Mark II High-Pressure RF Test Cell Measurements with Molybdenum Electrodes at Lab G

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Overview and Summary

These are the first results from the second (Mark II) 800 MHz RF Test Cell (TC) to be used at Lab G for the study of high voltage breakdown in dense gases. This work is part of a DOE STTR Phase II grant[1] to develop RF cavities that work at high gradient by virtue of being filled with a dense gas to suppress RF breakdown. The cavities are to accelerate muons to be used in a Neutrino Factory, Muon Collider, or Intense Muon Source. The motivation and design requirements for test cells in this study were described previously[2]. The engineering note used for the safety analysis of the Mark II TC is appended to this document and includes ASME pressure vessel calculations and a flammable gas risk analysis. The engineering note for the Mark II used the same 500PSI maximum allowable working pressure as the old TC to simplify safety issues. The November 2003 study reported here had three goals: 1) to compare the new Mark II design with the old TC in the same pressure and temperature conditions, 2) to use molybdenum electrodes to push the hydrogen breakdown measurements to higher densities and voltages, and 3) to study the characteristics of molybdenum as an RF cavity construction material. The Mark II TC worked well; the aluminum seals were much more robust under temperature variations than the lead-tin solder seal of the first TC. The thick stainless steel walls of the Mark II are sufficiently stiff that the gas density can be determined from the resonant frequency, which depends on dielectric. The molybdenum electrodes also worked better than copper, allowing stable surface gradients of almost 80MV/m in hydrogen gas, compared to 50MV/m for copper. As with copper in pressurized gas, the molybdenum conditioned quickly, improving from 70MV/m to almost 80 MV/m in the last 3 hours of testing. It is likely that stable operating surface gradients larger than 80MV/m may be achieved.

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[1] The Phase I proposal can be seen at http://www-mucool.fnal.gov/mcnotes/public/ps/muc0247/muc0247.ps.gz
[2] http://members.aol.com/muonsinc/TC.pdf

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Test Cell Design Changes

Oilcan deformation reduction

The first test cell used at Lab G was limited to pressures of 34 atmospheres because of ASME requirements on the allowable yield strength of the **bolts**. The torque on the bolts that led to this limitation was caused by the “oilcan” deflections of the disks, where the centers of the disks bulge outward and cause the perimeter boltholes to toe inward. Consequently the design of the Mark II TC was modified to double the thickness of the **disks** from 1” to 2” and to increase the bolt (actually threaded rod) diameter from 7/16 inches to 5/8 inches. Only 24 of the larger bolts fit in the available space compared to 32 of the smaller ones in the first TC. Thus the force the bolts provide to contain the gas pressure and to compress the seal has been increased by their cross-sectional area and reduced by their number to give an overall improvement factor of $(24/32)*(10/7)^2=1.5$.

The increased thickness of the disks has reduced the “oilcan” effect. That and the reduction in the average distance from the bolts to the seal and to the center of the disk have effectively eliminated the torque on the bolts. The new ASME calculations in the appendix indicate that the new Mark II TC can operate to 2000 PSI without exceeding the stainless steel yield strength.

However, the requirement of derating to 80% of book yield value for non-certified construction gives a maximum allowed working pressure of 1600 PSI.

Gas temperature stability

Contributing to the additional pressure capability of the Mark II TC is the change in the **cylinder** construction material from copper to stainless steel. The original reasoning for the choice of copper was to have good heat conduction between the LN2 bath and the contained gas to be sure that the gas was at the temperature of the bath since the thermal conductivity of copper is 50 times better than that of stainless steel. Experience from operating the first TC indicated that this precaution was not necessary if an experiment to study breakdown in a gas as a function of pressure started by filling the cavity with gas and waiting until it comes to thermal equilibrium. Subsequent measurements involve only releasing gas from the TC, never letting warm gas enter the TC.

As is seen in figure 1 below and predicted by the calculations in the appended engineering note, the stainless steel provided adequate cooling to the gas to keep it at the temperature of the cooling bath even with all the klystron power going into sparks in the gas. The plots show that the relationship between the Mark II TC resonant frequency and the gauge pressure was linear over a wide range of breakdown conditions. That is, if the breakdowns had caused a temperature increase, the pressure would have increased although the gas density and corresponding dielectric strength would have remained constant since the gas system is closed during measurements.

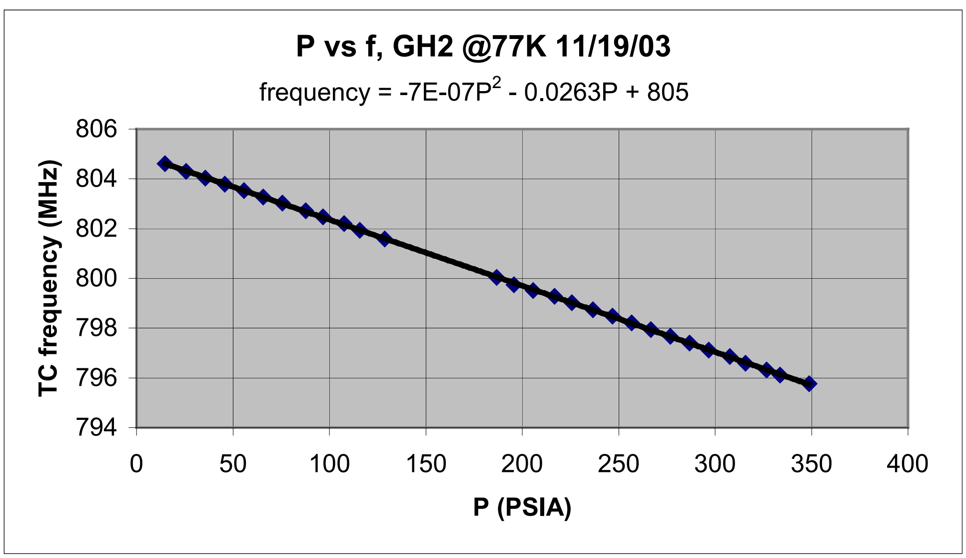


Figure 1. Measurements the Mark II TC resonant frequency and pressure for hydrogen gas at 77K over a wide range of operating conditions with various breakdown rates. The linearity of the plot as seen by the small quadratic coefficient of the fitted curve implies that the gas temperature was constant. The region near 801 MHz corresponds to a breakdown in the waveguide that prevented measurements in the Mark II TC. Below 796 MHz the klystron could not provide enough power cause breakdown.

RF/Pressure seal improvement
Two problems with the Pb-Sn solder RF/pressure seals in the first TC were addressed by changing to 0.017" aluminum gaskets for the Mark II TC. The first problem was that the solder seals flowed at room temperature under pressure such that gas leaks developed if the TC were not kept cold. Second, the electrical conductivity of the solder did not improve at low temperature compared to the copper such that the Q of the cavity also did not improve as much as expected. The aluminum seals worked well during the experiments reported here, with no detectable gas leaks over several days of operation at room and liquid nitrogen temperatures with pressures up to 500 PSI.

Copper plating consequences
The quality of the Mark II copper plating was not as good as on the first TC. By increasing the thickness of the TC disks we increased their weight to the point that our original vendor could no longer plate them. The plating under the doorknob electrodes seemed particularly vulnerable and 0.017" aluminum gaskets were placed between the plated disks and the new electropolished molybdenum electrodes. The increased capacitance by bringing the two electrodes closer together lowered the resonant frequency of the empty TC to 804 MHz, which had two notable consequences. The first was that with the TC filled with hydrogen at 77K and pressure greater than about 300 PSI, the klystron had to operate so far from its natural frequency that it could not provide enough power to condition the TC. The second consequence was that a resonant breakdown of the klystron waveguide was discovered, which coincided with one region of interest in the measurements of hydrogen breakdown where the Paschen curve meets the breakdown gradient of the metal electrodes.

Molybdenum electrodes
For the experiments reported here, we have used electropolished molybdenum electrodes for the first time. This choice was inspired by reports of success by the CLIC project at CERN operating at 30 GHz with pulse lengths of a few nanoseconds. They reported breakdown surface gradient maxima in ratios of about 1.0: 1.5: 2.0 for copper, tungsten, and molybdenum, respectively. These maxima were obtained after conditioning with millions of pulses, however, so the measurements reported below with limited conditioning time were difficult to predict.

Perry Wilson from SLAC presented a model of electrical breakdown in the October breakdown workshop at Argonne, in which he predicted that chromium should be even better than molybdenum. We have ordered a pair of chrome-plated electrodes to use in tests at Lab G in January 2004.

A small hole has been added in the side of each electrode so that a special tool can be used to secure it to the copper disk for good electrical contact.

Measured TC parameters and calibrations

A network analyzer was used to measure the Q_o of the old and new test cells and to calibrate the pickup probe at room temperature and at liquid nitrogen temperature. The program SuperFish was used to calculate the ideal Q_o and shunt impedance of the cavity from which the power for a given gradient was calculated. The first TC had a measured Q_o of 25,300 at 77 K and 13,600 at room temperature. The Mark II TC had a measured Q_o of 26,540 at 77 K and 14,345 at room temperature. The calculated room temperature Q_o for the TC geometry is 19,200. The measured room temperature Q_o is about 30 % lower than calculated for each. This, however, is within the expected normal range for cavities that are bolted together. One normally comes within 5 % of calculation with high purity copper cavity brazed or electron-beam welded together and with only a few small ports. The slightly better room temperature Q_o of the Mark II TC compared to the old TC may be an indication that the new aluminum seals are better than the Pb-Sn solder, especially since the molybdenum electrodes should have made the Q_o worse.

For the old and the new TC, the Q_o improved a factor of 1.85 at 77 K compared to room temperature. The resistance ratio for pure copper over this temperature range is 8. This corresponds to an expected Q_o improvement factor of 2.82 for highly purified copper since Q is inversely proportional to the square root of the resistively. However, neither TC was constructed of high purity copper.

The changes in the TC design may have had offsetting effects. The first TC had high-purity copper electrodes and cylindrical wall and only the disks were copper-plated. The Mark II TC was entirely copper-plated and had molybdenum electrodes. For these reasons the old TC should have had better Q_0 at low temperature. On the other hand, the lead-tin solder seals of the old TC should have had worse low temperature behavior than the aluminum seals of the Mark2TC. The relative importance of these construction parameters is yet to be sorted out.

Gas density from TC resonant frequency

A notable observation is that the stiffness of the Mark II TC allows a direct measurement of the gas density by measuring its resonant frequency. In the old TC, the oilcan distortion of the disks was a complication that confused this realization. With this distortion, the TC volume increases causing the frequency to decrease as a function of pressure. The distortion also causes the electrodes to separate as a function of pressure, causing the resonant frequency to rise because of decreased capacitance. With the new TC, these two effects are negligible. The TC resonant frequency is now only a function of the dielectric of the contained gas, which increases with gas density. Since the Q of the cavity is high, the resonant frequency during operation is easily and accurately determined by changing the klystron frequency to maximize the amplitude of the probe signal on the oscilloscope as shown in figure 2. There is no need now to have a means to directly measure the temperature of the gas in the Mark II TC.

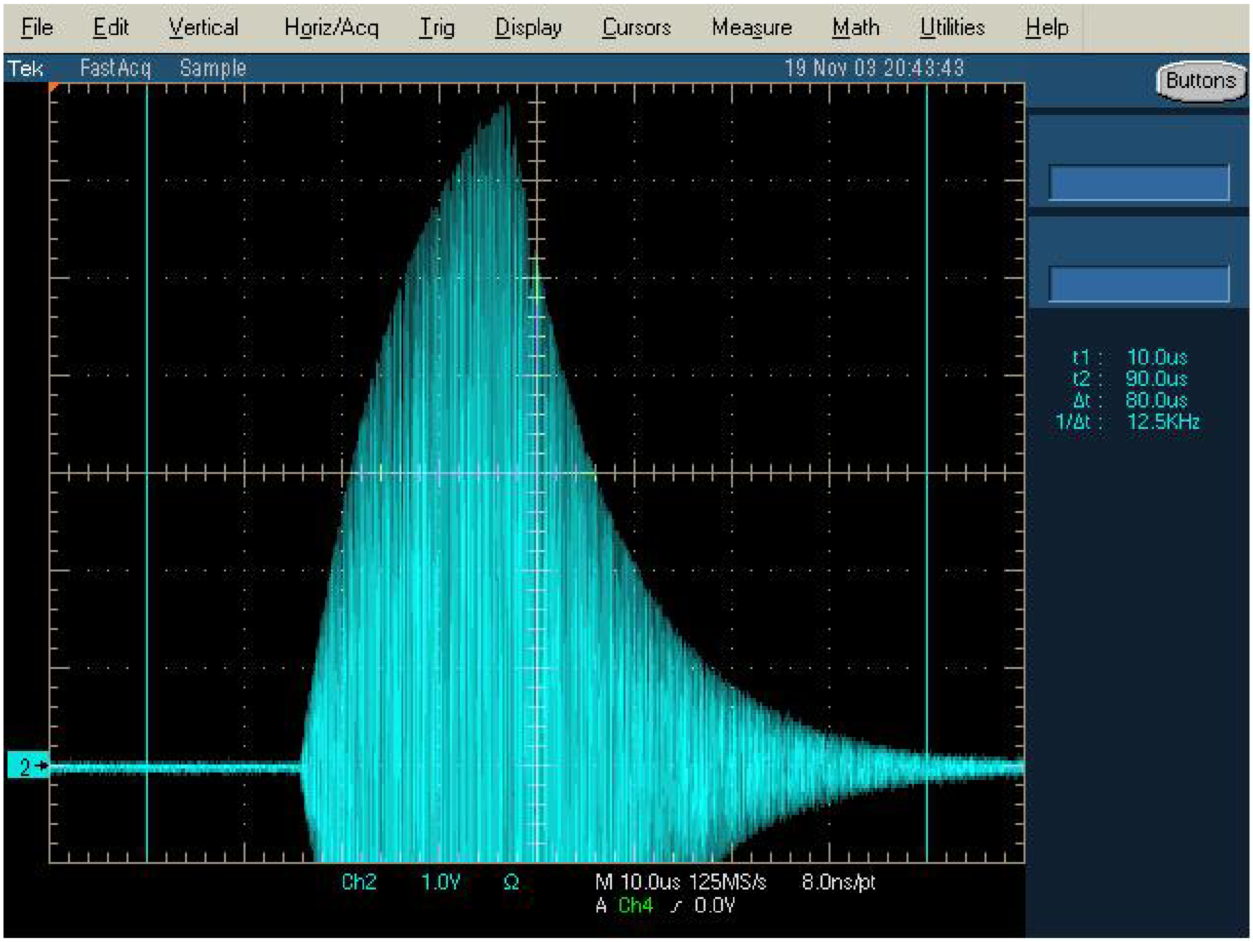


Figure 2. The probe signal taken during the last hours of operation at 250PSI and 77K. The pulse time of 20 μs corresponds to the rising part of the 800MHz envelope. The peak amplitude of 6.8Volts is measured after a 10x attenuator giving 68V on the probe and 68*1.17=79.9MV/m estimated gradient at the surface of the molybdenum electrodes.

Helium data

First measurements at room temperature

Figures 3 and 4 show the first Paschen curve data from the Mark II TC using helium at room and liquid nitrogen temperatures, respectively, taken on November 15. These data compare well to those taken with the first test cell in April 2003, where 28 MV/m was achieved at 77K and 500 PSI. The room temperature expectation is then 28*77/300=7.2 MV/m.

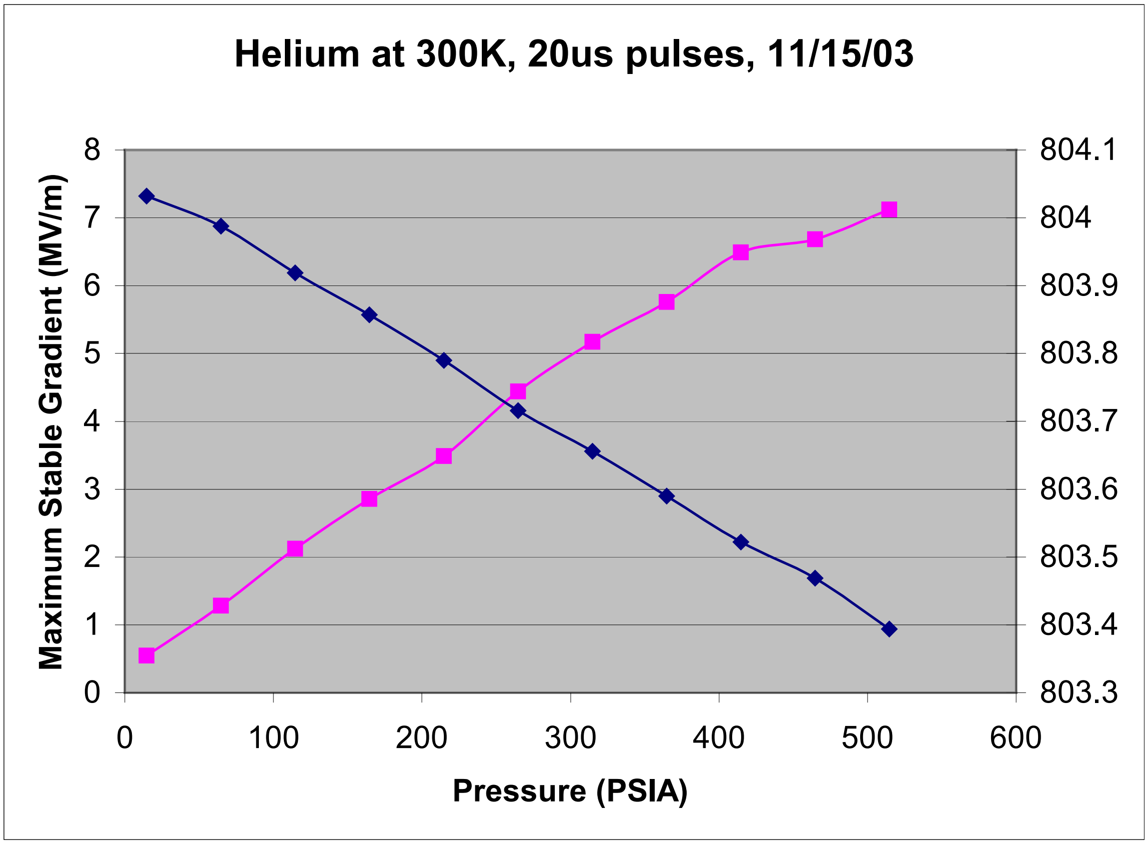


Figure 3. First Mark II Paschen curve measurements for helium at room temperature. The red points are maximum stable gradients, the blue points are Mark II TC resonant frequencies.

First measurements at LN2 temperature

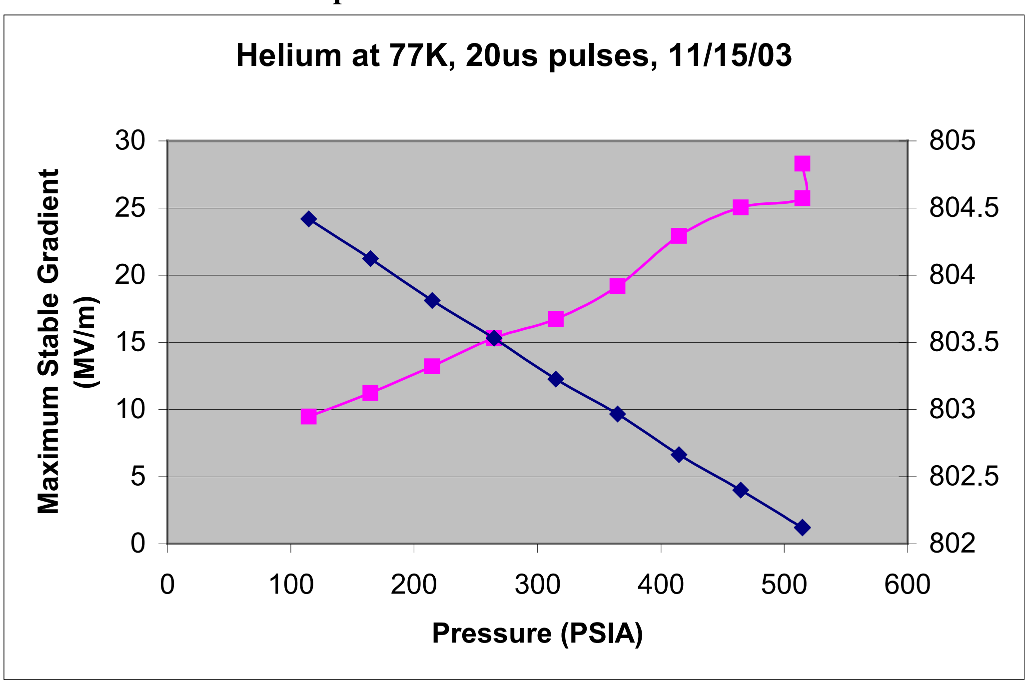


Figure 4. First Mark II TC Paschen curve measurements for helium at liquid nitrogen temperature. The higher gradient point at 514.7 PSIA represents 30 additional minutes of conditioning after the lower point was determined.

Flood in Lab G

After the data in figures 3 and 4 were taken, a heavy rainstorm interrupted operation. During the time of recovery, the Mark II TC was warmed and opened to air. Figure 5 is then a repeated measurement of the data shown in figure 4, four days later.

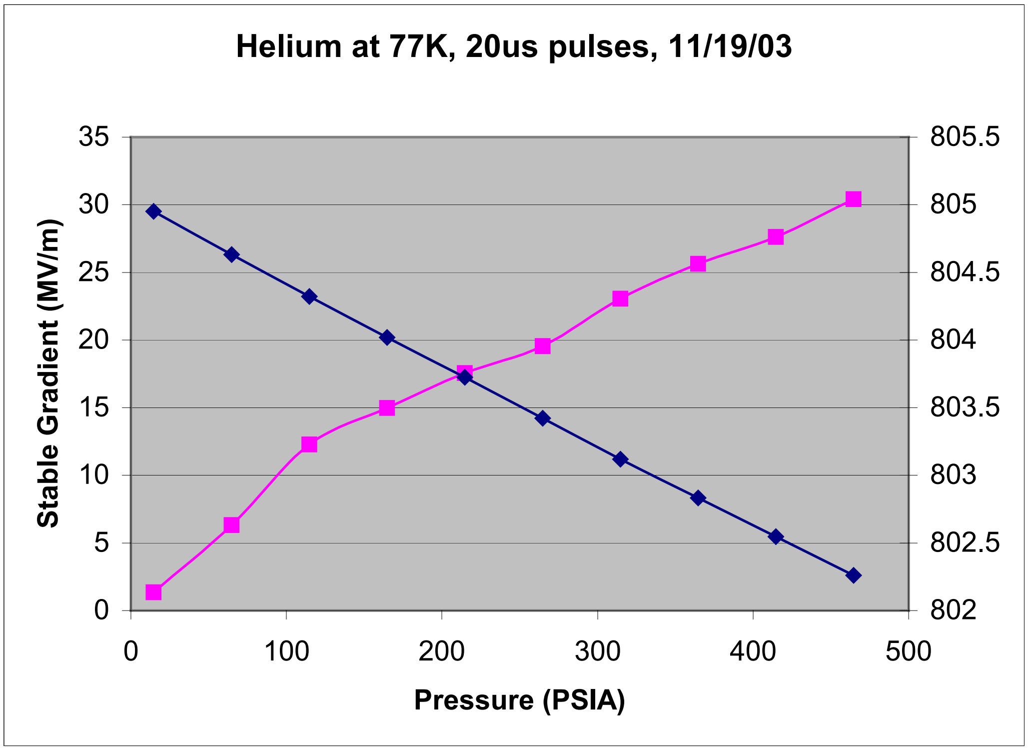


Figure 5. Repeat of the Paschen curve measurements for helium at liquid nitrogen temperature after the lab G flood.

Hydrogen data

Figure 6 shows the maximum stable gradients for hydrogen at 77K. The plot has data from two data acquisition sequences that each start from high-pressure and step downward by venting gas from the Mark II TC. Together the two sequences give a good picture of the character of the data. At high pressure, small changes in the pressure (or corresponding frequency) cause large changes in the maximum stable gradient. At lower pressure, the maximum stable gradient increases linearly and very reproducibly with pressure. This linear region is what we call the Paschen curve region. (The points at zero gradient are artifacts of the plotting program.)

The dip in the stable gradient data centered at 190 PSIA seems to be due to a breakdown in the waveguide. This breakdown has been studied subsequent to our studies and it has been verified that it is not related to the test cell and repeats at intervals of 7 MHz.

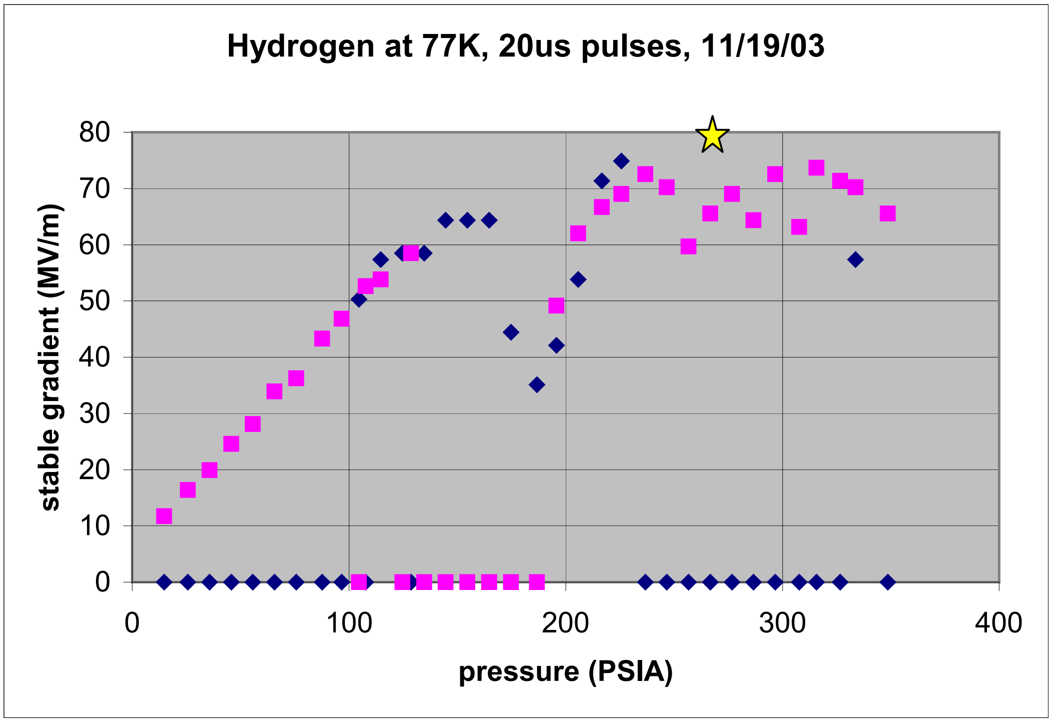


Figure 6. Paschen curve measurements for hydrogen at liquid nitrogen temperature. The blue and magenta points indicate two separate data runs. The points at zero gradient are artifacts of the plotting program. The gold star represents the result of the last 3 hours conditioning at 265 PSIA, where a maximum stable gradient of 79.9MV/m was attained.

Similar to the experience with copper electrodes, the molybdenum conditioned quickly. At a particular setting above the Paschen region it took about 3 hours to increase the stable operating gradient from 70 to 79.9MV/m. However, evidence of minor pitting on the electrodes suggests that the pulse length should be shortened as the breakdown gradient increases in order to condition the metal surface with smaller breakdown discharges.

Extrapolations

These latest measurements of the Paschen curve in hydrogen have the widest range of pressures we have used at 77K and can be used to estimate the breakdown suppression that could be expected with operating conditions we hope to achieve. Extrapolating to 110 atmospheres pressure, where the gas density is about half of liquid hydrogen density, the breakdown suppression should be about 690 MV/m. This number is important to us as a measure of how well the cavities will withstand the ionization created by an intense muon beam.

Assuming no distortion of the Mark II TC, the change in the resonant frequency from no pressure to 110 atmospheres is 42 MHz or 5.2 %. This is another important parameter for us for the design of cavities to be used in a real muon-cooling channel. That is, certain modes of operation may require the ability to tune the cavities.

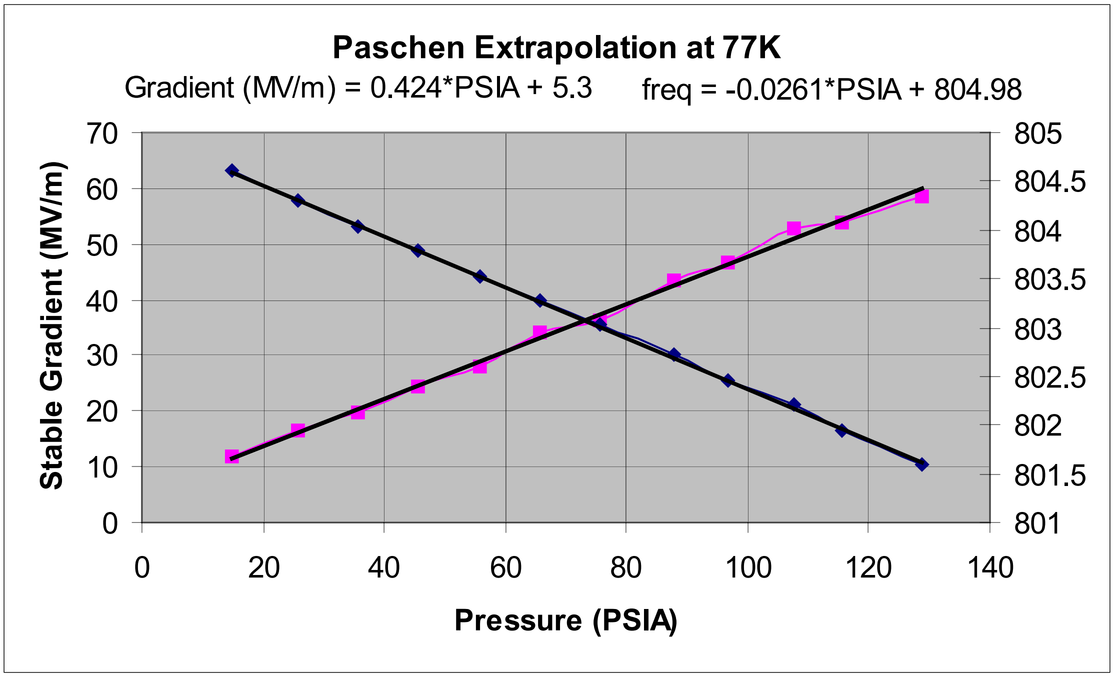


Figure 7. Linear fits to the data from the Paschen region.

Future Plans

The goal of this STTR project is to demonstrate that pressurized RF cavities will work for muon ionization cooling. The next steps are to demonstrate that such cavities will work in the high magnetic and radiation fields expected in an actual cooling channel.

Early in 2004 we expect to operate the Mark II TC inside the LBL 5T solenoid to compare to the breakdown behavior we have measured without a field and to the behavior of the evacuated cavities that have been already tested in the solenoidal field. For this first operation, we will eliminate the problem of providing a liquid nitrogen dewar inside the solenoid for the Mark II TC by operating only at room temperature, but higher pressure. The gas density is the important variable, and so the Paschen region of interest will be accessible without LN2 cooling if the Mark II TC is tested and certified for 1600PSI operation. A new engineering note is being prepared to extend its MAWP.

The extrapolated breakdown gradient of almost 700MV/m for hydrogen gas in our expected operating conditions gives confidence that the cavities will handle ionizing radiation well. Nevertheless, the demonstration of this prediction in the MTA is the ultimate goal of this project. Our top priority is to make sure that the MTA will have beam for us as soon as possible. We are hopeful and enthusiastic that a beam line design can be implemented so that we can do the required tests in 2005.

In order to push the technology for RF cavities, both evacuated and pressurized, we have begun to study construction materials and their breakdown behavior. The molybdenum results reported here are encouraging, and we look forward to our next tests with chromium.

Appendix: Lab G Mark II High-Pressure RF Test Cell
PRESSURE VESSEL ENGINERING NOTE PER CHAPTER 5031

Prepared by: **Rolland Johnson**
Preparation date: **Nov.11, 2003**

1. Description and Identification
Fill in the label information below:

This vessel conforms to Fermilab ES&H Manual Chapter 5031

Vessel Title **Lab G Mark II High-Pressure RF Test Cell**

Vessel Number ______________________________ ←**Obtain from Division/Section Safety Officer**

Vessel Drawing Number ______________________________

Maximum Allowable Working Pressures (MAWP):
Internal Pressure ___**500 psi**_________
External Pressure ______**N/A**______________
Working Temperature Range: **77K (LN2)** to **300K**
Contents **H_2, He (77K to 300K),or N_2 (270K to 300K)**
Designers/Manufacturer
Rolland Johnson, Robert Hartline/Muons, Inc.
Test Pressure (if tested at Fermi) Acceptance Date: 11/12/03 ←**Document per Chapter 5034 of the Fermilab ES&H Manual**

_X__550____PSIG, Hydraulic_________Pneumatic X ___________
Accepted as conforming to standard by
Roger Dixon ______________________________

of Division/Section__Beams Div._ Date:_11/12/03_______ ←**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: ____________________

Amendment No.:	Reviewed by:	Date:
________	________	________
________	________	________

Lab Property Number(s): **Property of Muons, Inc.**
Lab Location Code: **Lab G** (obtain from safety officer)
Purpose of Vessel(s): **The device is an experimental research instrument being developed to measure high-voltage RF breakdown in high-pressure gases**

Vessel Capacity/Size: **3.3 liters** or **0.12 ft^3** I. Diameter: **9 inches** Length: **3.2 inches**

(Note: The capacity of gas is reduced by the particular choice of internal electrode geometry (~0.2 liters) and, depending on the calculation of interest, can be increased by the pressurized volume of the attached coaxial RF pipe (~0.9 liters)).

Normal Operating Pressure (OP) **0 to 500 PSI**
MAWP-OP = **500 PSI**

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

Drawing #	Location of Original
Top Plate Schematic ______________________	Figure 6 below__________________________
Test Cell Schematic ______________________	Figure 7 below ______________________________________
______________________________________	____
______________________________________	____
______________________________________	____

2. Design Verification

Is this vessel designed and built to meet the Code or "In-House Built" requirements?
Yes__**X**__ No____.

If "No" state the standard that was used ________________.
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.

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)

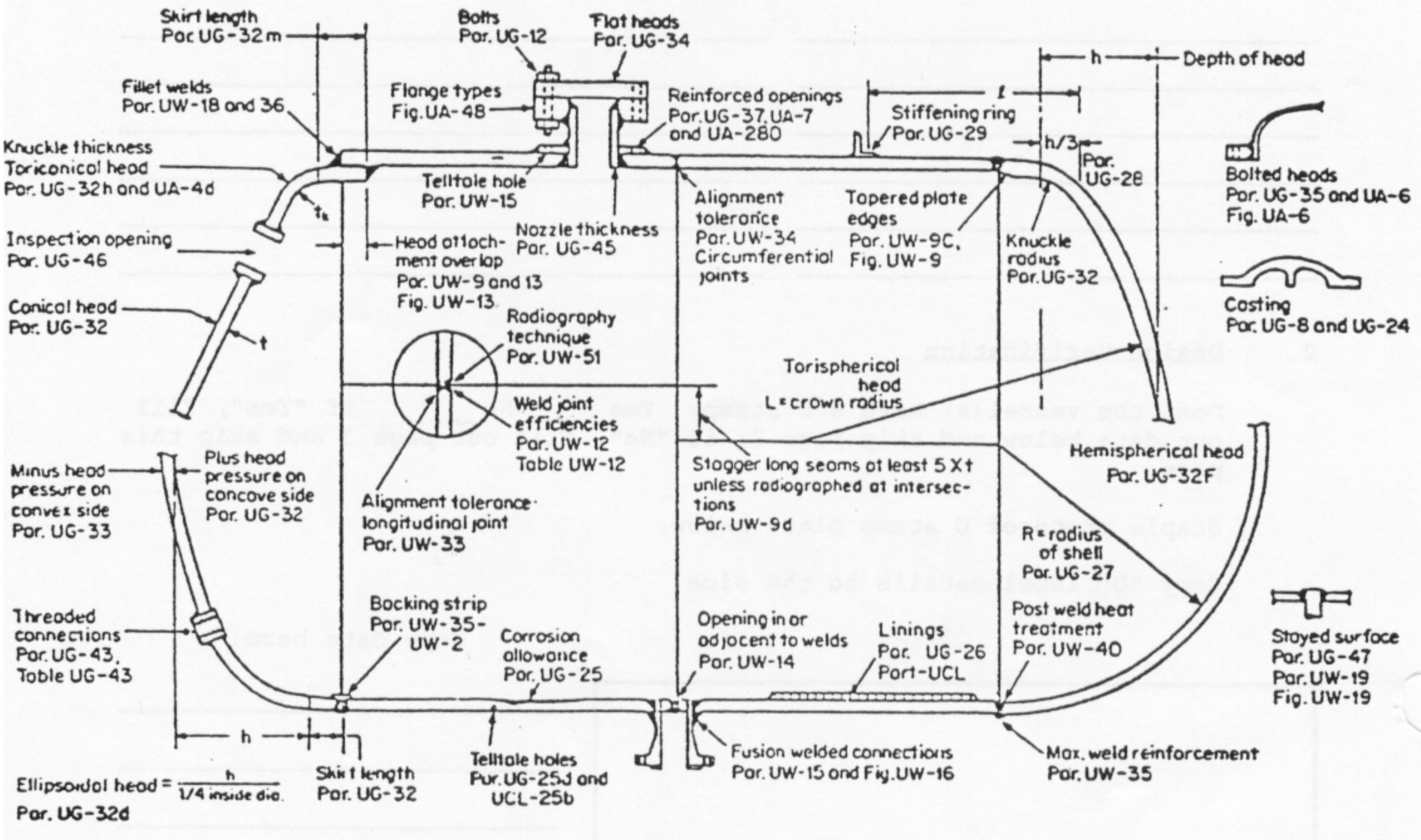


Figure 1. ASME Code: Applicable Sections

2B.

<u>Summary of ASME Code</u>

<u>Item</u>	Reference ASME <u>Code Section</u>	<u>CALCULATION RESULT</u> (Required thickness or stress level vs. actual thickness <u>calculated stress level)</u>
Disks_____________	UG-34 Flanges _____________	See MSG-EAR-03-338, below
Cylinder ___________	UG-27____________________	See MSG-EAR-03-338, below
Bolts _____________	UG-12____________________	See MSG-EAR-03-338, below
Holes in Top Plate	________________________	See MSG-EAR-03-338, below

3. System Venting Verification.

The vent system and the operational procedures are discussed in the flammable gas analysis section below. The procedures have been modified to acknowledge that the needle valve (FV) is too unwieldy to use as a means to fill the test cell and now is only used as a means to restrict the flow of gas into the blockhouse. The operator uses the valves PV or HV to fill the test cell with helium or hydrogen, respectively.

Discussions of gas flow requirements, which were included in the engineering note for the original test cell and showed considerable safety margin, are repeated below in sections titled "Additional Test Cell Venting Requirements" and " Note on Flow Rates of Compressible Gases through Pipes and Valves". There is additional discussion in the section below.

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___

A "no" response to both of the two proceeding questions requires a justification and statement regarding what standards were applied to verify system venting is adequate.

List of reliefs and settings:

Manufacturer	Model #	Set Pressure	Flow Rate	Size
Circle Seal	5120B-2MP 600	550 PSI	170 CFM	0.5-inch

Note that the maximum flow rate of the Matheson model 2-580 regulator is 5200 CFM. The Needle Valve is more restrictive.

4. Operating Procedure

Is an operating procedure necessary for the safe operation of this vessel?
Yes _**X**__ No____ (If "Yes", it must be appended) **See Chapter 4.**

5. Welding Information. **This device has no welds.**

6. Existing, Used and Unmanned Area Vessels

Is this vessel or any part thereof in the above categories?
Yes_____ No ___**X**__

7. Exceptional Vessels

Is this vessel or any part thereof in the above category?
Yes_____ No __**X**___

MSG-EAR-03-338
September 9, 2003

Stress Analysis of High-Pressure Test Vessel

BobWands

Introduction and Summary

The ASME Boiler and Pressure Vessel Code, Section VIII, Div. I, is used to verify the design of a 100 atmosphere test vessel.

The Code calculations show that the required cylindrical shell thickness is 0.369 in; the actual minimum shell thickness is 0.875 inches. The calculations also show that the required flat circular head thickness is 1.46 inches; the actual head thickness is 2 inches. The 1.5 inch diameter penetration in one head is shown to require no additional reinforcement, other than that inherent in the 2 inch thick head. The same is true of the blind holes used to bolt the pipe flanges to the head.

A 3-d finite element model was created to check the Code calculations, and to look at stresses associated with support. (The vessel, without the 1.5 inch diameter pipes, weighs approximately 175 lbs). The stresses in the center of the flat heads do not exceed 9000 psi; the hoop stresses in the cylindrical shell do not exceed 5000 psi. These maximum stresses are well below the allowable stress for SS316 steel of 18,800 psi.

This analysis does not address the piping and flanges that bolt to the heads, except as they affect the vessel stresses through their support function. The analysis shows that the contribution of support reactions to the head stress is negligible.

Cylindrical Shell

From the ASME Boiler and Pressure Vessel Code, Section VIII, Div. 1, UG-27, the thickness of a cylindrical shell under internal pressure must be no less than

$t = PR/(SE-0.6P)$

where t = thickness of shell
R = inside radius of shell = 4.5 in
P = internal pressure = 1470 psi
S = allowable stress = 18,800 psi (SA-249 welded SS316 tube, per Div. II Part D)
E = weld efficiency = 1 (welded tube allowable stress is used)

Substituting,

$t = 1470(4.5)/(18800(1)-0.6(1470)) = 0.369$ in.

The shell is perforated by 24 5/8 inch bolts. Although its maximum thickness is 1.5 inches, its minimum thickness (in a plane through a bolt hole) is only 0.875 inches. This is still larger than the minimum requirement of 0.369 inches. Therefore, the shell meets Div. I criterion.

Flat Head

From Section VIII, Div.1, UG-34(c)(2), Formula (1), the minimum required thickness of flat unstayed circular heads must be no less than

$$t = d(CP/SE + 1.9Wh_g/SEd^3)^{1/2}$$

where t = thickness of flat head
- C = factor for attachment = 0.25 (from Fig. UG-34(p))
- P = pressure = 1470 psi
- S = allowable stress = 18,800 psi (SA-240 SS316 plate, per Div. II Part D)
- E = weld efficiency = 1 (no welds)
- d = diameter of head = 10.5 in (from Fig. UG-34(p))
- W = total bolt load (calculated by Appendix 2; unneeded since $h_g = 0$)
- h_g = gasket moment arm = 0 (gasket symmetric about bolt)

Substituting,

$$t = 10.5(0.25(1470)/18800)^{1/2}$$

$$t = 1.46 \text{ in.}$$

Actual flat head thickness = 2.0 inches. Therefore, the head meets Div. I criterion.

Reinforcement of Penetrations

There is a single 1.5 inch diameter penetration through one of the 2.0 inch thick heads where a ½ inch thick flange is bolted to connect a stainless steel pipe. From UG-36(c)(3)(a), openings less than 2.375 inches in diameter in shells or heads greater than 0.375 inches thick require no reinforcement other than that inherent in the design.

No reinforcement is required for the 1.5 in. penetration, or for the blind bolt holes used to fasten the pipe flanges to the head.

Finite Element Model

The Code calculations are based on thin shell/plate theory; the test vessel components are relatively thick, and their actual stresses are not well predicted by the Code equations. A 3-D finite element model (Fig. 1) was created to verify the design. Bolt preload was applied such that the bolts reached a stress of 90% yield, or 67.5 ksi. This bolt load produces a total force of about 500,000 lbs, and a compressive stress on the gasket surface of over 10,000 psi.

An internal pressure of 1470 psi was applied to the model.

Seven inches of piping were attached to each head and constrained at the ends to simulate the dead weight support. This length is arbitrary; the actual pipe length may be more or less than assumed here. In any case, the analysis shows that the dead weight support is not a critical contributor to the vessel stresses.

Fig. 2 shows the deformed shape of the vessel. The deflection of the 2 inch thick flat heads is less than 0.001 inch at the center. For the support system assumed, the entire vessel will sag downward by about 0.004 inches.

Figures 3-5 show stresses along three lines through the critical sections. All stresses are less than predicted by the Code calculations, and less than the 18,000 psi allowable for SS316.

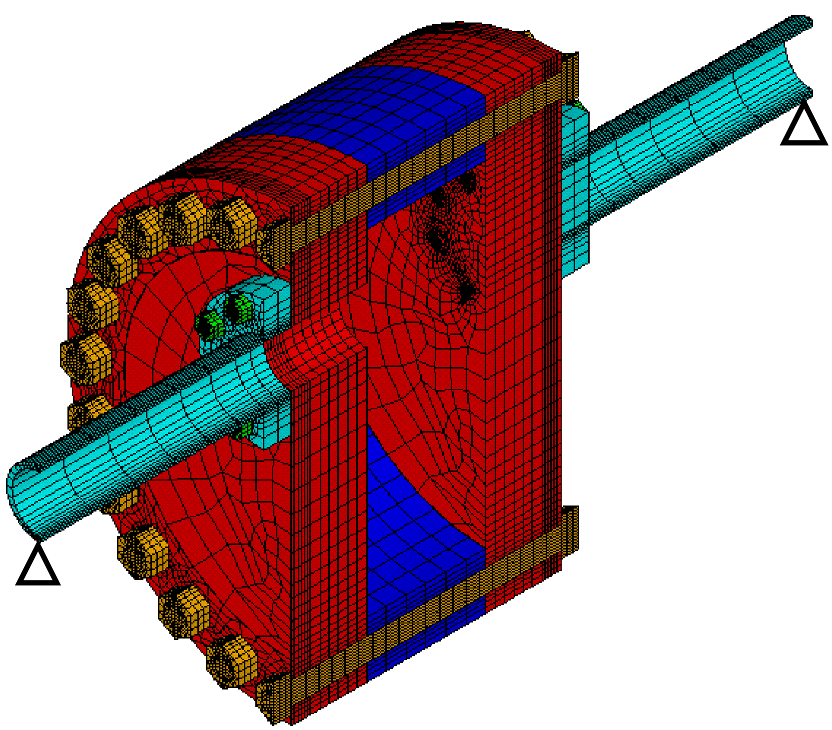


Figure 1. Finite Element Model of Test Vessel

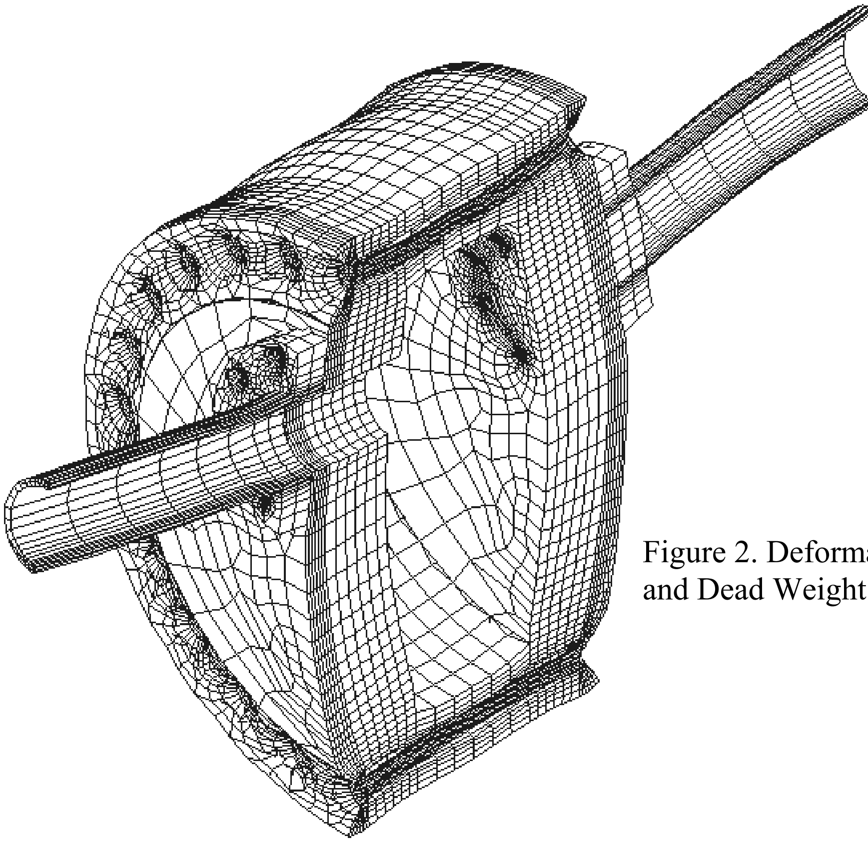


Figure 2. Deformation under Pressure and Dead Weight Loads

Figure 3.

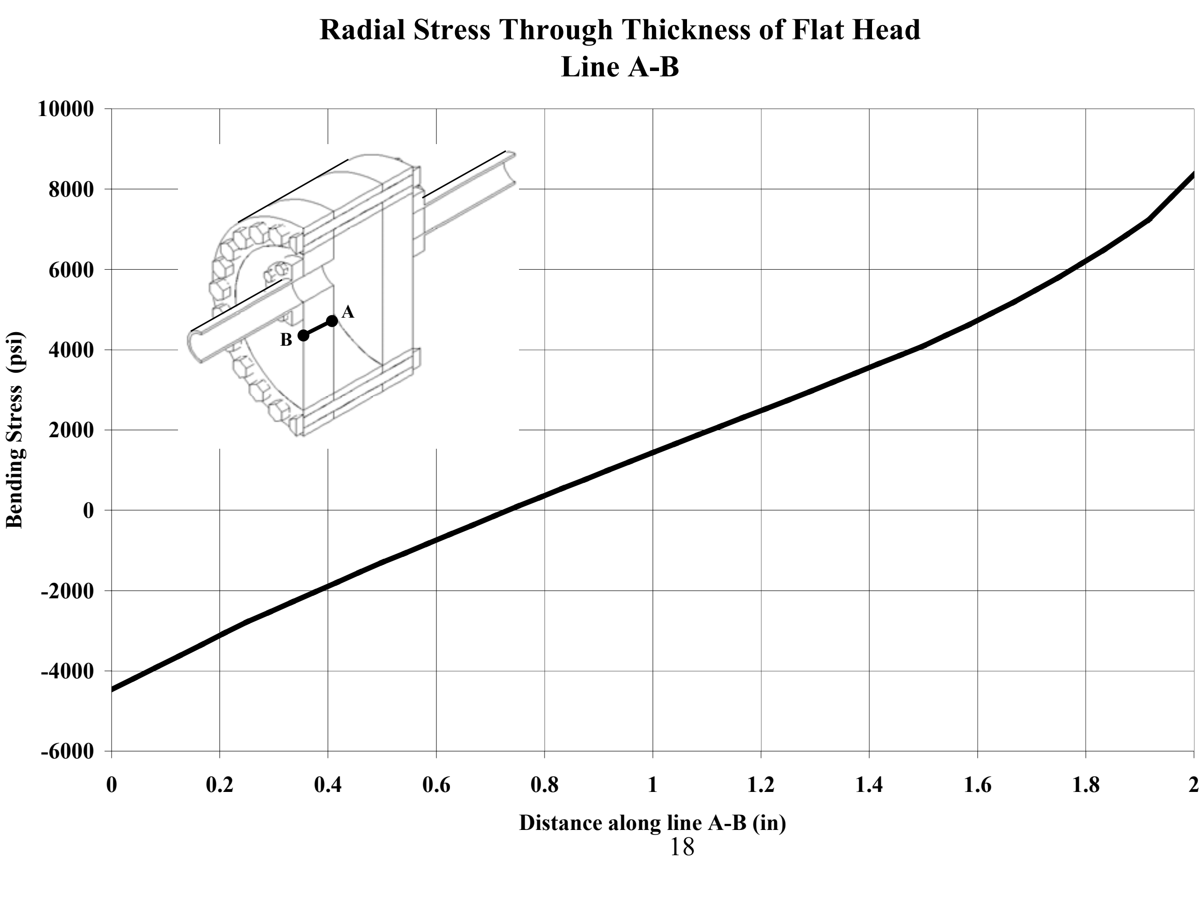


Figure 4.
Shell Hoop Stress
Line C-D

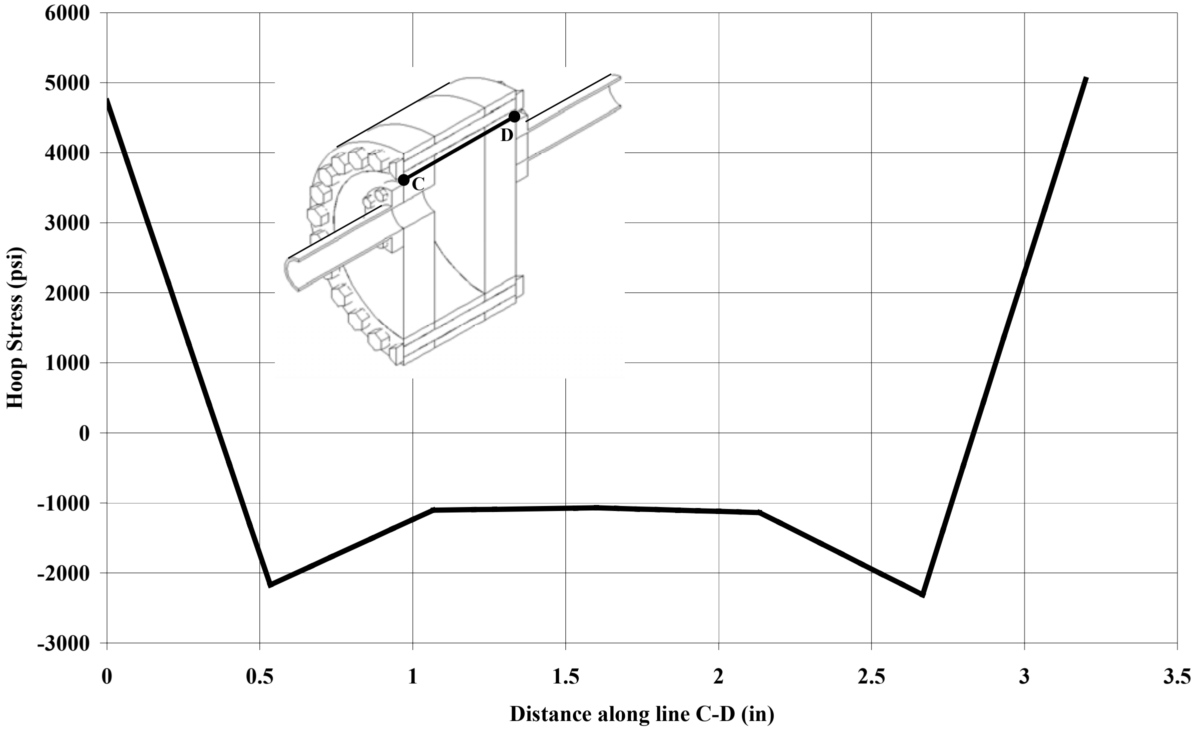
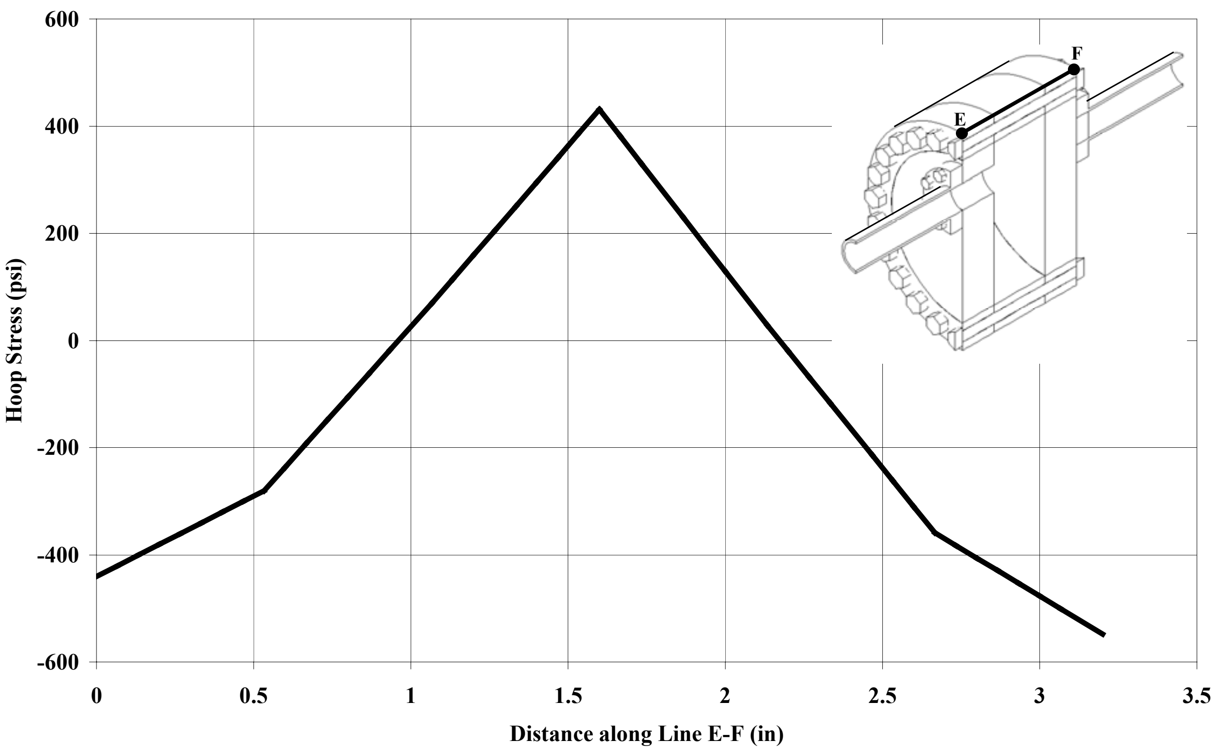


Figure 5.
Shell Hoop Stress - Line E-F



Conclusion

This analysis verifies with both ASME Code calculations and a finite element model that stresses in the test vessel are well within the limits imposed by the ASME Code for SS316 stainless steel.

This analysis is confined to the test vessel proper, and does not cover the piping and pipe flanges, which bolt to the vessel, except as they affect the vessel in their support function. No high stresses were observed in these regions, but further work should be addressed toward assuring that the piping and flanges are adequately sized for 1470 psi.

As relates to the vessel proper, the concept of support using the pipes bolted to the heads is sound; the vessel weight of 175 lbs produces additional stresses in the head of less than 100 psi, negligible compared with the pressure stresses.

Additional Test Cell Venting Requirements

Pressure Relief Required by RF Heating

The 12 MW klystron runs at 5 Hz. Each pulse could be as long as 50 μs, implying a maximum average klystron power of 600*5 = 3000 Watts. However, the 1.5-inch diameter coaxial line is only capable of transmitting 250 kW. Thus the maximum power to the TC is 0.25*50*5 = 62.5 W, or rounding up, 100 W.

Normally, this power is dissipated in the walls of the test cell. Thus, when operating at the full repetition rate at room temperature the TC can be cooled with a fan to remove 10 to 62.5 Watts, depending on the pulse length.

A spark across the electrodes causes the TC to detune. In this condition, the **RF cannot be fed into the cavity** and almost the entire incident wave is reflected back toward the klystron. The reflected wave is detected and used to turn off the klystron. A variable delay, currently about 8 seconds, inhibits the klystron from pulsing, allowing the TC to recover. Thus **the gas in the TC is inhibited from receiving significant direct heating by the process itself, since electrical conduction in the gas detunes the cavity, and by the electronic circuit that inhibits klystron operation into a detuned cavity.**

Nevertheless, we were asked the question "if all of the power of the klystron went into heating the gas, how fast would the pressure rise?" In the next two sections, we first calculate the rate that the temperature rises assuming 100 Watts of input, then we calculate the rate the gas cools from heat transfer by conduction to the body of the TC. Equilibrium is achieved with a 39-degree temperature rise, which corresponds to a pressure increase of 63 PSI. This increase takes 63/103 = 0.6 minutes. Thus 0.174*63/14.7 = 0.74 SCF must be passed through a ¼-inch line, ten feet long and out the relief valve in 36 seconds. **This is about 1 SCFM.**

The Circle Seal 5100-4MP relief valve is rated to carry 170 CFM at 500 PSID.

As shown below, the 15-foot long, ¼-inch diameter pipe between the test cell at 550 PSI and the relief valve at 60 F and 500 PSI will carry air at 66 SCFM, helium at 178 SCFM, and hydrogen at 250SCFM.

For the case when there is a vent to the outside of the Lab G building, we find that a 67'-long ¼-inch diameter pipe at 60 F will carry air at 76 SCFM, helium at 205 SCFM, hydrogen at 288 SCFM. At liquid nitrogen temperatures the numbers are: air at 144 SCFM, helium at 387 SCFM, hydrogen at 546 SCFM.

We conclude that nothing inhibits the required flow of 1 SCFM to relieve the pressure caused by some mechanism to directly heat the gas in the TC.

RF Heating

The amount of Energy needed to increase the Temperature of a mass with specific heat C is dE=dT*Cm or dE/dt=mCdT/dt. Where E is in Joules, C in Joules/(gram Kelvin), and the mass, m=(w=molecular weight)PV/22.4. Using PV=nRT or dP/P=dT/T at constant V and compressibility, we have dP/dt=[22.4/CwVT]dE/dt. Here are a couple of examples.

At **300 K**, 5.193 Joules are needed to raise 1 gram of Helium 1 degree K. The test cell volume is about 3 liters. At **33 atmospheres** the equivalent volume is 100 liters which holds 4*100/22.4 = 18 g of He. To raise 18 grams of helium 1 degree K requires 18*5.193=93 Joules. The maximum anticipated output of the Klystron is roughly 100 Watts or 100 Joules/s. The temperature rise in one minute, if the helium were isolated is 60*100/93=64 degrees K/minute. The fractional pressure rise is proportional to the fractional temperature rise at constant volume such that the **pressure rise** would be 33*64/300= **7 atmospheres/minute or 103 PSI/m.** Note this result is independent of the initial pressure since the heating rate is inversely proportional to the pressure. For ideal gases it only depends on the molecular weight and the heat capacity of the gas.

At **80 K**, we take 5.193 Joules as that needed to raise 1 gram of Helium 1 degree K. The test cell volume is about 3 liters. At **33 atmospheres** the equivalent volume is 100 liters which holds 4*(300/80)100/22.4 = 67.5 g of He. To raise 67.5 grams of helium 1 degree K requires 67.5*5.193=350 Joules. The maximum anticipated output of the

Klystron is roughly 100 Watts or 100 Joules/s. The temperature rise in one minute, if the helium were isolated is 60*100/350=17.11 degrees K/minute. The fractional pressure rise is proportional to the fractional temperature rise at constant volume such that the pressure rise would be 33*17.11/80= 7 atmospheres/minute.

Conductive Cooling

We can study the time constant for the gas to come to equilibrium with the stainless steel wall of the TC.

Using the coefficient of thermal conductivity of helium gas and a model where the outer cylinder is a heat sink and the gas is heated in the middle of the electrodes with 100 Watts we can calculate the temperature difference needed to achieve thermal equilibrium. For a radius of 11 cm and a cylinder area of $A = 8 \times 2 \pi\ 11.43 = 575\ cm^2 = .0575\ m^2$, $\lambda = 0.15$ W/(m K)
$dE/dt = (P \lambda A)\ dT/r$, so $dT = (0.11 \times 100)/(33 \times 0.15 \times 0.0575) = = 39$ degrees K.

That is, 39 degrees of temperature difference is sufficient to support 100 W of energy transport through 33 atmospheres of gaseous helium to the cylinder. This temperature rise corresponds to a pressure increase of 39/300 = 13% or 4.25 atmospheres or 62.5 PSI.

Pressure Relief Required by RF Heating in Case of Loss of the LN2 bath

The Test Cell will be bathed in air at room temperature or in a liquid nitrogen bath. If the bath were to be removed, the TC would warm up and the pressure would increase. We can calculate the rate that this would happen. The mass of the TC is about 80 kg. Take an average specific heat of 0.42 J/(g-K) so that it takes 80000*0.42 = 33600 Joules to warm it one degree K.

The surface area of the TC top and bottom is $2 \pi (6)^2$ $inches^2 = 226.5$ $inches^2 * 6.45 = 1461\ cm^2$, the outside cylinder is about 180 $inches^2 = 1159\ cm^2$. $A = .262\ m^2$ and $dT = 300-80 = 220$ K.

The thermal conductivity of air is $\lambda = 0.023$ W/(m-K) at room temperature. A transport distance of 1 cm, the air will carry $dE/dt = \lambda\ A\ dT/distance = 0.262*0.023*220/.01 = 130$ W, implying 33600/130 = 260 s or 4.3 minutes to warm the TC one degree causing an increase of pressure of 1.25% or 6 PSI. This result is more limiting than the case of the RF power from the klystron heating the TC, where only 62.5 W would be available. The combination yields about 200 W or 2.8 minutes to relieve 6 PSI. **A flow of less than 1 CFM is required to relieve these two sources of increased pressure.** As discussed in the previous case, the pipes and relief valve easily carry this flow.

Note on Flow Rates of Compressible Gases through Pipes and Valves

This note follows the procedures in "FLOW OF FLUIDS THROUGH VALVES, FITTINGS, AND PIPE, Technical Paper No. 410", Crane Co. www.cranevalve.com.

We are to determine the limiting flow rates for the piping system shown in the schematic below.

Case number 1, determine the initial flow rate in the vent line from the open relief valve through a 67-foot pipe to the outside of the Lab G building.

The form of Darcy's equation to be used is expressed as:

$$q_m' = 678\, Y\, d^2 \sqrt{\frac{\Delta P\; P'}{K\; T\; S_g}}$$

where q_m' is the rate of flow in cubic feet per second at standard conditions (SCFM),
Y is the net expansion factor for compressible flow through orifices, nozzles, or pipes, d is the internal diameter of the pipe in inches,
P is the gauge pressure in PSIG,
P' is the absolute pressure in PSIA,
K = f L /D is the resistance coefficient, f is the friction factor, L the length of pipe in feet, D is the internal diameter in feet,
T is the absolute temperature in degrees Rankine = 460 + t,
t = temperature in Farenheit,
and S_g is the specific gravity of a gas relative to air.

In our first application, we will assume a nominal 1/8-inch pipe with a smoothness corresponding to a schedule 40 pipe. From table B-16 we see that such a pipe has d = 0.269, d^2 = 0.0724, D = d/12 = 0.0224.
From the graph on A-25, for schedule 40 stainless steel pipe, f = 0.033.
Thus K=0.033 L / 0.0224 = 1.47 L.

Let P = 500 and P' = 514.7, and ΔP/P'=0.97. This number is so large for our cases that we are always in the condition of initial flow being limited by the speed of sound since our lines are relatively short. This situation can be seen by examination of the table on page A-22. Even for a 67 foot pipe, K= 100, and the maximum ratio of ΔP/P' = χ = 0.926. Since our ratio of 0.97 is larger than this, we have sonic flow and a maximum value of Y = 0.710. For a 15 foot pipe, K=22 and χ = the maximum ΔP/P' = 0.84. We derate ΔP by the factor χ such that the formula becomes:

$$q_m' = (678)\,(0.71)\,(0.0724)\sqrt{\frac{\chi\,(514.7)^2}{(1.47)\,L\,(460+t)\,S_g}} \quad \text{or} \quad q_m' = 14800\sqrt{\frac{\chi}{L(460+t)S_g}}$$

A 67' pipe at 60 F will carry air at 14800 sqrt (.926/(67 520)) = 76 SCFM
Or helium at (76) * sqrt(1/(S_g = .1381)) = (76) 2.69 = 205 SCFM,
Or hydrogen at (76) * sqrt(1/(S_g = .0695)) = (76) 3.79 = 288 SCFM.

Thus, In the case of a pipe to carry hydrogen out of the Lab G building, a 67-foot long 1/8-inch pipe is sufficient.

Case number 2. Determine the initial flow rate between the TC at 550 PSIG and the relief valve at 500 PSIG.
This is the case where the relief valve has opened, but its spring reseats the valve so as to keep the pressure at 500 PSI.

Let ΔP = (550-500) = 50 and P' = 564.7, and ΔP/P'=0.09.

$$q_m' = (678)\,(0.71)\,(0.0724)\sqrt{\frac{(50)\,(564.7)}{(1.47)\,L\,(460+t)\,S_g}} \quad \text{or} \quad q_m' = 1512\sqrt{\frac{1}{(460+t)S_g}}$$

A 15 pipe at 60 F will carry air at 1512 sqrt (1/(520)) = 66 SCFM, helium at 178 SCFM, and hydrogen at 250SCFM. Rates are higher for lower temperature gas. (Tom Peterson estimates 167 SCFM hydrogen gas using a different model for the gas flow for a steady state flow rather than an initial condition). These flow rate estimates are more than adequate, being over two orders of magnitude more than those required by the calculations of the preceding section labeled "Additional Test Cell Venting Requirements. "

Case number 3. Determine the maximum flow rate through the Needle Valve, FV, into the blockhouse assuming a 2000 PSI gas bottle regulator has failed and the pipe to the TC has opened inside the blockhouse.

The Needle Valve was measured to allow 12 liters/sec of air to flow with a pressure differential of 100 PSIG. Scaling with the square root of pressure for this case of sonic flow and including the specific gas density implies a flow rate of (12/28)*sqrt(2000/(100*0.0695) = 7.27 SCFM of hydrogen. Which severely limits the amount of gas that could flow into the blockhouse before the operator could shut off the valve in the case of a regulator failure.

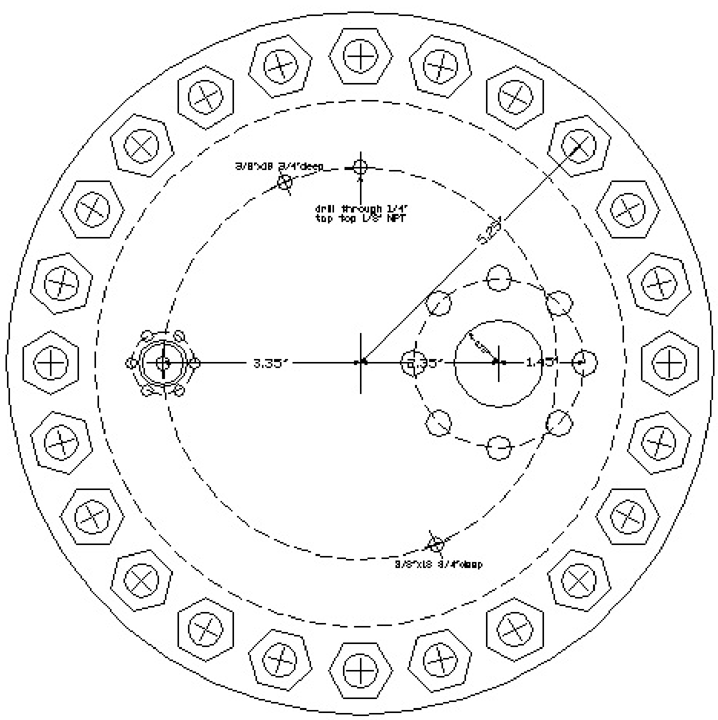


Figure 6. Test Cell Top Plate Schematic

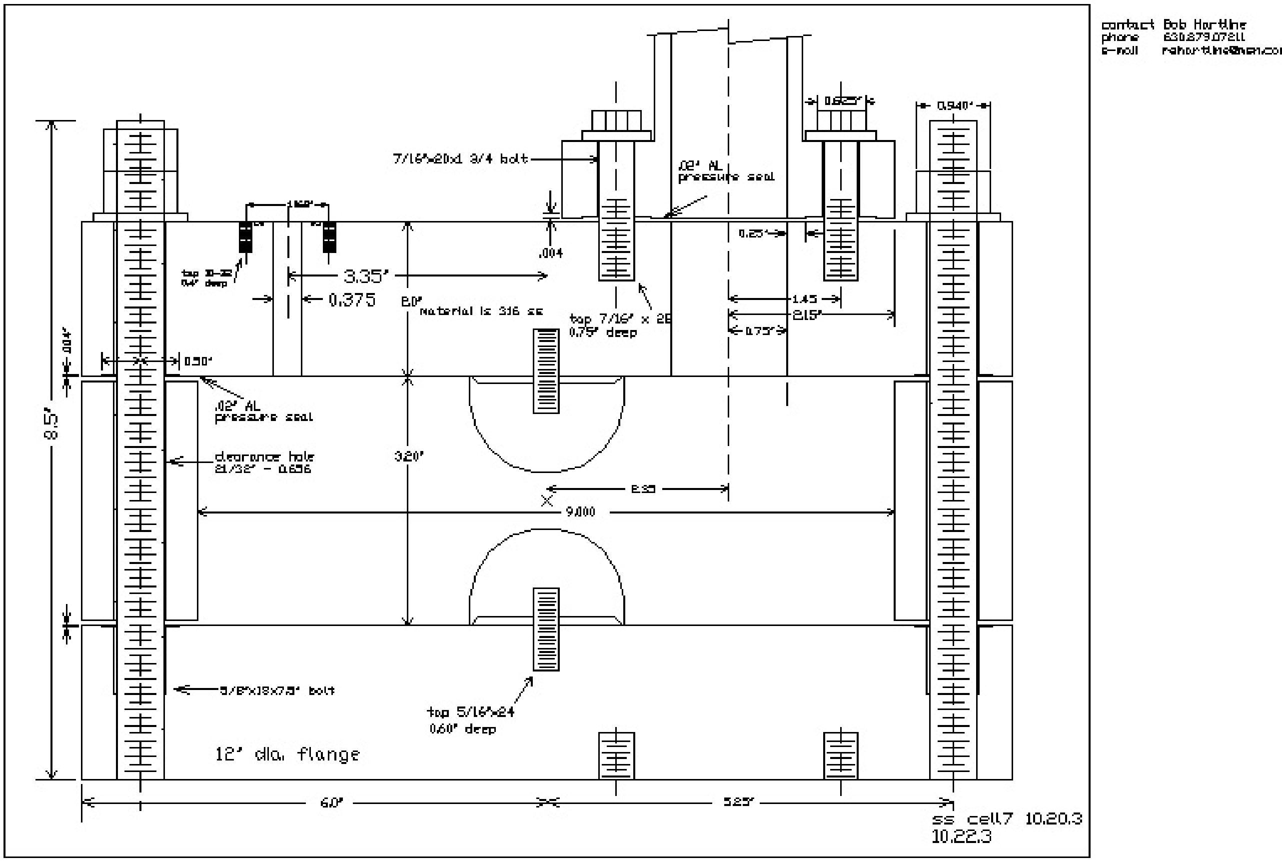


Figure 7. Test Cell Schematic

Figure 8. Picture of the Mark II Stainless Steel Disks and Cylinder before copper plating. Compared to the first test cell, the thickness of the disks has been increased from one to two inches, the cylinder has been changed from copper to stainless steel and made thicker, and the bolt diameter has been increased from 7/16 inches to 5/8 inches. The RF/Pressure seals have been changed from Pb-Sn solder rings in grooves to flat aluminum gaskets.

Flammable Gas Analysis for the High-Pressure RF Test Cell Setup at Lab G

Rolland Johnson
1/25/2003, revised 11/12/03

This Test Cell is required by Fermilab to conform to the Guidelines for the Design, Testing, Installation, and Operation of LH2 Targets. In addition we have elected to conform to the features of FESHM chapter 6020.3 listed below.

This document describes the Flammable Gas analysis for the high-pressure RF Test Cell (TC) to be used at Lab G for the study of high voltage breakdown of dense hydrogen gas. Depending on the tests, the TC must operate at liquid nitrogen (LN2) or room temperatures. The TC will be filled using a manifold that allows an operator to pressurize the TC from a gas bottle, to depressurize the TC by venting the gas outside of the Lab G building, or to purge the TC by alternately pressurizing and then venting out gas to the roof. A schematic of the gas system is shown in the Flammable Gas Analysis section below along with operation procedures and the checklist for preparations and conclusions to flammable gas operation in Lab G.

In the sections below, the relevant sections of the FESHM manual chapter 6020.3 Rev 8/95 are discussed. The extracts from the FESHM are in normal type and *Analysis and Comments are in italics.*

CLASSIFICATION OF GAS STORAGE AND USAGE FACILITIES

The Test Cell requires a maximum of 22 SCF of hydrogen to operate at 34 atmospheres and at liquid nitrogen temperature. A bottle of 250 SCF is the most that will be needed for several fills and the most that will be allowed in Lab G at one time. By the rules of FESHM chapter 6020.3 revised, as shown in figure 1 of that manual using the values for hydrogen shown in Table 2, the Test Cell and its associated gas storage area are Risk Class 0.

PROCEDURES FOR APPROVAL

1. **Risk Class 0**

The risk analysis shall be reviewed by the Fire Hazard Subcommittee or by an independent reviewer appointed by the Division/Section head. A copy of the independent review shall be sent to the FHS. Approval by the Division/Section head is required before the introduction of flammable gas into a system.

REQUIREMENTS FOR FLAMMABLE GAS INSTALLATIONS

A. <u>Risk Class 0 Installations:</u>

1. The area shall be posted "Danger-Flammable Gases, No Ignition Sources" using standard signs available from the Fermilab ES&H Section, Health and Safety Group. A list of responsible persons with their phone numbers shall also be posted.

The TC will only be filled with hydrogen when it is being actively studied. Two responsible persons will always be in Lab G when hydrogen is being used. The appropriate signs will be posted. These and other requirements are part of the procedures for preparation and conclusion of hydrogen operation as listed in Hydrogen Operation Checklists.

2. Combustibles and ignition sources shall be minimized within three meters of gas handling equipment, piping, or apparatus.

Combustibles will be kept away. The equipment in the blockhouse will be examined for possible ignition sources and a plan for any needed changes will be developed and implemented before hydrogen is introduced. The electrical components relating to the RF equipment are necessarily well shielded and well grounded.

3. A pressure regulator appropriate for the gas and its environment shall be used.

The regulator is certified for use with hydrogen.

4. An orifice, excess flow valve or other fixed means of limiting the flow to no higher than ten times the maximum operational flow rate shall be installed.

The valve used to raise the pressure in the TC (FV in the schematic below) is a needle valve with a maximum measured flow rate of 12 liters/minute for ΔP=100 PSI according to Cary Kendziora and Jim Tweed.

*In the case of a hypothetical broken regulator on a 2000 PSI hydrogen bottle, the maximum flow through FV becomes (12/28)*sqrt(2000/100)* sqrt(1/S_g=.0695)= 7.27 SCFM. For Helium the specific gravity S_g is 0.1381 and the maximum rate is reduced by root 2, or 5.14 SCFM. These two rates define the actual maximum operational flow rates rather than a rate10 times higher than maximum.*

These two rates have three implications for Lab G operation:

First, regarding the maximum overpressure the TC could be exposed to in the case of a regulator failure. As shown in the "Note on Flow Rates of Compressible Gases through Pipes and Valves", even with a long thin vent pipe, the flow of gas through the relief valve is 288 SCFM for hydrogen, roughly 40 times the maximum current through the FV needle valve. Thus the pressure on the TC side of the needle valve will drop once the relief valve opens and there will be no TC overpressure above the relief valve opening pressure.

Second, regarding the need to consider the case where the entire 250 SCF of the hydrogen bottle is accidentally emptied into the blockhouse. Since the operating procedures have been changed such that the TC is filled only once and then FV is closed, we only have to consider the few minutes when an operator is actively at the manifold bleeding the gas into the TC. If the regulator failed during this carefully monitored filling operation, the manifold pressure MP would increase thereby signaling the operator to close the fill valve FV. In the seconds it would take to close FV, less than 1 SCF of gas could pass through even at the maximum 7.27 SCFM flow rate.

Third, regarding the need for hoods and special vents around the test cell. With the maximum amount of hydrogen in the blockhouse limited to the contents of the TC (22 SCF), the fraction of hydrogen in the blockhouse volume (2100 SCF) is about 1%, which is below the ignition *fraction. Additionally, since the ODH analysis requires the blockhouse air to be exchanged every 3 minutes, the effective blockhouse volume is larger for hypothetical leaks even with large rates. The blowers providing the air exchange will ensure good mixing so that no dangerous condition can exist at or beyond the 3-meter ignition source boundary. The only way to develop a potentially dangerous condition within the blockhouse is to prevent the gas from a hypothetical TC leak from mixing with the air from the exchange blowers.*

5. All gas cylinders shall be secured. Cylinders not in use shall be capped. Empty cylinders shall be promptly removed.

6. Enclosed volumes containing piping or equipment shall be incapable of becoming pressurized. For example, chest freezers shall not have latching doors. Electrical devices enclosing or enclosed within these volumes shall be listed for use in Class 1, Division 2 locations per NEC article 500 or otherwise be documented and approved as non-sparking devices.

There are no such enclosed volumes in this experiment.

7. Leaks from experimental devices such as drift chambers shall be measured and documented prior to initial operation (with nonflammable gas, if possible). Leakage above seven liters/hour from any one chamber shall be mitigated. Recheck for leaks after major repairs or modifications, and at least every twelve months. Leakage exceeding 20% of the lower explosive limit at a distance over two inches from an identified "point" leak shall be repaired.

*One liter is 1000 cm^3 or $1000/(2.54cm/in\ 12\ in/ft)^3 = 1/28.317\ ft^3$. Seven liters/hour is thus ¼ SCFH. At 500 PSI the TC contains 34*0.15 SCF = 5 SCF. A leak of 7 liters/h would cause the pressure to drop at 0.25 * 500 / 5 = 25 PSI/h. The TC pressure gauge (TP in figure 1) is calibrated and a pressure change of 10 PSI can be easily seen. Thus in a period of ½ hour of constant conditions (thermal equilibrium at room temperature) it can be verified that there is no leak greater than seven liters/h.*

An additional test to verify that the TC is still leak tight after being cooled to LN2 temperatures was discovered in testing sealing methods. This involves looking for gas bubbles rising through the liquid nitrogen from the TC after it has been cooled, submerged, and pressurized. A sealed flashlight suitable for this purpose will be placed near the cryostat. Although this technique has not yet been calibrated, it seems extremely sensitive, as anyone who has ever fixed a tire with a slow leak using this method will understand. Nitrogen gas or air cannot be used to pressurize the TC for this test as any liquefaction within the TC could obscure a leak.

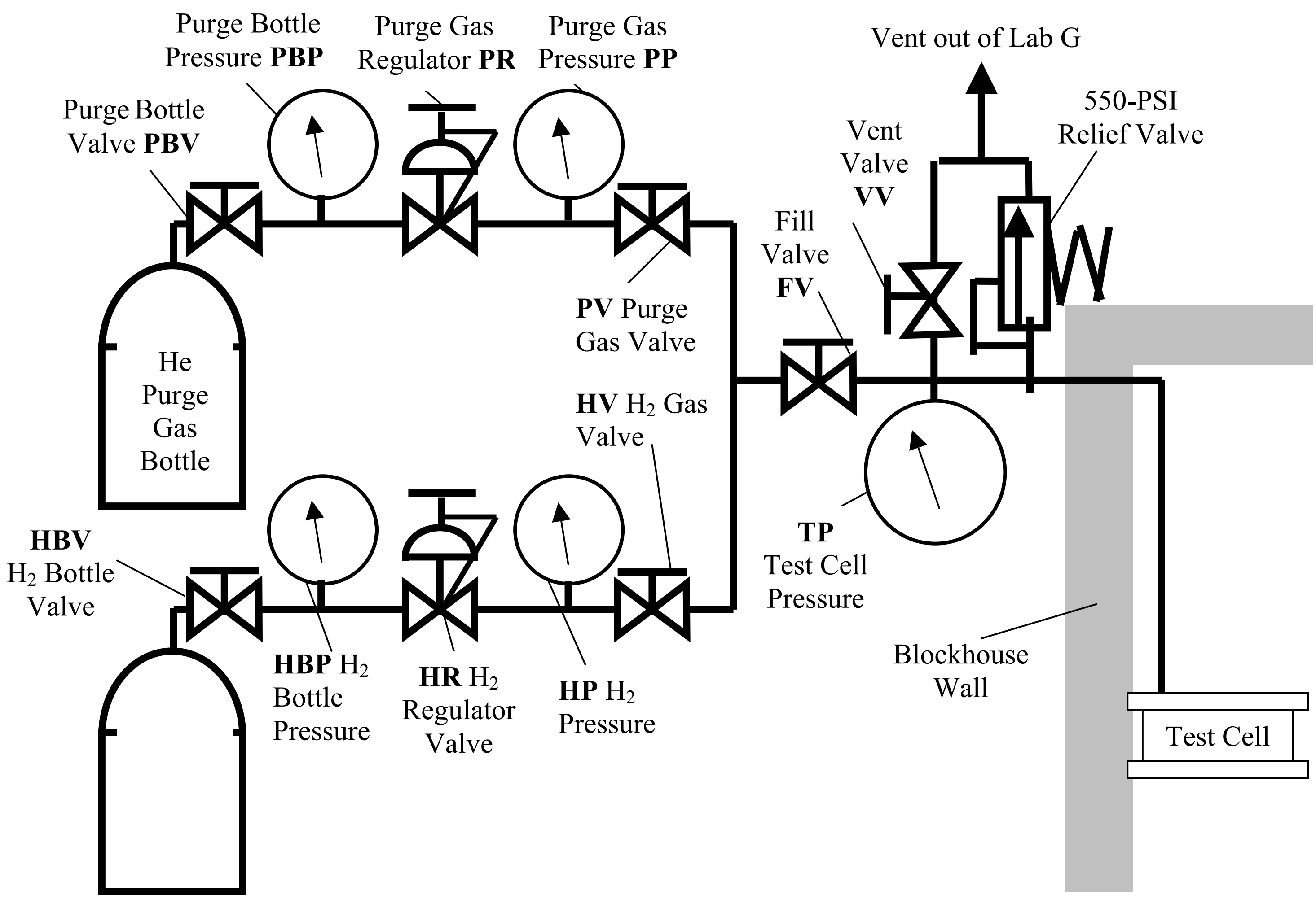
8. Ventilation above one air change per hour shall be maintained in areas using or storing flammable gas. This may be accomplished by mechanical or natural ventilation. For natural ventilation, a room vent with a minimum of 1/2 square foot free area shall be provided per 1000 cubic feet of room volume.

The Lab G high bay is estimated to be 77 ft. long by 51 ft. wide by 24 ft. high. The volume is 94,248 cu. ft. Natural ventilation in the main part of Lab G where the 250 SCF hydrogen bottle sits is sufficient. Within the 2101 cubic feet of the blockhouse, ODH considerations require forced ventilation of 20 air changes per hour. This blower system will be operational and is included in the checklist for hydrogen operation.

9. Welding permits shall not be issued for areas within ten meters of the equipment containing flammable gas unless approved in advance by the responsible Division/Section head or designee.

Since the hydrogen gas is only being used when responsible people are nearby, welding activity will not be allowed.

TC Gas Schematic



Lab G High-Pressure Test Cell Gas Control

TC Operation Procedure

See the gas system schematic below for reference. **Two responsible operators are required to be in Lab G while hydrogen and/or liquid nitrogen are being used**. After the test cell has been cooled down or if hydrogen has been used, the two operators are required to be present until "After Cooldown or Operation with Hydrogen" checklist is complete. The valves and gauges are labeled:

There are five pressure gauges:
HBP - **H**ydrogen **B**ottle **P**ressure,
HP – **H**ydrogen gas **P**ressure,
PBP – helium **P**urge **B**ottle **P**ressure,
PP – helium **P**urge gas **P**ressure, and
TP - **T**est Cell **P**ressure .
There are eight manual valves or regulators:
PBV –helium **P**urge **B**ottle **V**alve,
PR – helium **P**urge **R**egulator Valve,
PV – Purge **V**alve
HBV - **H_2 B**ottle **V**alve,
HR - **H_2 R**egulator **V**alve,
HV - **H_2** **V**alve
FV – Test Cell **F**ill **V**alve (needle valve), and
VV – Test Cell **V**ent **V**alve.

For Normal Operation:

1. Verify all eight manual valves are closed: **PBV, PR**, **PV, HBV**, **HR**, **HV, FV**, **VV**.

2. Purge the TC with Helium to reduce residual H_2, N_2, or O_2 levels:
Open PBV and FV. Use PR to set PP to 500 PSI. Open PV. Use PV to raise TP > 450 PSI.
Close PV. Verify TP is steady, signifying no leaks.
Use VV to lower TP to ~0 PSI. Close VV.
Close PBV and PV.
Repeat Step 2 if the TC has been open to air.

3. Purge the TC with H_2 to reduce residual He levels:
Open HBV. Use HR to set HP to 500 PSI. Open HV. Use HV to raise TP > 450 PSI.
Close HV. Verify TP is steady. Use VV to lower TP to ~0 PSI. Close VV.

4. For measurements of RF breakdown, the TC must be filled with hydrogen and then remain in a static condition for several minutes to make sure the gas temperature has come to thermal equilibrium with the TC. Subsequent measurements at lower pressure are made by venting gas from the TC.
Use FV to raise TP to the maximum desired operating pressure (e.g. 500PSI}.
This may take several minutes, especially when filling the cold Test Cell.
Do not leave the manifold unless HV and PV are closed.
Use VV to lower TP for new breakdown measurements.

5. When finished, Close HV and HR, and repeat step 2 to purge to helium. Use checklist below.

Hydrogen Operation Checklists

Before Operation with Hydrogen:

1. Post Signs at the 3 entrances to Lab G and near the Gas Manifold. The signs must say "Danger-Flammable Gases, No Ignition Sources" using standard signs available from the Fermilab ES&H Section, Health and Safety Group. Post a list of responsible persons with their phone numbers near the Gas Manifold.

2. Check for combustibles or ignition sources within 3 meters of the TC or Gas Manifold. Remove combustibles and disable or remove ignition sources.

3. Verify the condition of the gas system noting that the approved hydrogen regulator is functioning properly.

4. Verify that the approved hydrogen flow restriction needle valve RV is functioning properly.

5. Verify that gas cylinders are secured and that cylinders not in use are capped. Remove empty cylinders.

6. Verify that the blower system (with 20-air changes per hour) is operating in the blockhouse.

7. Verify that the required hydrogen hood with vent out side of the blockhouse is in place over the TC and that the required hydrogen gas detector and alarm are functional.

8. On the first purge cycle, verify that the TC maintains pressure for ½ hour to ensure that there are no leaks.

After Cooldown or Operation with Hydrogen:

1. Complete the Operation Procedure, ending with the purge to helium gas to 0 PSI as shown in step 2 and with all valves closed. Remove liquid nitrogen from the blockhouse.

2. Verify that gas cylinders are secured and that cylinders not in use are capped. Remove empty cylinders.

3. Remove the Danger signs from the Lab G entrances and near the Gas Manifold. Leave the list of responsible persons posted near the Gas Manifold.

To Change a Hydrogen Bottle:

1. Purge the system to helium as described in step 2 of the normal TC operation Procedure above.

2. Change the bottle, removing the empty one from Lab G.

3. Purge the system to hydrogen as described in step 3 of the normal TC operation Procedure above.

TC Cooldown Procedures

Workers on this project must be ODH qualified and must have a personal ODH monitor when in the blockhouse.

When the TC cooldown is in the blockhouse, the blowers must be supplying the 700 cfm ventilation required by the ODH assessment.

Place the TC in the cryostat and connect it to the klystron with the waveguides and adapters. (As we have learned from our first experience with klystron operation, the safest and least complicated method to attach the klystron to the TC is with the TC resting inside on the bottom of the cryostat, with the cryostat sitting on the floor near the waveguide. The RF connections are shorter and the wheels on the cryostat facilitate the connection of the components. In this configuration, the cryostat is as low as possible making it very stable against tipping and much easier to fill and monitor. In our original conception, clamps to the wall from the stainless steel coaxial pipe provided the support of the TC. This, we now believe would place unnecessary stress on the TC to pipe joint. We have also learned that the beer-keg cryostat is quite robust, easily providing support and insulation in the dozen times we have cooled the old TC in it.)

To cool the TC, hand-carried Dewars will be filled on the Lab G landing area and carried to the cryostat and poured in. Approximately 30 liters of LN2 will boil off during this cooldown. An additional amount will be needed depending on the anticipated time of the measurements. This amount will depend on heat leaks and RF loads and will have to be learned by experience.

For cooldown outside the blockhouse but in the Lab G building, needed for tests and calibrations without the klystron, no special ventilation blowers should be required. Although this experimental situation wasn't explicitly discussed in the ODH analysis, it was implicitly in that the only ODH requirement for TC cooldown is to blow the boil-off out of the blockhouse into the Lab G building.