, is smaller than that of the cold mass. Cavallari, et al, estimated that a heat influx of 4 W/cm^2 is used to calculate air condensation due to an air leak into the cavity [9]. This heat influx results in a required helium flow rate of 2551 g/sec through a burst disk. With both scenarios resulting in similar required helium flow rates, let the required flow rate of helium through the burst disk be 2600 g/sec. The result is that a 2.30-inch diameter orifice is required. It is equivalent to a 1700 SCFM air capacity for 15 psig at the rupture disk. Detailed calculations are shown in Appendix C. For both scenarios, the surface areas for both items were taken from three-dimensional models in IDEAS. The part number for the 1.3 GHz RF cavity is 4904.010-MD-439181. The part number for the helium vessel is 4904.010-MD-439212. These parts are not the original models of the DESY Type II cavities, they are similar enough in design for this exercise.

C.4 – Summary

Below is a summary of the relief devices for the helium system (same as Table 2).

Requirement	Required capacity (SCFM air)	Device	Size/capacity of device	Set point of device (psig)
Primary relief (CGA 5.2.2)	191 at 12 psig	Rupture Disk	3-inch diameter / 2188 SCFM air at 12 psig	12
Fire relief (CGA 5.3.3)	1440	Rupture Disk	3-inch diameter / 2188 SCFM air at 12 psig	12
Air condensation (secondary relief)	1643 at 12 psig	Rupture Disk (2.3-inch diameter minimum)	3-inch diameter / 2188 SCFM air at 12 psig	12

Appendix D – Detailed Calculations for Relief Sizing

For C.1: CGA S-1.3-1995 Primary Relief Valve Sizing

$T := 6.0$ K (Sizing temperature at which the square root of specific volume over specific heat input is a ma at the relieving pressure of 12 psig)

$T := T \cdot 1.8$

$T = 10.8$ R

$F := 1$ (Correction factor for cryogenic systems)

$Gi := 52.5$ (Gas factor for insulated containers for liquid helium, used in US units)

$k\_cond := 0.09$ Btu/hr-ft-F (thermal conductivity of insulation)

$t\_insulation := 0.125 + 0.20 + 0.062 + 1.0$

$t\_insulation = 1.387$ inch (thickness of 80K and 5K shielding and insulation)

$$t\_insulation := \frac{t\_insulation}{12}$$

$t\_insulation = 0.116$ ft

$$U := \frac{k\_cond}{t\_insulation}$$

$U = 0.779$ Btu/hr-ft^2-F (overall heat transfer coefficient of the insulatin material of the vacuum vessel)

$$A\_vac := \frac{12658}{12^2}$$

$A\_vac = 87.903$ ft^2 (surface area of vacuum vessel)

$A\_vessel := 2636$ inch^2 (surface area of cold mass, including helium vessel, li level dewar, and piping)

$$A\_vessel := \frac{A\_vessel}{144}$$

$A\_vessel = 18.306$ ft^2

$$A := \frac{A\_vac + A\_vessel}{2}$$

$A = 53.104$ ft^2 (mean surface area between vacuum vessel and cold mas

$$Qa := \frac{(590 - T)}{4 \cdot (1660 - T)} \cdot F \cdot Gi \cdot U \cdot A$$

Qa = 190.603 SCFM air (Required flow capacity for the primary relief dev

For C.2: CGA S-1.3-1995 Fire Relief Valve Sizing

F = 1

Gi = 52.5

k_cond := 0.122 Btu/hr-ft-F (mean thermal conductivity of 1 atm GHe between 4K and 922 K, Tab

t_insulation := 0.116 ft

$$U := \frac{k\_cond}{t\_insulation}$$

U = 1.056 Btu/hr-ft^2-F

A = 53.104 ft^2

$$Qa\_fire := F \cdot Gi \cdot U \cdot A^{0.82}$$

$Qa\_fire = 1.44 \cdot 10^{3}$ SCFM air

For C.3: Relief for loss of insulating vacuum or air leak into RF cavity

$A\_vessel := 2636$ in^2 (surface area of helium vessel, liquid level dewar, and piping)

$A\_vessel := A\_vessel \cdot 2.54^2$

$A\_vessel = 1.701 \cdot 10^4$ cm^2

$Q := 2.0$ W/cm^2 (heat flux for air condensation in a superinsulated vacuum vessel with an uninsu
helium vessel - Lehmann and Zahn)

$q := Q \cdot A\_vessel$

$q = 3.401 \cdot 10^4$ W (total heat that boils away helium liquid into gas)

$P\_max\_set := 29.7$ psia

$LH := 14.5$ J/g (Minimum specific heat input at venting pressure - minimum for 12 psig, which occu
T=5K)

$m\_dot := \frac{q}{LH}$

$m\_dot = 2.346 \cdot 10^3$ g/s (mass flow rate vent rate)

$m\_dot := \frac{m\_dot}{1000}$

$m\_dot = 2.346$ kg/s

$A\_cavity := 1354$ in^2 (surface area of RF cavity)

$A\_cavity := A\_cavity \cdot 2.54^2$

$A\_cavity = 8.735 \cdot 10^3$ cm^2

$Q\_cavity := 4.0$ W/cm^2 (heat flux for air condensation due to air leak into uninsulated RF cavity - Cava
et al)

$q\_cavity := Q\_cavity \cdot A\_cavity$

$q\_cavity = 3.494 \cdot 10^4$ W (total heat that boils away the helium liquid into

$m\_dot := \frac{q\_cavity}{LH \cdot 1000}$

$m\_dot = 2.41$ kg/sec

So, for either scenario, the helium in the helium vessel would boil off at a mass flow rate of approximately 2.5-2.6 l
For calculating the required burst disk size, use 2.6 kg/sec.

m_dot := 2.4 kg/sec

The pressure drop from the helium vessel through the piping that leads to the feedcan is shown below.

$\Delta P := 0.35$ psi (total pressure drop from helium vessel to burst disk)

$P\_inlet := P\_max\_set - \Delta P$

$P\_inlet = 29.35$ psia (orifice inlet pressure, or pressure at the burst d

$P\_inlet := (P\_inlet) \cdot 6894.8$

$P\_inlet = 2.024 \cdot 10^{5}$ Pa (orifice inlet pressure)

$\beta := 0.5349 \cdot 10^{-2}$ 1/kPa (compressibility of helium at inlet pressure, T=9 K)

$\rho := 11.71$ kg/m^3 (density of helium at inlet pressure, T=9 K)

$$a := \sqrt{\frac{1}{\beta \cdot \rho}} \cdot \sqrt{1000}$$

$a = 126.353$ m/sec (sonic velocity at inlet pressure, T=9K)

$d\_vent := 2.167$ inch (diameter of vent pipe)

$$A\_vent := \pi \cdot \left(\frac{d\_vent}{2}\right)^2$$

$A\_vent = 3.688$ inch^2 (area of inlet)

$$A\_vent := A\_vent \cdot \frac{2.54^2}{100^2}$$

$A\_vent = 2.379 \cdot 10^{-3}$ m^2

$$v\_flow := \frac{m\_dot}{\rho \cdot A\_vent}$$

$v\_flow = 86.135$ m/sec

$$Ma := \frac{v\_flow}{a}$$

$Ma = 0.682$

k := 1.667 (ratio of specific heats for GHe)

$$P\_stag := P\_inlet\left[1 + \left(\frac{k-1}{2}\right)\cdot Ma^2\right]^{\frac{k}{k-1}}$$

P_stag = 2.901•10^5 Pa (stagnation pressure)

$$\rho\_stag := \rho\cdot\left[1 + \left(\frac{k-1}{2}\right)\cdot Ma^2\right]^{\frac{1}{k-1}}$$

ρ_stag = 14.534 kg/m^3 (stagnation density)

Cd := 0.62 (coefficient of discharge)

$$A\_disk := \frac{m\_dot}{Cd\cdot\left[\sqrt{k\cdot\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}\cdot\sqrt{P\_stag\cdot\rho\_stag}\right]}$$

A_disk = 2.596•10^−3 m^2

$$A\_disk := A\_disk\cdot\frac{100^2}{2.54^2}$$

A_disk = 4.024 in^2

$$d\_disk := 2\cdot\sqrt{\frac{A\_disk}{\pi}}$$

d_disk = 2.263 inch (required diameter of burst disk)

Now, calculate the standard volumetric flow rate of air through the required diameter of the bu

T_inlet := 300 K (burst disk, or orifice, inlet temperature)

R_air := 287.1 N-m/kg-K (ideal gas constant of air)

$$\rho\_inlet := \frac{P\_inlet}{R\_air\cdot T\_inlet}$$

ρ_inlet = 2.349 kg/m^3 (inlet density at T=300K)

$k\_air := 1.4$ (ratio of specific heats for air)

$$m\_dot\_air := Cd \cdot \left(A\_disk \cdot \frac{2.54^2}{100^2}\right) \cdot \sqrt{k\_air \cdot \left(\frac{2}{k\_air + 1}\right)^{\frac{k+1}{k-1}}} \cdot \sqrt{P\_inlet \cdot \rho\_inlet}$$

$m\_dot\_air = 0.912$ kg/sec (mass flow rate of air through burst disk)

$$\rho\_std := \frac{101326}{R\_air \cdot T\_inlet}$$

$\rho\_std = 1.176$ kg/m^3 (standard density of air)

$$V\_dot\_air := \frac{m\_dot\_air}{\rho\_std}$$

$V\_dot\_air = 0.775$ m^3/sec (standard volumetric flow rate of air though burst disk)

$$V\_dot\_air := \frac{V\_dot\_air}{0.3048^3} \cdot 60$$

$V\_dot\_air = 1.643 \cdot 10^3$ SCFM air (standard volumetric flow rate of air through burst d

Appendix E – Cavity Stress Analysis of RSB 513 taken from FNAL Pressure Vessel Engineering Note – DESY Superconducting Radio Frequency Capture Cavity II "RSB 569"

Appendix 1

Cryo Capture Cavity II Heluim Vessel Stress Calculations

Michael McGee (AD/MS)
July 16, 2005

The maximum allowable working pressure (MAWP) is based on the constraint which protects the cavity from detuning. Cavity detuning was not considered in a similar vessel used at A0 (Fermilab) in 1997 "RSB 513." The original initial 9-cell 1.3 GHz cavity operated at A0 has a MAWP of 44.1 psid, per "Tesla Test Facility Linac - Design Report (v1.0, March 1, 1995)," by D.A. Edwards. This appendix was fashioned after "Design Note DESY/Siemens Superconducting RF Cavity S12," by J. Fuerst. The maximum pressure within the helium vessel to avoid detuning while the cavity is under vacuum must be 2 bar. A pressure test is required as part of the vessel certification process at Fermilab. ES&H Manual Section 5031.1a requires that a pressure shall satisfy a pressure test of 110% of the MAWP. Therefore, the MAWP is limited to 2 bar/110% or 1.82 bar at room temperature (20 degrees C).

Maximum Allowable Working Pressure (-15/12.02 psig@-456 F/100)

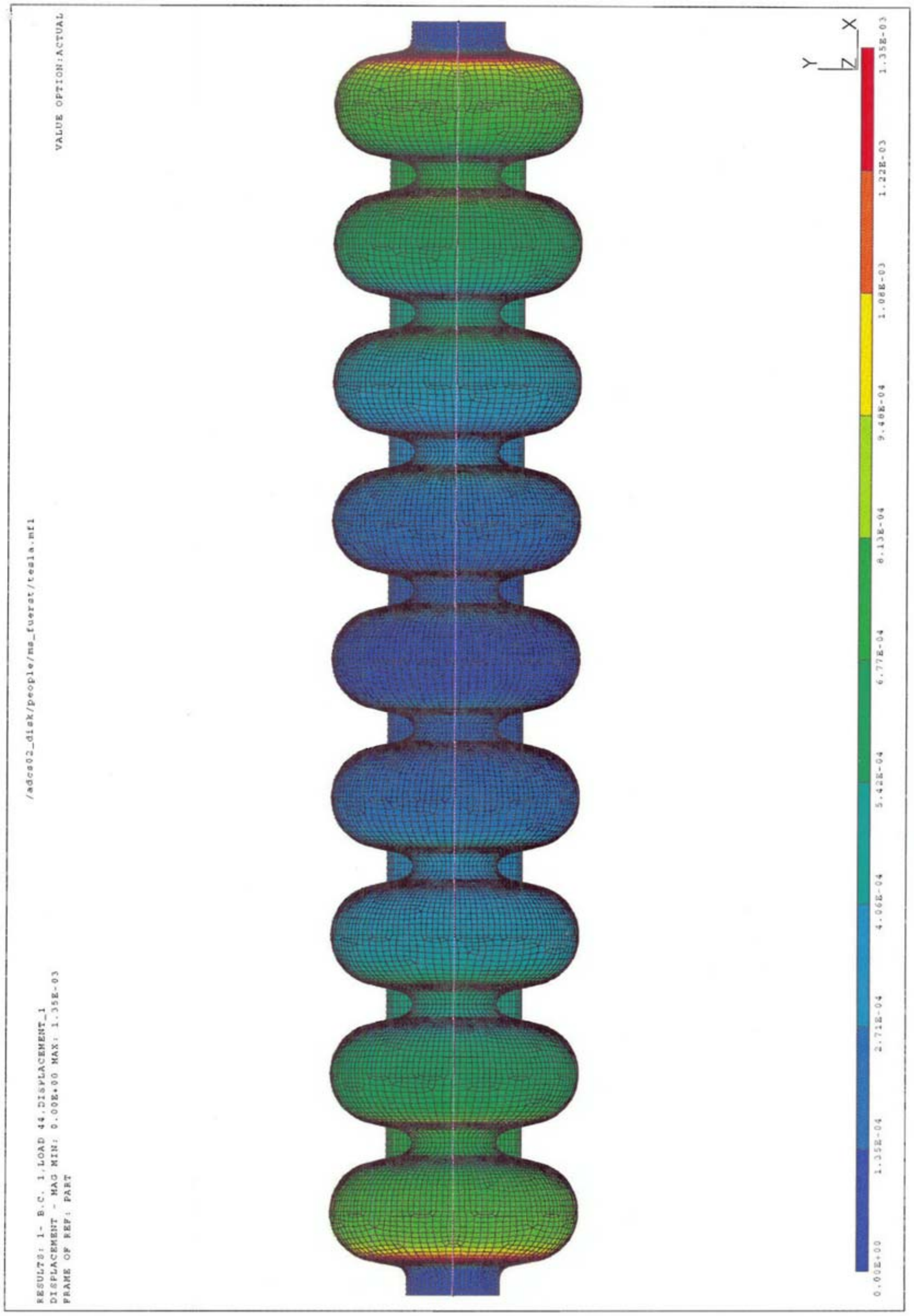
$$MAWP := 26.7 lb \cdot in^{-2}$$

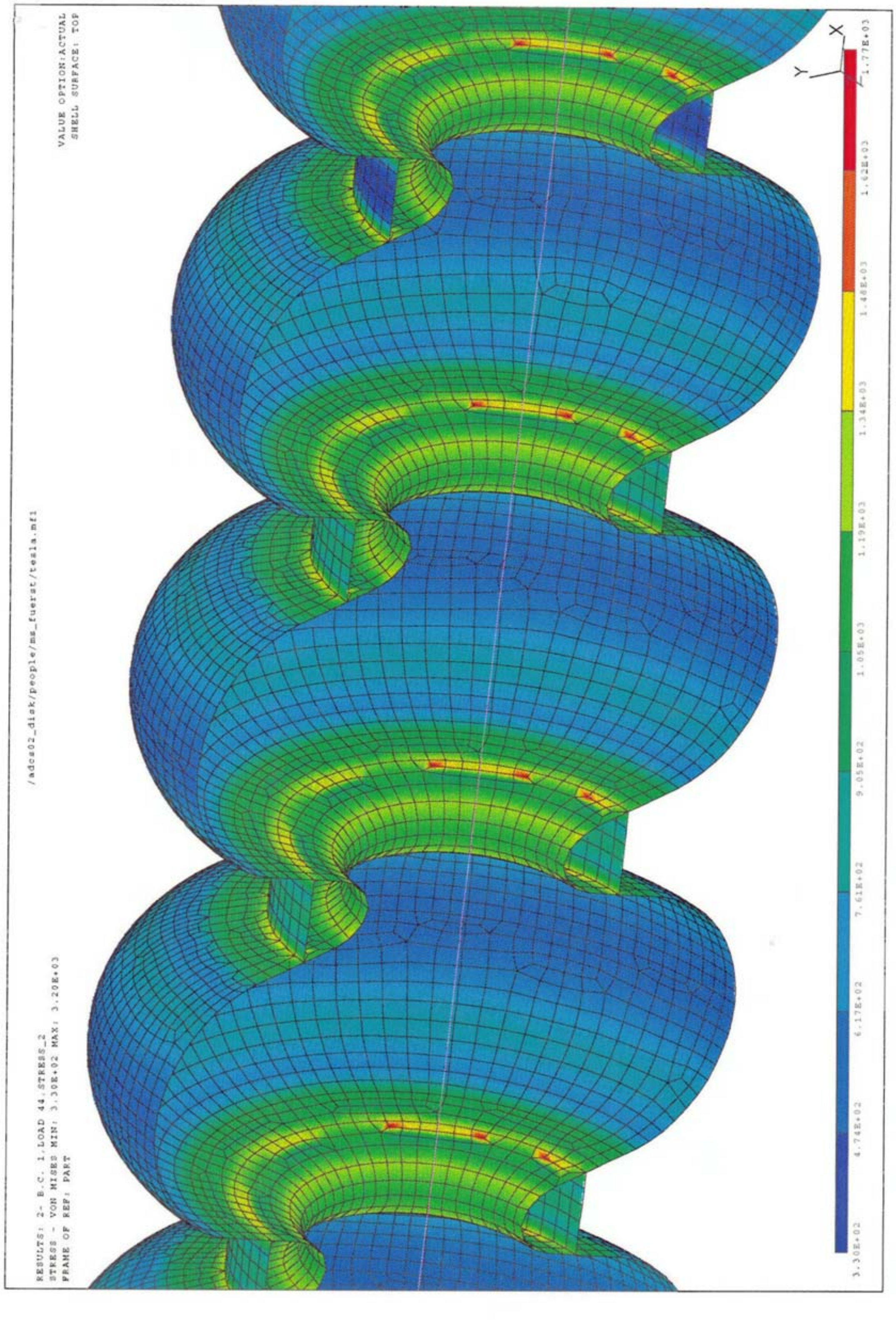
Stress Analysis for Vessel Components

Three Cases: 1) in-house stress analysis of the niobium cavity under full external pressure
2) in-house stress analysis of the large titanium bellows under full external pressure
3) in-house stress analysis of the titanium shell under full internal pressure

1) Cavity Stress Analysis

In 1997, Joel Fuerst constructed a half model of the full 9-cell cavity in IDEAS. His model, shown in Appendix 1a, conforms to the cell geometry and has the stiffening rings. This model was based on face pressure boundary condition of 44.1 psid on all surfaces except the stiffening rings. The results attached show a von Mises stress in the cells of 12.2 MPa. This result is consistent with the TTF Design Report of a stress beneath 12 MPa under similar conditions. Higher stress values of 22 MPa were found at the ends. However, all stresses within the model were well below the yield published by Rao & Kneisel of 50 MPa. Material properties for pure, annealed niobium are taken from Rao and Kneisel, "Thermal and Mechanical Properties of Electron Beam Welded and Heat-Treated Niobium for Tesla." The stresses found within capture cavity II will be even lower, given the lower MAWP requirement needed to prevent detuning during pressure testing at Fermilab.


RESULTS: 1- B.C. 1,LOAD 44,DISPLACEMENT_1
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.35E-03
FRAME OF REF: PART
/adcs02_disk/people/ms_fuerst/tesla.mf1
VALUE OPTION:ACTUAL
0.00E+00
1.35E-04
2.71E-04
4.06E-04
5.42E-04
6.77E-04
8.13E-04
9.48E-04
1.08E-03
1.22E-03
1.35E-03
Y
Z
X


RESULTS: 2- B.C. 1,LOAD 44,STRESS_2
STRESS - VON MISES MIN: 3.30E+02 MAX: 3.20E+03
FRAME OF REF: PART
/adcs02_disk/people/ms_fuerst/tesla.mf1
VALUE OPTION:ACTUAL
SHELL SURFACE: TOP
3.30E+02
4.74E+02
6.17E+02
7.61E+02
9.05E+02
1.05E+03
1.19E+03
1.34E+03
1.48E+03
1.62E+03
1.77E+03
X
Y

Fermilab

Date:________________________

EXHIBIT B
Pressure Testing Permit*

Type of Test: [ ]Hydrostatic [X] Pneumatic

Test Pressure 29.0 psig **Maximum Allowable Working Pressure** 26.4 psig

Items to be Tested
DESY SCRF Cavity Type II (C22)

Location of Test MDB **Date and Time** ________________

Hazards Involved
Pressurized vessel and equipment failure due to over-pressurization.

Safety Precautions Taken
Posting door guard, signs and locking doors to prevent access into SMTF cave area of Meson building during pressure test.
Properly sized safety relief valves to protect the vessel and equipment against over-pressurization.

Special Conditions or Requirements
Pressure test per Chapter 5034 of FESHM.

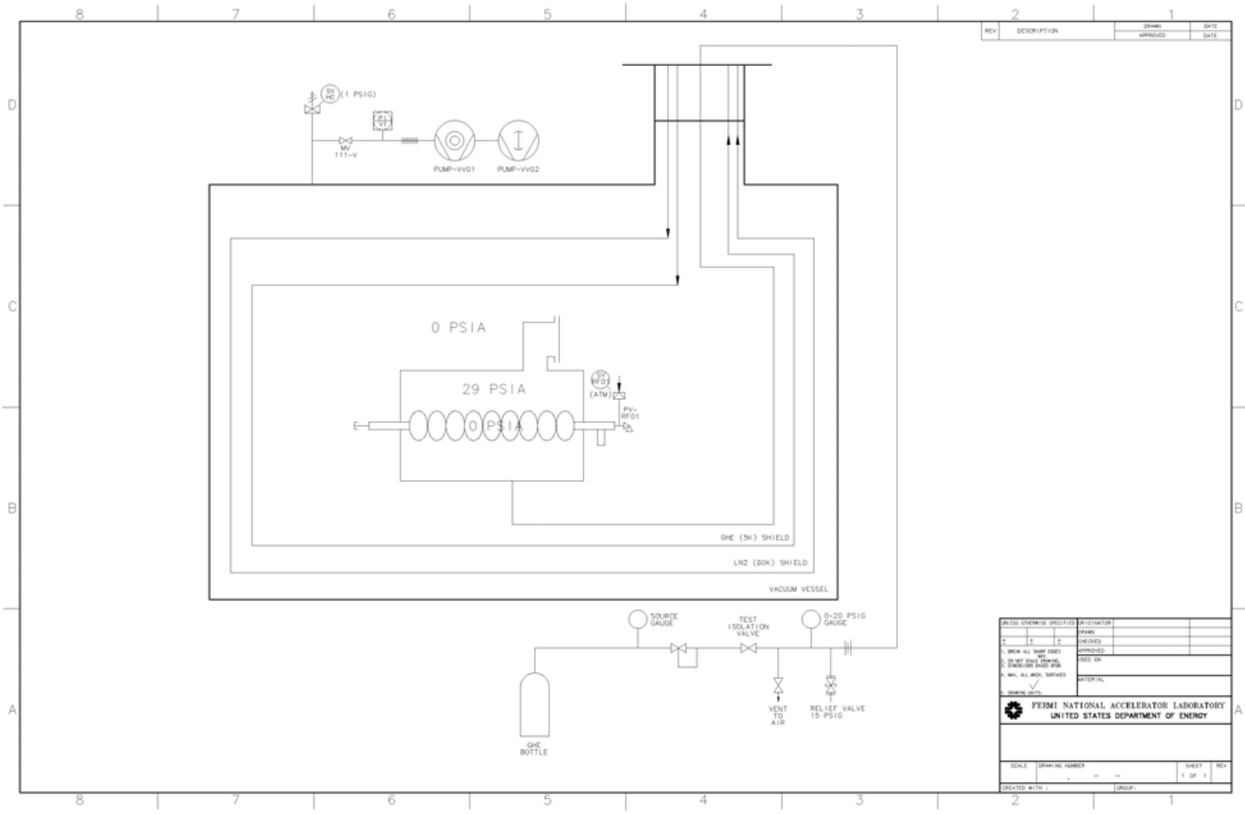
Qualified Person and Test Coordinator Mike McGee x3904 and Mayling Wong x2532
Dept/Date AD/MS and TD/SRF Dev

Division/Section Safety Officer Rich Ruthe
Dept/Date TD/Support/ES&H

Results

Witness ____________________________ **Dept/Date** ________________
(Safety Officer or Designee)

* Must be signed by division/section safety officer prior to conducting test.
It is the responsibility of the test coordinator to obtain signatures.


(1 PSIG)
MV
111-V
PUMP-VV01
PUMP-VV02
0 PSIA
29 PSIA
0 PSIA
(ATM)
PV-
RF01
GHE (5K) SHIELD
LN2 (80K) SHIELD
VACUUM VESSEL
SOURCE
GAUGE
TEST
ISOLATION
VALVE
0-20 PSIG
GAUGE
VENT
TO
AIR
RELIEF VALVE
15 PSIG
GHE
BOTTLE
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

Time	Internal Pressure Differential (psid)	Comment